

RESEARCH ARTICLE



Estimating the Water Balance of Irrigated Rice Fields in Dry Season Makurdi, Nigeria

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ABSTRACT

The water balance (WB) of three irrigated and isolated rice fields (1, 2, and 3) was examined during the dry season of rice cultivation in Makurdi from April 5 to May 6, 2023. Rice is mostly cultivated in the wet season, while dry season rice cultivation is limited by high irrigation costs, funding, and technical knowledge amidst vast water resources around the floodplains. Limited or no research estimates the water balance of a rice field in dry season Makurdi. WB took account of water inputs, outputs, and changes in soil water content (ΔW) in each water balance period. In Field 1, the WB showed a negative ΔW (-42.94 mm), which suggests that adequate water inputs are required to balance the water lost (outputs). The WB showed a positive ΔW of (89.36 mm and 464.75 mm) in Fields 2 and 3, suggesting that the water inputs be minimized to avoid wastage. The total irrigation in Fields 1, 2, and 3 was 499.28 mm, 1,186.95 mm, and 1,400.27 mm, respectively. The irrigation efficiency in Fields 1, 2, and 3 was 39.8%, 29.9%, and 20.9% respectively. The result indicates that Field 1's rice cultivation can be improved by providing adequate irrigation and enhancing the soil water retention capacity, while proper irrigation scheduling can improve Fields 2 and 3 rice productivity.

Introduction

Rice is a staple crop in Nigeria, which contributes significantly to food security and livelihoods [1,2]. Approximately 80 to 90% of small-scale farmers produce total rice output in Nigeria, with 75% of those farmers cultivating rice only in the wet season, while the remaining 25% cultivate rice in dry seasons [3,4]. Nigeria has vast land resources, estimated to be approximately 4.6 million hectares suitable for rice production but only 1.8 million hectares (39%) are used for rice cultivation [4–7]. The current annual output of rice production is approximately 5 million metric tons, which is lower than the national demand of 8 million metric tons per annum. Therefore, a deficit of 3 million metric tons was imported to close the gap needed to meet the demand of the growing population [6–8]. Various programs and policies have been initiated to increase rice production in Nigeria such as the National Rice Development Strategy I & II (NRDS I; 2008–2018, NRDS II; 2020–2030) [5,6]. The major objective of the strategy is to increase rice production in rain-fed lowland areas from 450,000 ha to 1.2 million hectares with supplementary irrigation and irrigated areas to 1.5 million hectares by 2030 [5,6]. Despite the abundance of water resources and significant investment in irrigation facilities, irrigation practices in Nigeria have not been able to achieve its goals of food self-sufficiency and socioeconomic development [6–8].

From previous studies [5,7,9], the average yield of rice grown in irrigated conditions is around 6 to 8 tonnes ha^{-1} higher than the average yield of rainfed lowland rice of 2 to 3 tonnes ha^{-1} . However, an estimated 3.14 million hectares of irrigable land are available for rice cultivation in Nigeria, but only 50,000 hectares are currently under rice irrigation [5,9]. This is insufficient to attain food sufficiency by 2030. To significantly increase rice productivity, small-scale farmers should be empowered with skills, tools, and prerequisite knowledge for irrigation design and management [6,10]. Approximately 60% of farmers produce rice once a

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year, while 13% of farmers use irrigation to produce rice twice a year [4]. Hence, there is an urgent need to increase irrigated farming to 50% by 2030 [5,11]. Rice can be grown in all agroecological zones in Nigeria, regardless of variations in rainfall patterns, temperature, vegetation, soil moisture, water availability, sunshine, etc. in each agroecological zone [6,8,10]. The total water required for rice consumption varies from 1,200 to 1,600 mm across agroecological zones [7,9]. The rice water requirement in these zones is dependent on soil properties, duration of variety, and local weather conditions [7,9,12,13].

Estimating the water balance requirement for rice in all agroecological zones will help irrigation managers and farmers manage and apply water effectively in both the dry and wet seasons. Water balance is defined as the amount of water that enters and exits a system (especially in rice fields) [14]. Water balance estimations depend on the soil type, crop type, and weather conditions of the fields. The input components are rainfall and irrigation, while the output components are evapotranspiration, surface runoff, horizontal percolation, infiltration, vertical percolation, etc. The measurement of these parameters can be complex and expensive. Most of the water balance measurements can be estimated. The results of estimating water balance are used for irrigation design, scheduling, and management.

The estimation will help control water losses from irregular irrigation such as horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land, which accounts for 50 to 80% of total water inputs [15]. Water-saving techniques, such as the System of Rice Intensification (SRI), Alternate Wetting and Drying (AWD), and Soil and water conservation (SWC) technologies are gradually being implemented to reduce field water consumption while enhancing crop productivity [16]. During the panicle initiation and ripening stages, rice requires a large amount of water for effective development and yield [17]. Therefore, proper estimation of water balance can enhance irrigation strategies to improve water-use efficiency during rice cultivation while minimizing water loss [18].

Potentials and Challenges of Dry Season Irrigation Farming in Makurdi, Benue State

Approximately 90% of the food produced in this state is produced by small-scale farmers [19]. Rice is produced only in the wet season with an average yield of 4.93 tonnes ha⁻¹, with no outputs recorded in the dry season (Figure 1) [4].

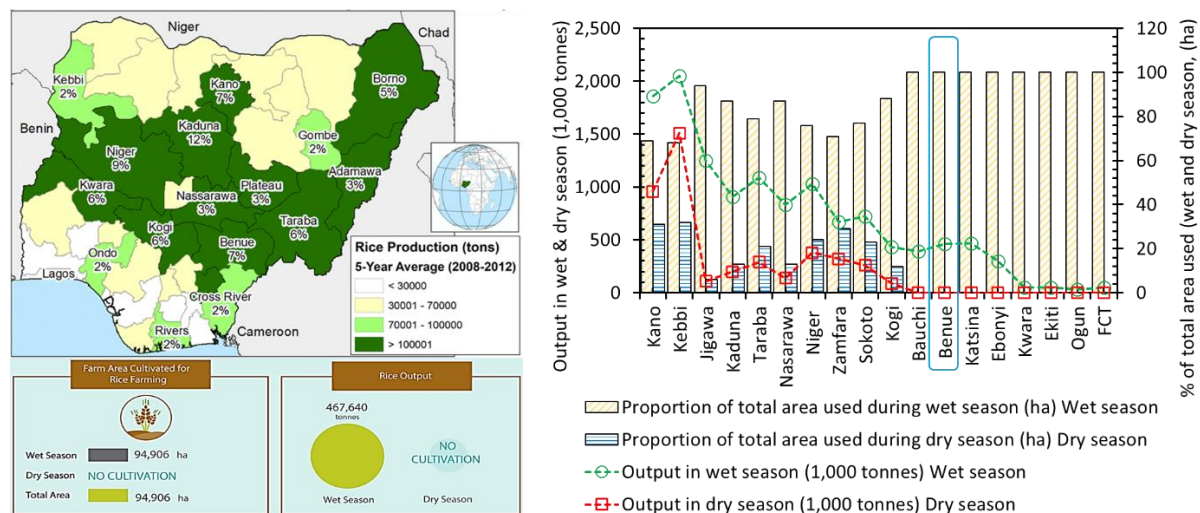


Figure 1. Rice production in Nigeria and the wet /dry rice statistics in Benue [4,20]

Benue State has huge land and water resources and is referred to as the “food basket of the nation” [21]. Makurdi is the capital of Benue State. River Benue is the second largest river in the country and the major source of water in the region with other sources such as rivers, streams, and groundwater that contribute to the overall water availability in the state [22]. Dry season irrigation in Makurdi remains underutilized because of several factors: high irrigation costs, expensive inputs (such as fertilizers, labour, and pumps), fire hazards, pests, inadequate government policies and incentives, herdsman-farmer conflicts, and a lack of technical knowledge among farmers [6,19,23]. Approximately 86.5% of the land in Benue is highly suitable for rice farming, which could be pivotal for enhancing food security and optimizing agricultural land use in Benue State [1]. During the dry season, upland streams experience significant seasonal water deficits, resulting in poor rice production in the dry season. However, approximately 600,000 hectares of land are suitable for dry

season agriculture in periodically flooded areas [19,24]. The Benue River stretches 34 km across Makurdi, with an estimated 115,600 hectares available for irrigated farming and fishing around the riverbanks/floodplain.

The floodplains have great potential for irrigated agriculture, however, the risk of seasonal flooding in floodplains in the wet season requires the implementation of appropriate management practices, including the need for drainage systems to prevent crop damage [25]. Most of the farming population along the riverbanks prefer to plant high-cash vegetables, such as (pumpkin leaves, okra, white-seed melon, jute leaves, etc.) during the dry season, which are cost-effective compared to rice farming [26]. Investments in small-scale irrigation facilities will boost dry-season and wet-season farming in Makurdi. According to Usman et al. [2,27], upland soils have a higher sand-clay ratio responsible for the high infiltration rates and erosion in the wet season, leading to severe water stress on crops in the dry season, while the floodplain has moderate infiltration, high water retention ability, and high fertility, thereby requiring little soil management to maintain their productivity. However, the lack of research on estimating the water balance in uplands and floodplains has not been properly exploited in Makurdi. Therefore, this study aimed to estimate the water balance of one upland and two lowland (floodplain) experimental fields in Makurdi during the rice milking stage to ascertain the rice water use of each field during the dry season. Irrigation efficiency was estimated to determine the performance of each irrigation system.

Materials and Methods

Study Area

The experiment was carried out at three different locations (Adaka farms, Field 1; The University of Agriculture farm, Field 2; and Benue University farm, Field 3) in Makurdi from April 1 to May 6, 2023, towards the end of the dry season. Makurdi is the state capital of Benue state which falls within the southern Guinea Savannah Zone of Nigeria ($7^{\circ}44'27.96''N$, $8^{\circ}30'43.56''E$). It covers 804 km² of the landmass in a 16 km radius [2] with slightly undulating topography and at an elevation between 70 to 163 m above sea level [1]. The state is drained by the Benue River, other smaller rivers, and streams. River Benue stretches 33.27 km through Makurdi dividing into North and South of Nigeria in Figure 2. It has a sub-humid tropical climate with two distinct seasons: the dry season, from November to early April, and the rainy season, from mid-April to November. The annual precipitation varies from 800 to 1500 mm, and the temperature ranges between 30.14 to 37.8 °C.

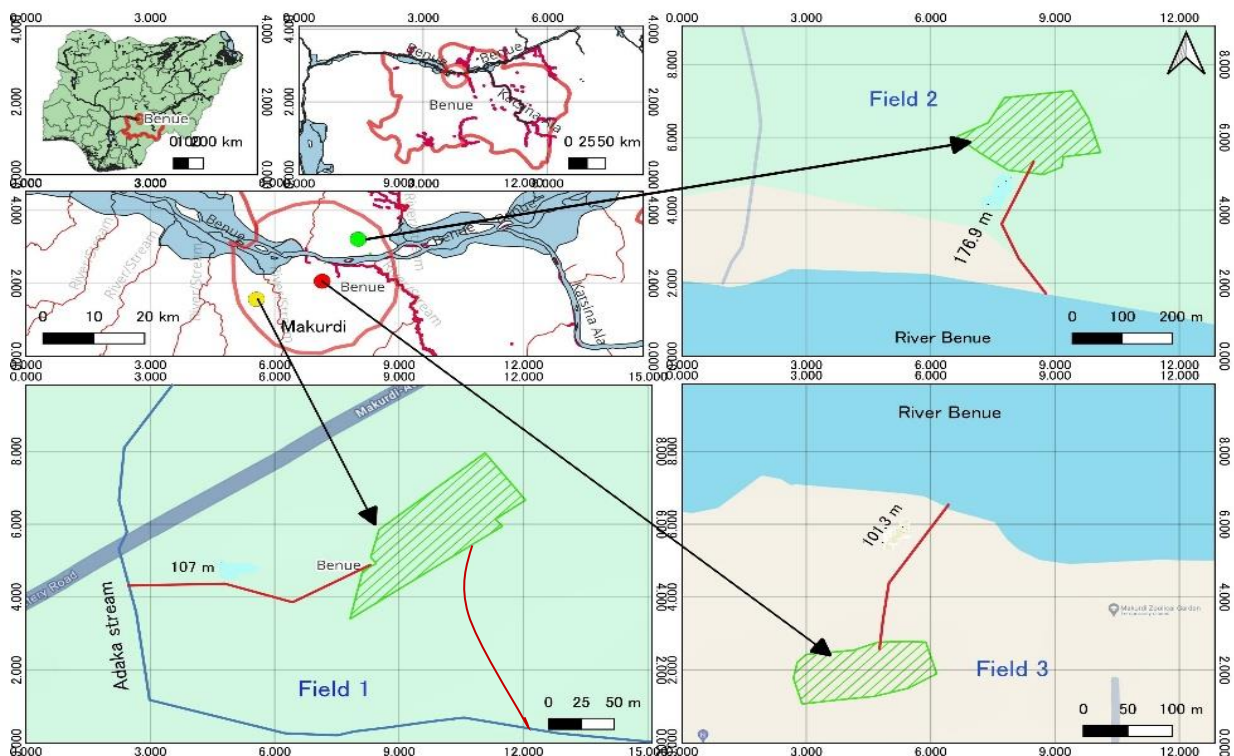


Figure 2. The map of the experimental fields in Makurdi from April 5 to May 6, 2023.

Experimental Design and Field Selection

The fields were selected based on the number of rice farmers in the Local Government Area (LGA) during the dry season. This was done by asking the rice-farming community. Only three rice farmers were identified in the experimental sites (Field 1, Field 2, and Field 3) as described in Table 1.

Table 1. Characteristics of the three experimental fields in Makurdi.

S/N	Latitude	Longitude	Area (ha)	Land type	Water sources
Field 1	7°41'33"N	8°27'60"E	0.790	upland	Stream
Field 2	7°44'59"N	8°38'02"E	0.840	Floodplain	River
Field 3	7°43'55"N	8°33'16"E	0.397	Floodplain	River

In Table 1, Field 1 is located inland of the city near a community stream while Fields 2 and 3 are located along river Benue floodplains (lowland). All fields made use of water pumping machines to pump water using flexible pipes of varying lengths connected from the pumping station by a stream or river (100–180 m) away from individual fields. Water is offloaded at the entrance of the earth canal created by the division of bunds (Figure 3 (c)). The farmers manually opened each bund to fill in the irrigated water. Fields 2 and 3 drew water for free to their farmlands, whereas Field 1 paid a water fee to use the stream shared by the village communities, adding to the cost of upland irrigated rice farming in the dry season. The size of the fields was measured using an application called the Field Area Map. It utilizes a real-time GPS satellite locator to measure the area of the field in real time by selecting a starting point while walking around the perimeter of the field and back to the starting point.

Farmers in Makurdi used the FARO 44 rice cultivar, which is a lowland, high-yielding, drought-tolerant rice variety with a maturity period of 90 to 110 days [12,13]. FARO 44 rice cultivar (*Oryza sativa*) was transplanted one seedling per hill into bunds so that rice plants could benefit adequately from irrigation in each field. In Field 1, rice seedlings were transplanted one seedling per hill in (5 × 5 m bund; a total of 110 bunds) at a transplanting space of 20 x 20 cm to give a plant population of 625 plants per bund. Rice seedlings were transplanted at one seedling per hill at irregular plant spacing in irregular bunds in Field 2, while in Field 3, rice seedlings were transplanted at one seedling per hill at a plant spacing of 25 x 25 cm in irregular bunds. Field experimental data such as infiltration rates (mm h^{-1}), pump flow rates ($\text{m}^3 \text{s}^{-1}$), and agronomical data on each of the fields were collected. The following land and crop management were recorded during the growing season: land preparation, planting date, cultivation, fertilizer application, weeding, pest, and disease control, and harvest dates at the three experimental fields, the details of which are shown in Table 2.



Figure 3. Field 1 (a–d): stream, pump station, irrigation, earth channel; Field 2 (e–g): River Benue, pumping station, irrigated field; Field 3 (h–j): River Benue, Pumping station, and irrigated field.

Table 2. Land and crop management (Day After Transplanting/DAT).

Site No.	Land prep & cultivation	Planting	Fertilizer Appl.	Weeding	Pest and disease control	Harvesting
Field 1	Manually ploughed with hoe and designed in bunds (5 m by 5m; 110 bunds)	Transplanted one seedling per hill at a plant spacing of 20 x 20 cm to give a plant population of 625 plants per bund at (25 plants m ⁻²)	Organic manure (chicken dung compost) was tilled within each bund at 2.5 kg per bund and Urea was applied 20 DAT	Manual weeding (more than 3 times), use of Agri force 100 mL and NOMINEE GOLD HERBICIDE 100 ml etc. as selective, systemic post-emergence rice herbicide control weeds, pests, and rodents at 8 DAT	Rice insect and disease attacks on crops had no observable effects.	At 116 DAT, the mature rice paddies were harvested, dried to a moisture content of 12 to 15 percent, threshed, winnowed, weighed, bagged, and sold
Field 2	Manually ploughed with herbicides (organic carbon and Agric-Boom) into irregular bunds.	Two weeks after sowing, the seedling was transplanted at one seedling per hill at irregular plant spacing	NPK was applied 14 DAT	Manual weeding by handpicking combined with hoes was carried out 15 DAT	Rice insect and disease attacks on crops had no observable effects.	At 119 DAT, the mature rice paddies were harvested and dried to a moisture content of 12 to 15 percent.
Field 3	Manually ploughed with a hoe and designed irregular bunds	Seedlings were transplanted at one seedling per hill at a plant spacing of 25 x 25 cm in irregular bunds	Organic fertilizers and Urea were broadcasted 12 DAT	Manual weeding by handpicking combined with hoes was carried out regularly	Rice insect and disease attacks on crops had no observable effects.	At 110 DAT, the mature rice paddies were harvested, dried to a moisture content of 12 to 15%.

Soil Properties

The soil in the study area was adopted from [2,28], classified as Vertic Endoaquepts/Vertic Gleysols, Aeric Glossaqualfs/Lixic Gleysols, and Typic Epiaquults/Ferralsic Acrisolstextural. The classes of horizons of the pedons were predominantly sandy clay loam [28]. The texture of upland soil is coarse, with a high percentage of sand compared to silt and clay, while the floodplain soil has a medium texture with more balanced proportions of sand, silt, and clay [25].

Estimation of Irrigation and Irrigation Rates

Water was pumped from the river or stream with a pumping machine using a 7.62 cm diameter flexible PVC water pump pipe of varying lengths in each field (Figures 3b, 3f, and 3i). The distance of each pumping station was 107 m for Field 1, 176.9 m, and 101.3 m for Field 2 and 3. The pumping machines in Fields 1 and 2 had similar pump discharge rates of 36 m³ h⁻¹, while Field 3 had 95 m³ h⁻¹. The pumping machines were owned by farmers and powdered using gasoline. Pumping machines do not operate optimally owing to aging or mechanical faults. To measure the discharge rate, a bucket was used to remove the water from the pipe during irrigation. The discharge rate was measured using the bucket and stopwatch method. The stopwatch recorded the time for water to fill the bucket in liters per second. The averages of 10 replicates for each irrigation period are presented in Table 3.

Table 3. Pumping rates for each field in each irrigation period.

	Area m ²	Flow rates (L s ⁻¹)				Irrigation rate (mm h ⁻¹)			
		IR 1	IR 2	IR 3	IR 4	IR 1	IR 2	IR 3	IR 4
Field 1	7,900	3.17	3.20	3.15	3.42	1.44	1.45	1.44	1.56
Field 2	8,400	3.74	3.77	3.89	4.12	1.60	1.61	1.67	1.77
Field 3	3,970	5.01	5.05	4.66	4.91	2.28	2.30	2.12	2.24

Note: Irrigation Period (IR) for each field.

Four irrigation periods (IR1, IR2, IR3, and IR4) were recorded in each field during field measurements. The difficulty in the bucket and stopwatch method is that it requires two or more people to perform. The pipe leakage can also affect the actual pump flow rate. The irrigation (mm) in each irrigation period was calculated by multiplying the irrigation rate (mm h⁻¹) by the total number of hours (h) in each irrigation period (Equation 1). The irrigation rates (mm h⁻¹) were estimated by multiplying the area of each field (m²) by the pump flow rate (L s⁻¹) divided by the time (h), as shown in Table 3. Note: The pump flow rate was converted from (L s⁻¹) to (m³ s⁻¹) to estimate the irrigation rate in (mm h⁻¹).

$$Irrigation (mm) = irrigation\ rate (mm\ h^{-1}) \times irrigation\ period (h) \quad (1)$$

Irrigation was periodically applied at the discretion of the farmers to avoid rice water stress. The irrigation was estimated in all fields from the onset of one irrigation period to the onset of another irrigation (Table 4). Bunds were used to control and retain water in each field during irrigation as shown in Figure 4. Irrigation measurements are reliant on the bucket and stopwatch method which are prone to marginal errors. A reliable method would use an irrigation flow meter to measure flow rates.

Table 4. Irrigation periods in each field.

Date	April	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	May	1	2	3	4	5	6	Tot. (mm)
P	(mm)							8.65				1.65				15.40	25.51					1.69		0.12											77.20
Field 1 (0.790 ha)	Irrigation	69.33	104.99					138.00				186.95																							499.27
Field 2 (0.840 ha)	period							307.49									387.26										280.37					211.81			1,186.93
Field 3 (0.397 ha)	(mm)										383.74							441.88									305.92					268.72		1,400.26	

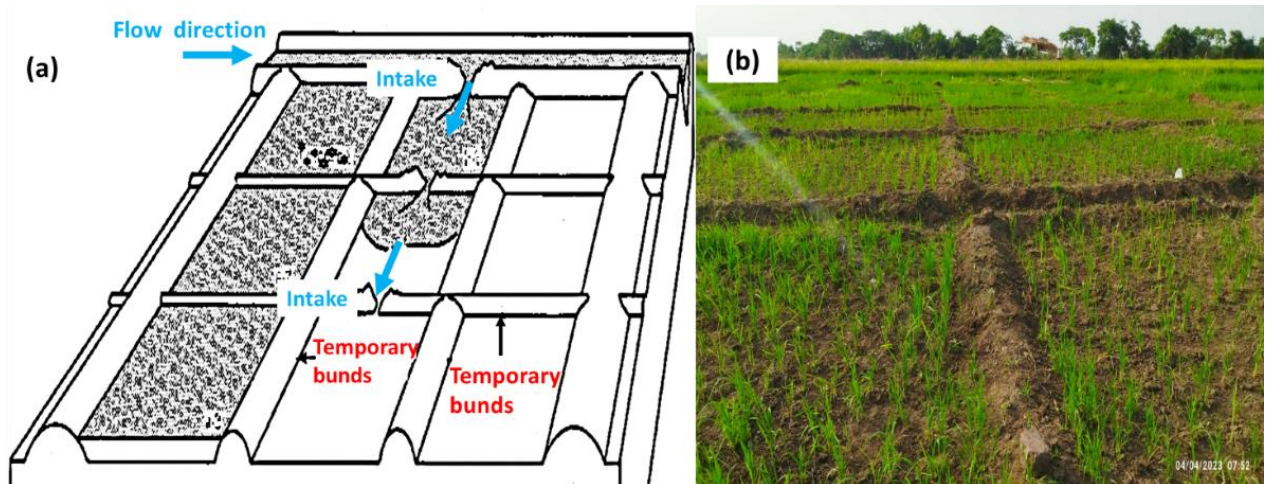


Figure 4. (a) Sample of flow direction of irrigation adopted from FAO and (b) Bund arrangements in Field 1.

Water Balance Estimation in Rice Fields

The water balance was estimated under irrigated field conditions. Water balance accounts for all water inputs, outputs, and changes in soil water content (ΔW) within a specified period. The water balance was estimated in all fields from the onset of one water balance period to the onset of another irrigation. The total number of days in each period for Field 1 was 14 days, 30 days for Field 2, and 26 days for Field 3. The water balance equation can be written as Equations 2 [14].

$$P + IR = ET + I_f + \Delta W \quad (2)$$

On the left side of the equation are the water inputs, such as precipitation (P) and irrigation (IR). On the right side of the equation are the water outputs, such as crop evapotranspiration (ET), infiltration (I_f), and the changes in soil water content (ΔW), as illustrated in Figure 5. Crop ET was estimated by Equation 7, precipitation was measured by ATMOS 41 (METER group, USA), irrigation supplied was measured by the bucket and stopwatch method (Table 3), and infiltration was measured using the double ring infiltrometer (Figure 6).

WB measurement is tedious and expensive. We were able to estimate ET, irrigation, infiltration, precipitation, and changes in soil water content (ΔW). We assumed that if the changes in soil water content (ΔW) did not change during the water balance period, ΔW would consist of horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land, as those were not measured or estimated individually. According to Oue and Laban [29], a large percentage of water inputs are usually lost through horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land. They were lost through the levee and infiltration during conveyance along the earth canals. These water outputs can be difficult to measure and are assumed to be very small or negligible.

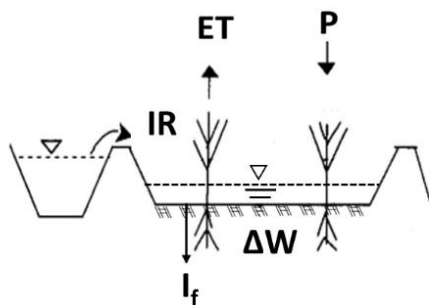


Figure 5. Water balance mechanism in a rice field.

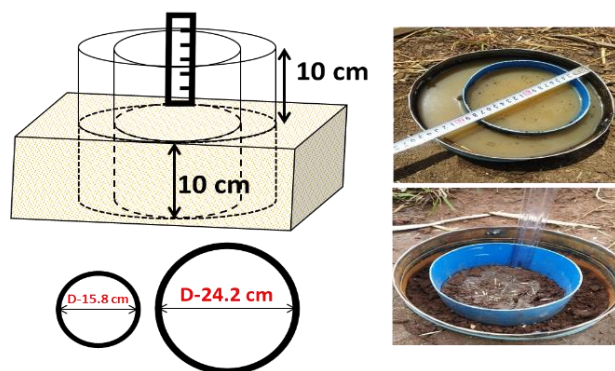


Figure 6. Estimation of infiltration rates using a double ring infiltrometer in Makurdi from April 5 to May 6, 2023.

Estimation of Potential Evapotranspiration from Meteorological Data in The Dry Season

Penman's 1948 equation was used to estimate potential evapotranspiration E_p from meteorological data measured from ATMOS 41 (METER group, USA) installed at 2 m height above ground level. Penman combines the rate of evaporation from the energy balance method with the rate of evaporation from the aerodynamic method in Equation 4 [30].

$$E_{pen} = \frac{\Delta(Rn - G - \Delta S)}{\Delta + \gamma} + \frac{\gamma E_a f(u)}{\Delta + \gamma} \quad (4)$$

Where E_{pen} is hourly latent heat flux in Wm^{-2} . Δ , is the slope of the saturation vapour pressure curve at the air temperature (t). Rn is net radiation in Wm^{-2} , soil heat flux (G) in Wm^{-2} , and ΔS is the change of heat energy stored in water in Wm^{-2} . $E_a f(u)$ is the rate of evaporation from the aerodynamic method as a function of wind function $f(u)$ at 2 m height. $f(u)$ defined as $(0.26(1+0.537u))$, γ is the psychrometric constant $0.66 \text{ hPa } ^\circ C^{-1}$, E_a is $(e_{sat}(T_a) - e_a)$, where $e_{sat}(T_a)$, is the saturation vapour pressure in kPa at mean air temperature T_a , e_a , is the actual vapour pressure in kPa. $(Rn - G - \Delta W)$ data were used from previous field measurements as a ratio to the solar radiation St in Wm^{-2} . The hourly values of E_{pen} were converted from Wm^{-2} to $mm \text{ h}^{-1}$ Equation 5.

$$L = (2499 - (2.52Ta)) \quad (5)$$

$$Ep = \frac{E_{pen} \times 3.6 h}{L} \quad (6)$$

Where L is latent heat in (J g⁻¹) and Ta is the average of the minimum and maximum temperature during the experiment [31]. Crop evapotranspiration ET was estimated by multiplying Ep by the crop coefficient (Kc) of rice during the rice milking stage. The Kc was adopted from [32] during the ripening stages. This was substituted to estimate ET in the study area. ET was converted from mm h⁻¹ to mm d⁻¹ in the study area.

$$ET = 1.18 \times Ep \quad (7)$$

Determination of Soil Infiltration Rates in Each Field

Infiltration is influenced by the percentage of sand, silt, and clay, ratio [33]. The soil water content is lower in the dry season compared to the wet season [34]. Therefore, the test was carried out based on the FAO measurement of basic infiltration rates [35]. Two randomly selected areas were chosen within each field with little or no vegetative disturbance. A total of four replications were carried out in each field to measure infiltration rates. A double-ring infiltrometer consisting of two cylinders with different diameters was used. The diameters of the inner and outer ring cylinders were 15.8 cm and 24.2 cm, respectively. The double-ring infiltrometer was driven 10 cm into the soil with a hammer and wood wedge in Figure 6. The water used for the test was supplied from the river or stream. To measure infiltration rates, the inner and outer ring cylinders were constantly filled with water and maintained at a given level. The water in the outer ring reduces the lateral flow from the inner ring. A ruler was installed in the inner cylinder to observe the infiltration rates in mm min⁻¹. Infiltration rates were observed at 2, 5, 10, 10, 15, 15, 20, and 20, 30, 30, 30-minute intervals. Measuring infiltration is tedious and time-consuming. One measurement might require the whole day. Adequate focus is required to ensure reliable data collection. The relationship between the measured infiltration rate and time for each given field was empirically estimated by Kostiakov's infiltration equation [36]. In 1932, Kostiakov proposed an equation to calculate cumulative infiltration. It expresses the cumulative infiltration equation as.

$$I = Ct^n \quad (8)$$

Where I, cumulative infiltration (mm), t, time from the start of infiltration (min). Also, a and b are constants that depend on the soil's initial conditions. Where, C > 0 and 0 < n < 1 [36]. The parameters in Kostiakov's equation are obtained by taking the logs of both sides of Equation 8.

$$\text{Log } I = \text{log } C + n \text{Log } t \quad (9)$$

A plot of log I against log t gives a straight line. The slope of the plot is n, and the intercept log (C). The value of C was obtained from the anti-log C. The estimated C and n are functions of the soil in the study area.

Estimation of Irrigation Efficiency as a Function of Water Balance

Irrigation efficiency is the ratio of water used by crops to the amount of irrigation water applied [37]. Which is available to plants to utilize for growth and development. Irrigation efficiency depends on the soil type (texture, permeability, and moisture), irrigation method, local weather conditions, and available water resources. Irrigation efficiency is the ratio of the outputs available (crop water requirements) to the inputs (total water used) [37].

$$\text{Irrigation efficiency} = \frac{(ET)}{(IR+P)} \times 100 \quad (10)$$

Irrigation efficiency (IE) was calculated for each water balance period. The sum of IE for each IR within each field gave the total IE for individual fields. IE is subject to the type of irrigation system. A 50 to 60% irrigation scheme efficiency is considered good; 40% is reasonable; and 20 to 30% is considered low [38].

Results and Discussion

Meteorological Data in The Dry Season

Meteorological data was measured during the rice milking stage in Makurdi from 16:00 on April 5 to 14:00 on May 6. The mean temperature (T) during the experiment was 29.9 °C, the mean relative humidity of 72.9 %, and the highest solar radiation was 933.4 Wm⁻². The total precipitation was 77.3 mm in Figure 7. The data logger failed to read data on April 12 due to technical uncertainty.

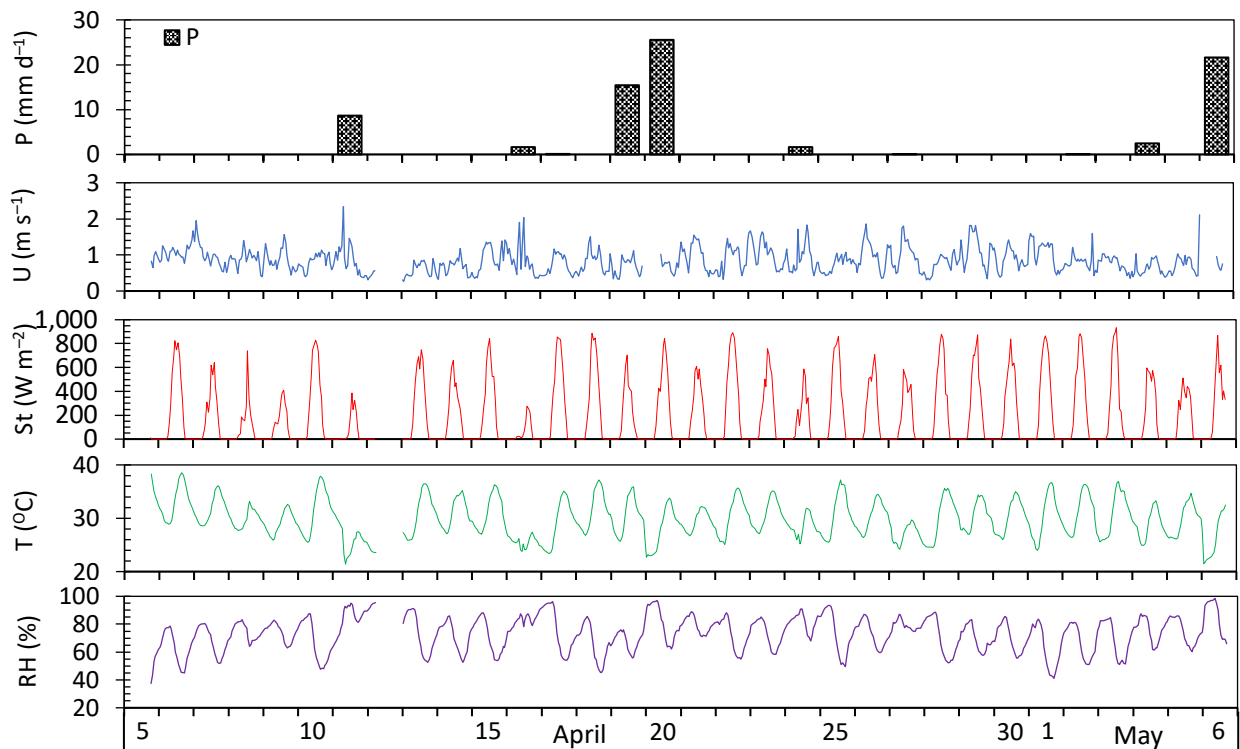


Figure 7. Daily variation of precipitation (P), and hourly variation of global solar radiation (St), wind speed (u), air temperature (T) at 2 m height, and relative humidity (RH) at 2 m height in Makurdi from April 5 to May 6, 2023.

E_p was estimated during rice milking stages (grain filling) in all fields as shown on the last graph in Figure 8. The milking stages for Fields 1, 2, and 3 was (94–110) DAT, (87–95) DAT and (80–86) DAT. To estimate ET, Equation 7 was applied. Hourly E_p was estimated from Equation 4 [31]. The total ET and E_p during the experiment were 110.4 mm and 93.5 mm, respectively.

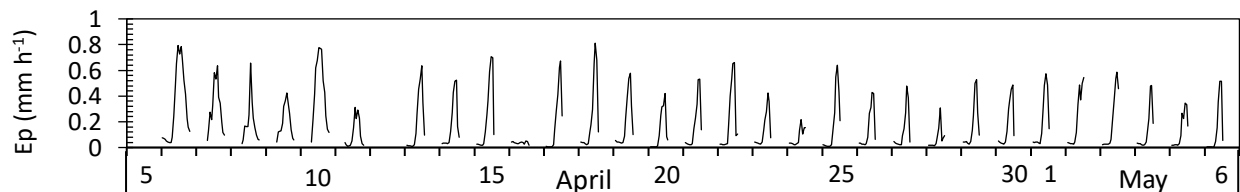


Figure 8. Hourly potential evapotranspiration (E_p) in Makurdi from April 5–May 6, 2023.

Comparison of Infiltration Rates Between Fields

By applying Kostiakov equation (Equation 8), the infiltration rate between each field is shown in Figure 9. Field 1 had the highest infiltration rate due to the difference in soil composition compared to Fields 2 and 3. This is consistent with [25], which reported that an unsaturated field condition had produced a higher infiltration rate than a saturated condition. Kostiakov equation (Figure 9) was applied to reproduce the measured I_f . The estimated C and n are functions of the soil in the study area. By using Kostiakov equation, I_f in the three fields were $I_{f1} = 4.205t^{0.7825}$, $I_{f2} = 4.96214t^{0.5813}$, and $I_{f3} = 7.0590t^{0.5013}$ in Fields 1, 2, and 3, respectively. The final infiltrations (I_e) estimated in the three fields by the Kostiakov equation were too large because the experiments were not conducted under completely saturated conditions. Therefore, we used a reference infiltration (I_{f_ref} , 1.5 mm h^{-1}) from a previous study in the same study area [25], to estimate reference infiltration (I_{f_ref}) as described in the next chapter. The total (I_{f_ref}) for Fields 1, 2, and 3 was 504 mm, 1,080 mm and 936 mm respectively.

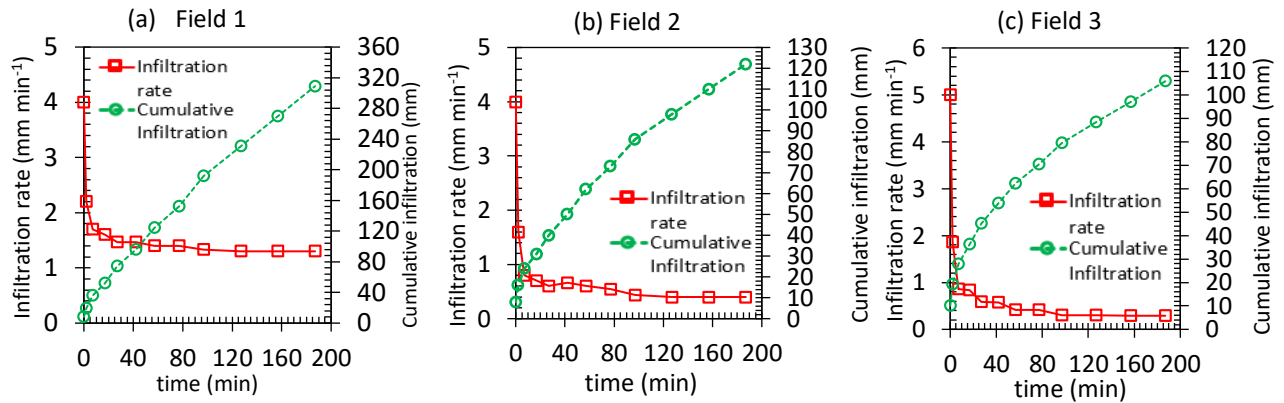


Figure 9. Observed infiltration rate and cumulative infiltration in the three fields in Makurdi, between April 5 to May 6, 2023.

Water Balance Estimations in Rice Fields

One of the most critical periods to irrigate rice fields sufficiently is during the (rice milking stage) grain filling stage [39]. The average water requirement for rice during the milking stage is between 400 to 420 mm, and the total water requirement for rice growth is between 1,100 to 1,250 mm [17]. Therefore, estimating the water balance during the rice milking stages (grain filling) in each field would help to understand how water is distributed and utilized [14,40]. The water balance took account of water inputs, outputs, and changes in soil water content (ΔW) in each water balance period, assuming that horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land were small or negligible. All the fields in this experiment were non-flooded and isolated with no adjoining plantations. If rice is cultivated in an isolated field, irrigation water can be lost to adjacent fallow fields through horizontal percolation. This phenomenon was reported by [41], who said that the horizontal percolation out of a saturated field is a gain to the adjacent fallow fields and no net loss to the system, however, water balance demonstrated that (ET and I_f) wouldn't be the only loss in such a system. A complete WB estimation should measure or estimate other output forms of water outputs including horizontal percolation to adjacent fallow fields. The results of the water balance of the three irrigated and isolated fields are presented in Figure 10. Table 5 illustrates the variation in water balance across the three fields.

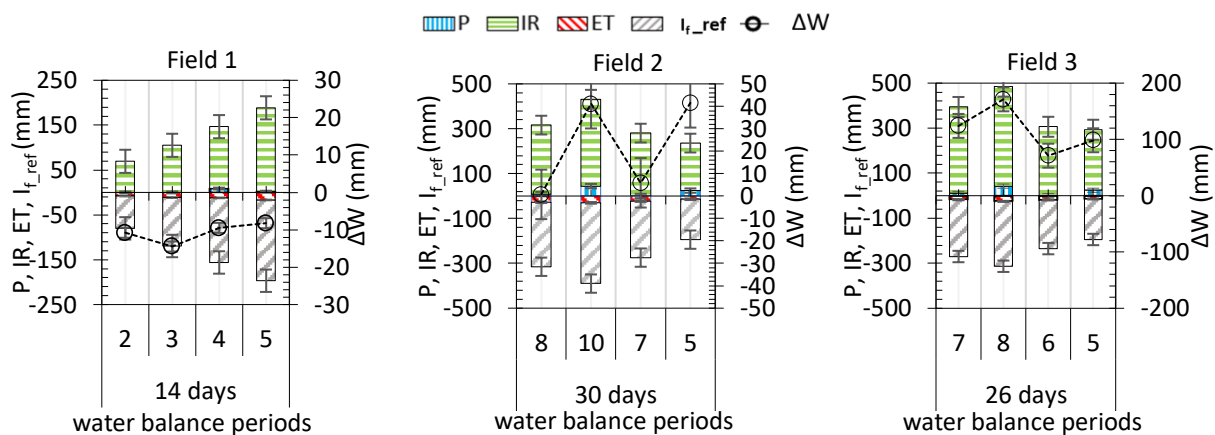


Figure 10. Water balance in each water balance period in Makurdi, April 5 to May 6, 2023.

The final infiltration (I_e) for each field was estimated when the fields were not completely saturated. This led to very too large infiltration rates. So, we used a reference infiltration (I_{f_ref} , 1.5 mm h^{-1}) [25]. We assumed (I_{f_ref}) to be the same for all fields, so we could evaluate the water balance in each water balance period using Equation 2. However, if the changes in soil water content (ΔW) did not change during the water balance period, ΔW would consist of horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land in these fields as discussed earlier.

Table 5. Total water balance (mm), and daily averages (mm d⁻¹) are shown in brackets in Makurdi, April 5 to May 6, 2023.

Site	water balance periods	No. of days per period	Total Irri. period days	Total water balance in each period (mm)				
				P	IR	ET	I _{f_ref}	ΔW
				mm	mm	mm	mm	mm
Field 1	5–6 April	2	14					
	7–9 April	3		10.30	499.28	48.52	504.00	-42.94
	10–13 April	4		(0.62)	(35.39)	(3.57)	(36.00)	(-3.56)
	14–18 April	5						
Field 2	7–14 April	8	30					
	15–24 April	10		77.20	1186.95	94.79	1080.00	89.36
	25 April–1 May	7		(2.59)	(39.89)	(3.14)	(36.00)	(3.34)
Field 3	2–6 May	5	26					
	11–17 April	7		77.20	1400.27	76.72	936.00	464.75
	18–25 April	8						
	26 April–1 May	6		(2.91)	(53.69)	(2.95)	(36.00)	(17.66)
	2–6 May	5						

Field 1 experienced a negative water balance because the total water inputs were less than the total water outputs Table 5. A negative ΔW (-42.94 mm) suggests that the upward capillary rise of groundwater or stored water beyond the root zone was able to compensate for rice ET under limited water inputs. The total water inputs were higher than the total outputs in Fields 2 and 3 resulting in a positive +ΔW (89.36 mm and 464.75 mm). The positive ΔW suggests that the excess water inputs applied in both Fields 2 and 3 were above the soil water field capacity resulting in excess water being lost to adjacent fallow fields through lateral percolation. This phenomenon agrees with [41], where water balance was able to account for horizontal percolative losses to adjacent fallow fields. Nevertheless, the yield of rice in all fields was not affected by the outcomes of water balance in all fields (personal communication from farmers). It is imperative to ensure that irrigation is applied in the right quantity and time.

Field 1 experienced a shortage of irrigated water because he shared the water resources (stream) with a fishing community. Water withdrawal in Field 1 was limited by the fishing community so they could have fish to catch. This played a major part in Field 1's negative water balance. The water situation in Field 1 can be improved by tapping into other sources of water such as wells, reservoirs, and boreholes. However, these facilities are expensive for upland (Field 1) farmers. The lack of these facilities, finance, and support discourages farmers from investing in upland dry season rice cultivation. Whereas farmers along the floodplain enjoyed unlimited access to water resources in the dry season but lacked the prerequisite knowledge about irrigation water management. Irrigation was applied solely on traditional observation of rice crops for signs of water stress.

To encourage farmers and to meet the SDG goals to attain food sufficiency, farmers in the study area need to be properly empowered and educated on water conservation measures in rice fields both in dry and wet seasons such as direct Seeding, rain harvesting, irrigation scheduling, use of drought resistant varieties and the use of organic manures and compost to improve soil structure and fertility. The water balance analysis could estimate the water use of each field, assuming that horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land were small or negligible. An extensive assessment of the water balance should include the measurement of other components such as horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land to provide a comprehensive understanding of water usage during the dry season.

Irrigation Efficiency in Rice Fields

Irrigation efficiency is the ratio of water used by crops to the amount of water applied [37]. The irrigation efficiency in each water balance period was calculated as the crop consumptive water use (ET) over the water inputs (Irrigation and precipitation) in percentages Equation 10. Irrigation efficiency (IE) was calculated for each water balance period and the total irrigation efficiency for each field was calculated by adding the sum of all the irrigation efficiencies in each water balance period Table 6. Hence, the total irrigation efficiency in Fields 1, 2, and 3 was 39.8%, 29.9% and 20.9%, respectively. Field 1 had the highest irrigation efficiency which implies that the ratio of the water outputs to inputs was slightly proportional, but additional water inputs or improved water retention strategies might be needed.

In Fields 2 and Field 3, the irrigation efficiencies suggest the water outputs were largely not proportional to the water inputs, with much of the unused water being lost to adjacent fallow fields through lateral percolation. Other irrigation water losses such as conveyance losses, pipe breakages, pump malfunctions, and horizontal percolation weren't accounted for and might have reduced the overall efficiency. Estimating the overall irrigation efficiency of a scheme can be expensive and tedious. The efficiency of surface irrigation systems ranges from 30% to 70%, depending on the irrigation management [42]. A 50–60% irrigation scheme efficiency is considered good; 40% is reasonable; and 20–30% is considered low [38]. Field 1 had a higher irrigation efficiency of 39.8 % within reasonable percentages. Fields 2 and 3 had poor irrigation efficiencies of 29.9% and 20.9%.

Table 6. Total irrigation efficiency in each field in Makurdi, April 5 to May 6, 2023.

Site	SN	water balance (mm d ⁻¹)					Irrigation efficiency %	Total Irrigation efficiency %
		Water balance period	P mm d ⁻¹	IR mm d ⁻¹	ET mm d ⁻¹			
Field 1	2	5–6 April	0.00	34.66	4.05	11.69	39.79	
	3	7–9 April	0.00	35.00	3.82	10.91		
	4	10–13 April	2.16	34.50	3.03	8.27		
	5	14–18 April	0.33	37.39	3.37	8.92		
Field 2	8	7–14 April	1.08	38.44	3.43	8.67	29.88	
	10	15–24 April	4.43	38.73	3.03	7.03		
	7	25 April–1 May	0.02	40.05	3.23	8.06		
	5	2–6 May	4.84	42.36	2.89	6.12		
Field 3	7	11–17 April	1.47	54.82	2.58	4.59	20.91	
	8	18–25 April	5.33	55.24	3.16	5.22		
	6	26 April–1 May	0.02	50.99	3.15	6.18		
	5	2–6 May	4.84	53.74	2.89	4.93		

Discussion

As earlier stated, the total water needed for rice consumption varies from 1,100 to 1,250 mm, depending on the soil's properties, duration of variety, and agroclimatic conditions [13,17]. But the average water requirement for rice during the milking stage as reported by TNAU [17], varies from 400 to 420 mm. The WB was estimated during the grain filling stage (Milking stage), a critical period to irrigate rice fields sufficiently [39]. Using Equation 2, we analysed the water balance inputs, outputs, and the changes in soil water content (ΔW) of the three fields during the milking stages in the dry season. We assumed that the changes in soil water content (ΔW) consist of horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land. Because the fields were not completely saturated during the infiltration measurements, the estimated I_e by Kostiakov equation was very large, so we used a reference infiltration (I_{f_ref} , 1.5 mm h⁻¹) from a previous study in the same area to estimate reference infiltration (I_{f_ref}). Though (I_{f_ref} , 36 mm h⁻¹) was applied to all three fields, the negative ΔW in Field 1 was significant. This shows that the negative ΔW in Field 1 would have been more significant if an actual I_e had been applied. It provides an idea of the infiltration conditions of Field 1 under slightly saturated conditions. More water inputs are required to keep Field 1 saturated for rice cultivation.

In each water balance period, water balance accounted for the changes in soil water content ΔW (positive and negative) in each water balance period. Field 1 experienced a negative water balance because the water outputs through ($ET + I_f + \Delta W$) exceeded the water inputs ($P + IR$). Fields 2 and 3 experienced a positive water balance because the water inputs ($P + IR$) exceeded the water outputs ($ET + I_f + \Delta W$). To ensure optimum water balance in irrigated fields, the water inputs should ideally balance the water outputs [14,31,43]. Therefore, water outputs in Fields 1, 2, and 3 can be reduced by cultivating other crops around isolated rice fields to minimize water output losses to adjacent fallow fields through lateral percolation. The fields should be properly levelled, pipe leakages should be minimized or avoided, and earth liners should be used in the main earth canals and bunds to reduce water outputs by horizontal percolation, vertical percolation to the deeper soil layer, and surface runoff to the adjacent fallow land [44].

Irrigation systems should ensure uniform water application throughout the entire field at the right time, minimizing water losses, and reducing costs [45]. These estimations have helped to identify the water consumption in each field during dry season rice cultivation. Sufficient irrigation is needed in these critical stages of rice growth such as the active tillering stage, during panicle initiation, booting, heading, and

flowering stages [39]. In Fields 1, 2, and 3, the water inputs (P+IR; 509.28 mm, 1,264.15 mm, and 1,477.47 mm) were higher than the average water requirement (400–420 mm) required during the rice milking stages. Farmers need to understand the water requirement for rice in each rice growth stage and the amount of water to apply in each stage. This can be overcome by educating farmers with practical solutions on irrigation scheduling and application, what time to apply, the uniformity of application, the influence of soil types on water consumption, effective farm management practices, weather conditions, and water resource management.

This will improve rice production in both dry and wet season. The water consumption in each field is influenced by factors such as soil type and water availability. Upland (Field 1) soils have a higher sand-clay ratio, lower water retention capacities, poor organic matter content, and texture, are prone to erosion, and are located near scarce water resources, while floodplains enjoy unlimited water resources and fair soil organic matter [25]. These attributes and the poor farm management practices in upland areas reduce rice productivity compared to lowland rice production [9]. Field 1 rice cultivation can be improved by combining traditional and modern techniques such as composting to improve soil organic matter, planting of cover crops to reduce erosion, rain harvesting, etc. Fields 2 and 3 (floodplain) rice can be improved by applying organic manures and the required quantity of irrigation. From previous studies [46,47], the adoption of these techniques has improved rice water consumptive use and yield. Farmers residing around areas with limited water resources in the dry season should reduce the sizes of their rice farms.

Conclusions

The water balance analysis made it possible to evaluate the water usage in each field during the rice milking stages. In each water balance period, water balance accounted for the water inputs, outputs, and changes in soil water content ΔW . Field 1 experienced a negative water balance because the water outputs through (ET + If + ΔW) slightly exceeded the water inputs (P + IR). Fields 2 and 3 experienced a positive water balance because the water inputs (P + IR) exceeded the water outputs (ET + If + ΔW). Frequent irrigation or improved water retention strategies are required in Field 1 to enhance water consumptive use. Irrigation scheduling and water resource management are required in Fields 2 and 3 to reduce water input wastage. The total irrigation in Fields 1, 2, and 3 was 499.28 mm, 1,186.95 mm, and 1,400.27 mm respectively. Field 1's total irrigation was slightly above (509.28 mm) the average range of rice water requirement (400–420 mm) during the milking stages. The total irrigation in Fields 2 and 3 was very high (1,264.15 mm, and 1,477.47 mm) above the rice water requirements of (400–420 mm) during the rice milking stages.

The irrigation efficiency in Fields 1, 2, and 3 were 39.8%, 29.9%, and 20.9% respectively, which showed how each field utilized water. Field 1 rice cultivation can be improved by tapping into other sources of water such as wells, boreholes, and reservoirs. Field improvement techniques such as the application of compost (animal dung, peat, plant waste, etc.), crop rotation with cover crops, and planting deep root base crops can enhance the soil and increase productivity. Field 1 rice cultivation should combine traditional and modern techniques such as composting for soil organic matter, planting cover crops for erosion reduction, rain harvesting, etc. For Fields 2 and 3 rice cultivation, applying organic manures and proper irrigation scheduling will help to avoid water wastage while increasing productivity. Farmers should be trained on irrigation scheduling, application rates, and water distribution to optimize their farming practices while increasing agricultural productivity during the dry season. Also, farmers residing around areas with limited water resources in the dry season should reduce the sizes of their rice farms. They should use drought resistant varieties while combining rice cultivation with less water demanding crops such as sorghum, maize, white-seed melon, etc.

Author Contributions

AU: Conceptualization, Methodology, Software, Investigation, Writing - Review & Editing; **HO:** Fund Acquisition, Supervision and Validation.

Conflicts of interest

There are no conflicts to declare.

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