Heliyon 7 (2021) e06703

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Supplementary irrigation for managing the impact of terminal dry spells on the productivity of rainfed rice (*Oryza sativa* L.) in Fogera Plain, Ethiopia

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ARTICLE INFO

Keywords:
Dry spells
Irrigation water productivity
Supplemental irrigation

ABSTRACT

A terminal dry spell is one of the main limiting factors for rice productions. Therefore, this study was conducted to assess the effect of supplemental irrigation for managing the impact of terminal dry spells on the productivity of different rice varieties grown under rainfed conditions in the Fogera Plain. The experiment was designed in a split-plot design with water regimes as main plot factors and rice varieties as a subplot factor with three replications. The water regimes were: dry planted rainfed rice (farmers practice) (FP), transplanted but not irrigated (IWOI), transplanted and irrigated to saturation (SAT), transplanted and ponding to 1 cm water (PD1), and transplanted and ponding to 3 cm water (PD2). The rice varieties were: X-Jigna (V1), Edget (V2), Hiber (V3), Fogera-1 (V4), and Nerica-4 (V5). The combined effect of PD2 with V1 had the highest grain yield (t/ha) (4.35 t/ha) while FP with V3 had the lowest grain yield (2.12 t/ha). The highest (205%) relative grain yield was obtained when V1 was grown under PD2 followed by V4 under PD2 (199%) and V5 under PD2 (192%) compared to FP with V3. Irrigation water productivity (WP_{IR}) varied between water regimes x varieties from as low as 1.84kg grain $mm^{-1}ha^{-1}$ for V3 in FP to as high as the yield of 3.07kg grain $mm^{-1}ha^{-1}$ for V1 in PD2. The highest and lowest net benefits were recorded for V1 grown under PD2 (65, 550 ETB) and for V3 grown under TWOI (33, 500 ETB ha^{-1}), respectively. Hence, the combined application of 3 cm ponding depth (PD2) with X-Jigna (V1) and 1cm ponding depth with Fogera-1 (V4) rice varieties could be suggested as effective terminal stress management to increase the yield and profitability of rainfed rice in the Fogera Plain and similar agro-ecologies.

1. Introduction

Worldwide, there is about 151.1 million ha of rainfed lowlands, which contribute 20% of the world's total rice production, and 14 million ha of rainfed uplands, which contribute 4% of the world's total rice production (FAOSTAT, 2019). However, water shortage is a major problem for crop production worldwide, limiting the growth and productivity of many crops, especially in rain-fed agriculture (Passioura, 2007). The dependency on the irregular input of precipitation can cause a shortage of water, commonly known as dry spells (Enfors and Gordon, 2007). The key challenge for lowland rice production is to reduce water-related risks posed by high rainfall variability rather than coping with an absolute lack of water (Rockström et al., 2007). Rice is introduced to Ethiopia in the early 1980s (Gebey et al., 2012). The average rice productivity in Ethiopia is estimated at 2.81 t ha^{-1}, which is much lower than the World's average of 4.7 t ha^{-1} (FAOSTAT, 2019). This is due to multi-fold factors. As reported by Gebey et al. (2012) lowland rice production in Ethiopia is constrained by occasional terminal drought, poor soil fertility, weeds, insect pests and it is also dry spell stress at the late season or due to early cessation of rainfall (Tadesse et al., 2013).

Crop yields are often reduced significantly due to the late start and early cessation of rain with long dry spells during the vegetative and reproductive growth stages (Tadross et al., 2009). A dry spell of any length could occur at any stage of crop growth; however, it is potentially detrimental if it coincides with the most sensitive stages such as flowering and grain filling (Stern and Coe, 1984). Rice has been identified as a water deficit susceptible to rainfed and drought-prone areas, showing negative effects, particularly in the booting, flowering, and grain filling

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https://doi.org/10.1016/j.heliyon.2021.e06703
Received 17 September 2020; Received in revised form 24 November 2020; Accepted 1 April 2021

stages leading to low crop productivity (Tsuda et al., 2010). Rice plants are the most sensitive to deficit moisture stress during the period about 10 days before flowering to the end of flowering (Yoshida, 1981).

The rice-based production system is intimately associated with sustainable water management practices mainly on developing and adopting strategies and practices through efficient use of resources. Such strategies and practices would produce more rice with low input of water (Renault and Facon, 2004). Kima et al. (2014) suggested that the application of 3 cm water depth above soil surface can be recommended to farmers as an alternative to save irrigation water and increase productivity. Similarly, as reported by Khairi et al. (2015) application of irrigation water at saturated to 1 cm ponding in a farmers' field for rice cultivation could be maintained optimal production. Bouman et al. (2005) and Atlin et al. (2006) suggested that the aerobic (saturated moisture level) rice system could be an option for farmers in rainfed lowland rice with a limited or an unreliable distribution of rainfall. More rice with less water can only be achieved through an integration of crop varieties and resource management practices at the field level (Tuong et al., 2005). Supplemental irrigation, the combination of rainfed farming and limited irrigation, are ideal choice for improving crop yield in the moisture-stressed situation (Deng et al., 2006).

Supplemental irrigation may be the tool for small-holder farmers to stabilize rainfed farming crop water supply and increase water productivity thereby increasing yields (Fox and Rockström, 2003). Supplemental irrigation is a key strategy, still underused, for solving rainfed yield potential, and water productivity (Rockström et al., 2010). Increased water use efficiency (WUE) of field crops was possible through proper irrigation scheduling by providing only the water that matches the crop evapotranspiration and providing irrigation at critical growth stages (Wang et al., 2001). Using a limited amount of water if applied during critical crop growth stages, result in a substantial increase in yield, water productivity, and improving livelihoods in the dry rainfed areas (Oweis and Hachum, 2006).

The rainfed-based rice farming in Fogera Plain is concerned with guaranteeing water accessibility at the terminal stage of the crop and subsequently stabilize rainfed rice yield. A major effort for rainfed rice farmers in the study area is to supply water to the rice farm and escape periods of water stress from heading to grain filling stages. Moreover, water access problems especially unable to use ground and river water properly and the lack of promising varieties, are closely linked to water management practices, in influencing the potential for grain yield production. With this intention, rainfed-based rice farmers in the study area need to integrate water management technologies, rice varieties, and rainfall dry spell patterns to overcome water deficit at the most sensitive growth stages of rice and thereby improving productivity. However, the study area lacks previously conducted supplemental irrigation for managing the effect of terminal dry spells studies which are supported by dry spell analysis results and data of the necessary popular rice varieties. Therefore, the objective of this study was to determine the effect of supplemental irrigation for managing the influence of terminal dry spells on the productivity of different rice varieties grown under rainfed conditions in the Fogera Plain, North-western Ethiopia.

2. Materials and methods

2.1. Description of study area

The experiment was conducted for two years (main rainy season) of 2017 and 2018 in Fogera District, North-Western Ethiopia. The study area is one of the rice production districts in the Fogera Plain located around the eastern part of Lake Tana Sub-Basin. The experimental site is located between Latitude $11^0 49'55$ North and Longitude 37^0 37′ 40 East

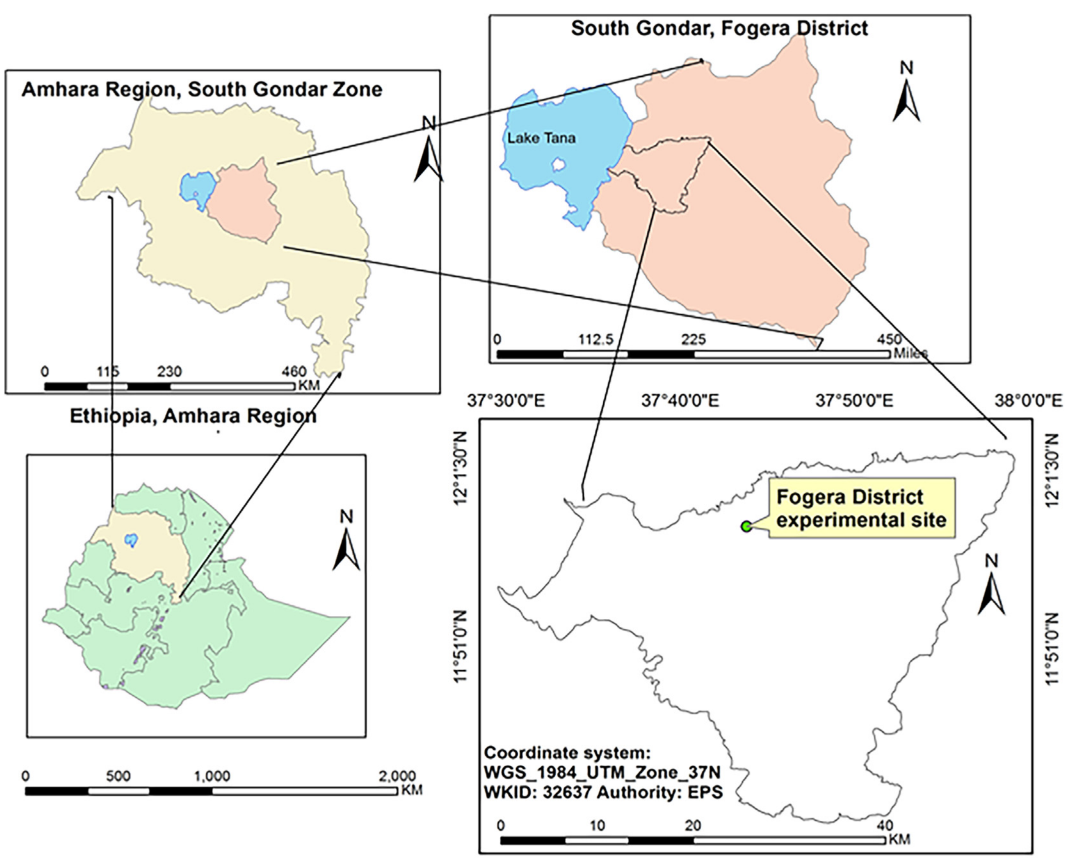

Figure 1. Location map of the study site (Fogera District).

(Figure 1). The altitude of the experimental site is 1815 m above sea level. Monthly rainfall and temperature data from the Woreta metrological station are summarized and presented in Figure 2. The study stations have a mean annual minimum and the maximum temperature of 12.75 °C and 27.37 °C, respectively with a mean temperature of 20.06 °C. The mean annual rainfall of the study district was received at 1320.20mm. The station receives high rainfall in July and August. As the data over the last 32 years show (Figure 2), the rainfall amount is relatively low in June (planting period) and September (flowering to grain filling period of rice). Table 2 presents the main physicochemical soil characteristics and climatic conditions of the experimental site.

2.2. Experimental design and procedures

2.2.1. Treatments and experimental design

The experiment was laid out as a split-plot design with two factors, water regimes as the main plot and rice varieties as a subplot with three replications. The water regimes were: dry planted rainfed rice (farmers practice) (FP); transplanted but not irrigated (IWOI), transplanted and irrigated to saturation (SAT), transplanted and ponding to 1 cm water (PD1), and transplanted and ponding to 3 cm water (PD2). The rice varieties were: X-Jigna (V1), Edget (V2), Hiber (V3), Fogera-1 (V4), and Nerica-4 (V5). The size of each gross plot was 4 m × 5 m (20 m^2) and 20 rows spaced at 22cm and with a gross experimental area of 60 m^2. The distances between the plots and blocks were 0.5m and 1m, respectively. The outermost rows at both sides of the plots and 0.5m row length at each end of the rows were used as borders. The third, fourth, and fifth rows at one side of the plots were designated for soil moisture measurement while the sixth, seventh, and eighth rows were used to guard the ninth to eighteenth rows which were used as a net plot for final biomass, grain yield, and measurements of yield components.

2.2.2. Field management and experimental procedures

The land was plowed four times and leveled using a shovel, a rake, and a leveling board. The experimental plot bund had 50 cm width and 30 cm height. The outer edge of each ridge was constructed by heavy clay and highly weathered (kaolinite types of clay) soil was compacted using a compaction rod to prevent water flow in and out of the ridges. Kaolinite clay was also mined from the local mine of clay pot makers. After the first leveling, soaking, and puddling, the soil was re-leveled and bund sealing was done. Similarly, ponding ridge construction was done next to the target plot ridge to maintain the water balance and control subsurface water flow out of the target plot during the application of supplementary irrigation. The direct application of irrigation water from the source to the command plot was maintained with 100% conveyance efficiency using plastic hoses. The puddling, bud sealing, and ponding to the minimum level reduced seepage and percolation losses with increased application efficiency. Puddling practice help to decrease seepage and percolation losses (Tomar et al., 2006). The soil is kept close to saturation and ponding to a 1 cm water level, thereby reducing seepage and percolation losses (Bouman et al., 2007). Combined seepage and percolation losses range from 1-5 mm d^{-1} in heavy clay soils to a massive 25–30 mm d^{-1} in sandy and sandy-loam soils (Bouman et al., 2005). Supplementary irrigation date was determined based on 32 years of rainfall dry spell length analysis, local farmers' experiences, and daily regular visits of rainfall amount from the nearby weather station during the experimental periods. When the rain stopped and/or greater dry spell at the terminal stage occurred, supplemental irrigation water was pumped from a previously constructed reservoir to the experimental plot through a delivery plastic hose. A valve and volumetric discharge measurement device were installed at the location where the plastic hose enters each plot and were used to control and measure the amount of water needed for each plot. Ponded water depths were measured in each main plot using perforated tubes of 10 cm diameter PVC and were installed in each main plot to 30 cm below the soil surface. The bottom 27 cm of the tubes was perforated with 3 mm-diameter holes at 2 cm intervals to record both above and below the grounds water level above grounds and below the groundwater level.

2.2.3. Plant material, planting, and fertilization

The planting material consisted of five rice varieties out of which four were improved varieties that have nearly similar days of maturity ranging from 110 to 130 days, and the other one was a local variety that has been cultivated by farmers in the study area for a long time. Seeds of the improved rice varieties (Edget, Hiber, Fogera-1, and Nerica-4) were obtained from Fogera National Rice Research Centre whereas seed of the local variety was obtained from farmers in the study area (Table 1). X-Jigna (local variety) is a tall variety", Fogera-1" and "Nerica-4" are medium in stature whereas "Edget" and "Hiber" are short varieties. A pre-germinated seed was prepared by soaking the seed over 24 h in clean water and then was incubated in a warm moist condition for 48 h by placing it in a sack filled to half its capacity. Sowing pre-germinated seeds was done in the nursery bed. The seedling that reaches 3–4 leaves stage or 20 days age was transplanted after the puddling experimental plot. Dry planting (farmers' practice) and transplanting were done in mid-June and at the end of the first week of July, respectively. Each plot received

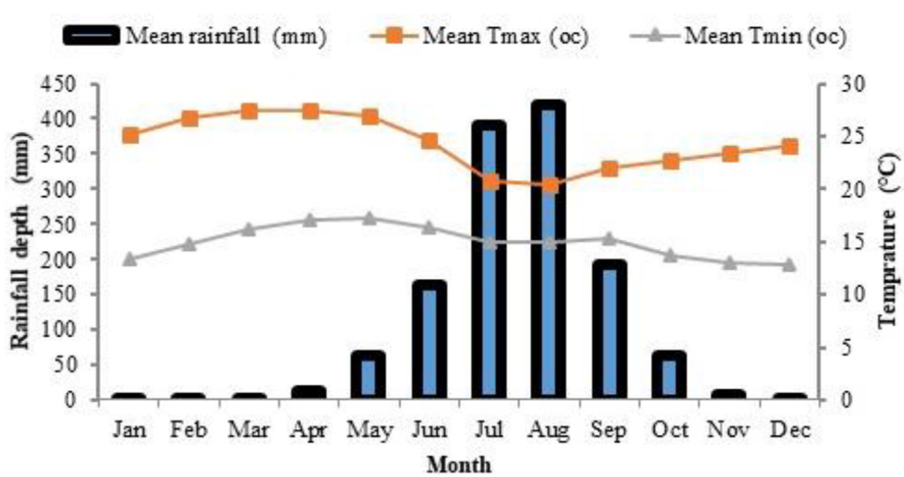

Figure 2. The monthly rainfall and temperature of Fogera District for the period 1986–2017.

Table 1. Description of the rice varieties used in the study area.

No.	Descriptor	Variety				
		X-Jigna	Edget	Hiber	Fogera-1	Nerica-4
1	Year of release	-	2011	2013	2016	2006
2	Plant height	95–100	80	75–80	85–90	80–85
3	Nos of days to maturity	130	132	110–141	120	110
4	Released Center	-	Adet/ARARI	Adet/ARARI	Fogera/EIAR	Pawe/EIAR
5	On farm productivity t/ha	3.4	3.2	3.5	3.2–3.9	3.0
6	On research productivity t/ha	5.0	5.2	4.2–5	4.2–5	3.4
7	Yield gap (t/ha)	1.6	2.0	0.7–1.5	1–1.1	0.4

ARARI, Amhara Regional Research Institute; EIAR, Ethiopia Institute of Agricultural Research Institute; Research centers (Adet, Pawe, and Fogera).

uniform doses of 69 kg ha^{-1} of nitrogen using urea (150 kg/ha of 46% nitrogen) and 23 kg ha^{-1} of phosphorus using diammonium phosphate (100 kg/ha of 18% nitrogen and 23% phosphorus) fertilizer sources. N was applied in two splits, one-third at planting, and two-third at the panicle initiation stage; whereas the full dose of phosphorus was applied at planting. The recommended agronomic practices were implemented based on the fertilizer recommendation of the Fogera national rice research center.

2.2.4. Soil water and crop water use determination

The soil water content of the rice field was taken from the depth of 60 cm from the central rows of each plot in two replications. The samples were taken per pit from the four directions of the pit at two depths with a 30 cm interval (0–30 and 30–60 cm) before and after irrigation. Soil water content was determined by gravimetrical method. Gravimetric soil water content was converted into a volumetric basis using a bulk density of soil cores taken from each depth. Based on the soil water data, before irrigation (actual moisture content) and after irrigation (soil in the saturated state) available water in the root zone was also determined (Lopez et al., 1996). Particle density was also determined by the graduated cylinder method (Bashour and Sayegh, 2007). Bulk density (BD) was again determined from the weight of undisturbed (core) soil samples, which were first weighed at field moisture content and then dried in an oven at 105 °C to constant weight (Baruah and Barthakur, 1997). The moisture content at ST (soil in the saturated state) was measured at 0 bars soil water potential using the pressure plate apparatus (Klute, 1986). The results were converted into volume percent (Vol%) by multiplying the gravimetric water content by bulk density. Irrigation scheduling was done using the information on crop coefficient (Kc), reference evapotranspiration (ETo) for proper irrigation scheduling. Allen et al. (1998) have presented updated values for crop coefficient and depletion level. Depletion level may vary due to climatic variation hence, numerically adjusted P for ETc rate is $P' = P$ presented $+0.04$ (5-ETc) where the adjusted P' is limited to $0.1 \leq P' \leq 0.8$, ETc is in mm/day. Reference evapotranspiration (ETo), which is an index for the evaporation demand of the atmosphere is estimated from the climatic data using the FAO-Penman Monteith equation (Allen et al., 1998). According to Brower and Heibloem (1986), irrigation water requirement of rice was determined using the following approach:

$IWR\ (mm) = DP(mm) + SAT(mm) + ET_c(mm) + SP(mm) - P_e(mm)$,

where, $IRW(mm)$ represents irrigation water requirement (mm); $DP(mm)$, depth of ponding (mm); $SAT(mm)$, depth of water required to saturate the soil (mm); $ET_c(mm)$, evapotranspiration of the crop (mm), $SP(mm)$ seepage and percolation losses (mm) (it was safely assumed 1–5 mm d^{-1} losses (Bouman et al., 2005)); $P_e(mm)$ effective rainfall during the period (mm).

2.2.5. Soil analysis

Initially, before planting, two composite soil samples (0–30 and 30–60 cm) were taken from six random spots across the experimental field with the auger. The soil samples were collected, air-dried, ground, sieved to pass a 2-mm mesh, and composited into one. Soil analysis was carried out from the composite sample in duplicates where soil samples were analyzed for soil texture using Bouyoucos hydrometer method (Bouyoucos, 1962). Total N content in the soil samples was determined titrimetrically following the Kjeldahl method as described by Jackson (1958). The pH of the soil was measured potentiometrically in the supernatant suspension of a 1:2.5 soil to water ratio using a pH meter as described by Chopra and Kanwar (1976). Organic carbon was determined using the wet digestion method (Walkley and Black, 1934) and Extractable P (available P) using the Bray II method (Bray and Kurtz, 1945). Extractable K, Ca, Na, and Mg were determined on the extracts solution with a flame photometer as described by Rowell (1994). The cation exchange capacity (CEC) of the soil was determined using the ammonium acetate method (Hesse, 1972). The electrical conductivity of the soil was measured by conductivity meter from saturation soil paste extracts as described by Rhoades (1996).

2.2.6. Climate data

Daily precipitation, relative humidity, wind speed, sunshine hour, and maximum and minimum air temperature for the site were collected from National Meteorological Agency (NMSA). Daily rainfall data monitoring was also collected during the experiment period from a nearby weather station (Woreta) almost one kilometer away from the experimental site.

2.2.7. Yield component parameters

Grain yield (GY t/ha) and above-ground biomass yield (AGB t/ha) were determined on harvesting the crop of the entire net plot area. Grain yield was represented based on moisture content set at 14%. For the adjusted grain yield = Moisture correction factors x non-adjusted grain yield obtained from each plot is recommended according to Birru (1979) and Mulvaney and Devkota (2020). Moisture correction factor (MCF) was obtained by the following formula:

$MCF = \frac{100\% - y}{100\% - x}$, where, $\dot{y}$ is the actual moisture content in% measured by using IRRI rice hand moisture tester instrument, $\dot{x}$ is the standard moisture content in % for rice crop. Dry matter accumulation of above-ground biomass was determined on two random spots of 10 hills from the net plot area. Samples plant tissues were dried at 70 °C in an electric oven to a constant weight using a forced-draft oven for drying. Harvest index was calculated by using the following formula: HI = (Grain yield)/(Grain + aboveground biomass yield) (Rahman, 1984; Fageria et al., 2011).

2.2.8. Irrigation water productivity

Irrigation water productivity (WP_{IP}) was calculated as: $WP_{IP} = \frac{GY}{SI+RF}$, where, WP_{IP} represents irrigation water productivity (mm); GY, grain yield kg/ha; SI, supplemental irrigation water (mm); RF, rainfall (mm). Whereas incremental irrigation water productivity (IWP_{IP}) was assessed using the following formula: $IWP_{IP} = \frac{YI-YN}{IR}$, where, YI, irrigated rice yield (kg/ha); ẎN, (non irrigated) rainfed rice yield (kg/ha); İṘ, irrigation depth of water (mm) (Cabangon et al., 2003).

2.3. Data analysis

2.3.1. Dry spell analysis

Daily rainfall data was employed for dry spell analysis using the first-order Markov Chain Model (The Instant Statistical Program (Version 3.37) (Stern et al., 2006).

2.3.2. Partial budget analysis

Data collected for economic analyses include the two experimental years' average labor cost of nursery management, transplanting and puddling labor cost, the labor cost of pumping water, water pump rent cost, and seed cost. Thus the average price for different rice seeds was 23 Birr kg^{-1}. Labor cost for nursery management, transplanting, and puddling labor cost, the labor cost of pumping water was 100 birr per man, per day. The cost of water pump rent was 250 birr a day. The average grain was adjusted by 10%. A partial budget analysis was conducted to evaluate the economic feasibility of the different water regimes + rice varieties under farmers' field conditions. Therefore, partial budget analyses were performed using CIMMYT agronomic manual (CIMMYT, 1988). The partial budget analysis was done by assigning the monetary values between each practice of input and each output resulted from the average of the applied treatments of the price data of over three years.

2.3.3. Statistical analysis

For all measured variables, normality was tested using the Shapiro-Wilk test of normality. Data from each year were analyzed separately, and homogeneity of variances was checked (Gomez and Gomez, 1984). A combined analysis of variance was done since the error of variances for the two years is homogenous. Whenever the treatment effects were found significant, treatment means were separated using the least significant difference (LSD) test at 5% (Gomez and Gomez, 1984) and using SAS (SAS Institute Inc, 2009).

3. Results and discussion

3.1. The pattern of dry spells across the rice-growing period

The estimated probability of dry spell lengths based on the first-order Markov Chain Model is presented in Figure 3. The analysis result revealed that dry spell lengths of 5 days (sp5), 7 days (sp7), 10 days (sp10), and 15 days (sp15) varied over the growing period from June to October. The probability of short dry spells (5–7 days) remains very low between DOY 160 to 240 at Woreta, whereas, the risk of short dry spells increases fast after DOY 240. The risk of long dry spells (10–15 days) is relatively low between DOY 150 to 260 in the study station but a fast increase of long dry spells was observed after DOY 260 (Figure 3). The longer dry spells pose greater adverse effects for rice crops at flowering and grain filling stages. It is therefore concluded that dry spell analysis and farmers' experience will support appropriate decisions when applying supplemental irrigation and appropriate planting date to minimize dry spell risk during the most sensitive stage of rice crop. A major constraint in realizing the potential yield of rice in the rainfed area is early out of rainfall due and causes a dry spell at the critical stage of rice.

As a result of substantial yield loss, long dry spells coincide with drought-sensitive growth stages such as flowering and grain filling stages (Stern and Coe, 1984). Long dry spells because of significant yield loss if they coincide with drought-sensitive growth stages such as flowering and grain filling stages (Stern and Coe, 1984). Generally, for the study periods, the probability of longer dry spells increased rapidly in Woreta starting from mid of September and it takes risks of longer dry spells. Thus, unless farmers get access to supplemental irrigation that minimizes the loss of moisture from the rice farmland, the condition could be severe to the extent of leading to substantial yield losses. The distribution of the dry spells presented in Figure 3, therefore, provides important information to plan site-specific rice planting and supplemental irrigation management in the Fogera Plain.

3.2. Daily rainfall monitoring and supplemental irrigation

The amount of daily rainfall and dry-spells of varying degrees occurred during September and the first week of October in Fogera Plain, Ethiopia, and the farmers perceived that the rice crop was stressed during the terminal growth stage.

This experience was confirmed in 32 years of daily rainfall dry spell analysis (Figure 3), and daily rainfall depth monitoring in the weather station during the experimental years (Figure 4a, b). The main season has four months (June, July, August, and September), including the first week of October which is the rice-growing period. From which only starting from mid of September to the first week of October was occurred was the time for the most frequently dry spell event (Figures 3 and 4a, b). Currently, it occurred at the heading to grain filling stages (from September 12 to October 5) of the rice crop development period whereby seven irrigations days with three days interval were applied at 12, 15, 18,

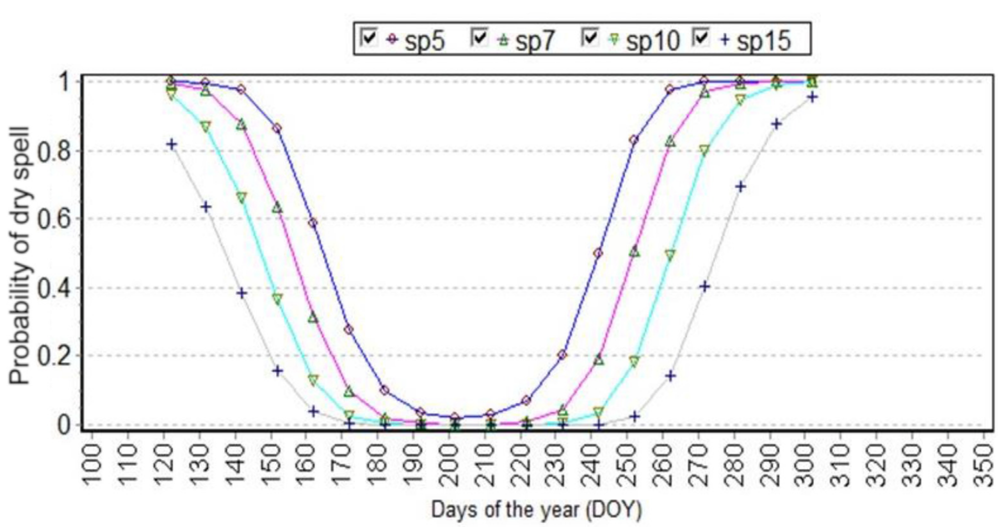

Figure 3. Unconditional dry spells length for Woreta station over the period 1986–2017.

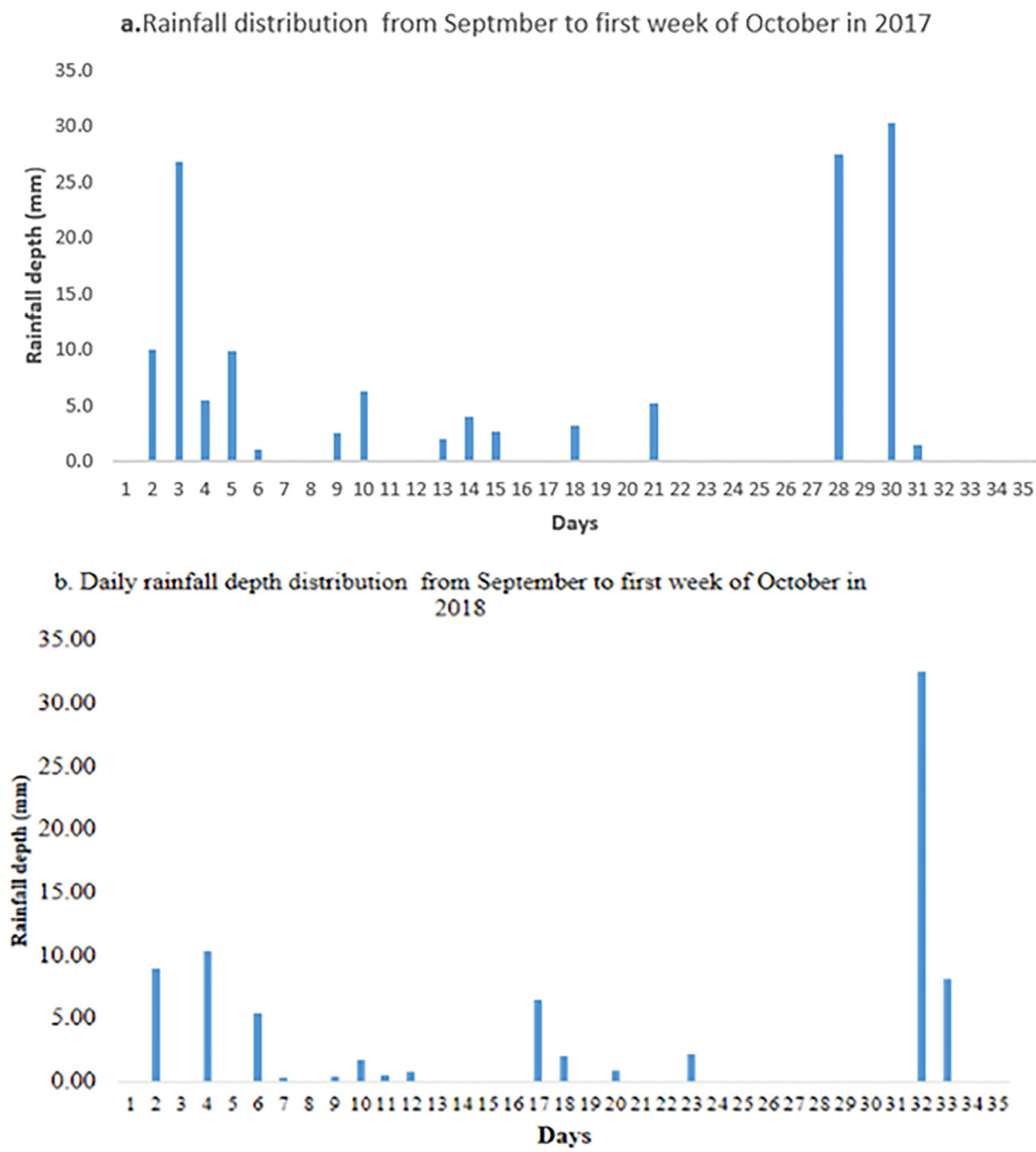

Figure 4. a, b. Daily rainfall distribution of September to the first week of October for the two growing seasons in 2017 and 2018.

21, 24, 27, and 30th of September (Figure 4a, b). The volume of water was applied based on irrigation water depth (Table 3). It is therefore concluded that dry spell analysis, daily regular visit rainfall depth and farmers' experience will support appropriate decision when to apply supplemental irrigation to minimize dry spell risk.

3.3. Experimental site soil characterization

The pre-plant soil (0–30 cm) and (30–60cm) depth analysis results showed that the top part of the experimental surface soil had 17% sand, 18% silt, and 65% clay, and the lower part of soil surface had 9% sand, 21% silt, and 70% clay. This implies that the textural class of the soil across depth belongs to clay texture. The analysis result indicated that the soil had medium bulk and particle density. Low bulk density and particle density values were recorded in topsoil (0–30 cm) as compared to lower depth soils (30–60cm). Bulk density was increased with increasing soil depth and the compactness of the soil due to the formation of the hardpan (Table 2). The total nitrogen (N) (0.21%) and available phosphorus (P) (9.85 mg/kg) of the soil were in the medium ratings. The level of available P and total N in the top surface soil was higher when compared to the lower depth (30–60cm depth) (Table 2). Similarly, organic carbon content (2.20%) follows the same pattern as total N and available P. Experimental site soil had a slightly acidic pH reaction which ranges between 5.38 and 5.87 across the upper and lower surface soil depth respectively. The surface soil had high cation exchange capacity (57meq/100gm of soil) and high base saturation due to the availability of medium level of exchangeable cations Ca^{++}, K^{+}, Na^{+}, and Mg^{++} (cmolc kg^{-1}) respectively. The higher cation exchange capacity (CEC) of the soil in this experimental site was due to high clay content and relatively better organic carbon percentage. Whereas, the amount of soil exchangeable cations decreased across the lower depth (30–60cm) of the surface soil due to decrease in CEC and increase soil compaction (Table 2).

3.4. Water balance component and seasonal water use

The water balance component of the ETc (evapotranspiration of the crop) and SP (seepage and percolation) losses, effective rainfall, and volumes of water used for supplemental irrigation are presented in Table 3. Evapotranspiration losses accounted for the largest volume water losses (40.4–47.33%) as compared to seepage losses (8–15%). The experiment was conducted under well-managed rice plots such as bund construction and compaction, leveling, puddling, bud sealing, and a low

Table 2. Selected soil physical and chemical properties of an experimental site (Fogera).

Physical properties						
Depth (cm)	Particle size (%)					
	Sand	Silt	Clay	Textural class		
0–30	17	18	65	Clay		
30–60	9	21	70	Clay		
Depth (cm)	Density		Moisture content (%) mm/m			
	BD ($_{g/cm3}$)	PD ($_{g/cm3}$)	SAT.	FC	PWP	TAW
0–30	1.24	2.73	54.0	41.65	29.15	46.13
30–60	1.30	2.80	54.0	43.15	32.01	43.50
Chemical properties						
Depth (cm)	pH (H_2O)	ECe (dS/m)	CEC meq/100gm of soil	Exch.Na ($cmol_C$ kg^{-1})	Exch.Mg ($cmol_C$ kg^{-1})	
0–30	5.38	0.025	57	0.74	15.1	
30–60	5.70	0.023	46.4	0.46	10.62	
Depth (cm)	Exch.Ca ($cmol_C$ kg^{-1})	Exch.K ($cmol_C$ kg^{-1})	TN (%)	Av.P (mg/kg)	OC (%)	
0–30	32.48	0.78	0.21	9.85	2.02	
30–60	17.5	0.05	0.12	6.25	1.22	

SAT, saturation; FC, field capacity, PWP, permanent wilting point; TAW, total available water, BD, bulk density; PD, particle density.

level of ponding reduced seepage and percolation losses. The seepage losses variation across the water regimes in Table 3 was due to variation of the level of ponding from 1 to 3cm depth. Efficient field-level water management performed satisfactorily show that the volume of seepage losses could have been greatly reduced thereby increasing application efficiency in Table 3. Seasonal water use in (mm) variation across the water regimes was due to variation of year wise seasonal rainfall (mm) and irrigation water required in (mm) (Table 4).

3.5. Yield and yield component and irrigation water productivity/WP_{IR}/

3.5.1. Grain yield

Table 5 illustrates the interaction effects of different water regimes with rice varieties on the yield of rice grains. The combination effect of PD2 with V1 had the highest grain yield (4.35 t/ha) while FP with V3 had the lowest grain yield (2.12 t/ha). The water regimes (PD1 and PD2) with rice varieties were higher grain yield than the farmer practices (FP) with V3 by a factor of 2 (Table 5). Compared to the (FP) with V3, the highest relative grain yield (205%) was obtained when V1 was grown under PD2 followed by V4 under PD2 (199%), and V5 under PD2 (192%) (Table 5). This might be attributed to the function of optimal supplemental irrigation during the dry spell at the terminal stage of rice. Similar results reported by (Cattivelli et al., 2008; Moonmoon and Islam, 2017), the water stress at critical growth stages reduce grain yield of rice. Improving the status of water at the reproductive stage helps to sustain reproductive success and the partition of assimilates for improving yields in water-limited conditions (Blum, 2009).

3.5.2. Above-ground biomass (AGB)

The effect of the different water regimes with rice varieties on above-ground biomass t/ha is summarized and presented in Table 5. The interaction effect of water regime (PD2) with rice varieties had significant AGB yield compared with water stress environment (FP and TWOI) with rice varieties. The combination effect of PD2 with V1 had the highest AGB yield (6.79 t/ha) while FP with V2 had the lowest AGB yields (4.27 t/ha) as shown in Table 5. This implies that the supplemental irrigation at flowering to grain-filling period could be favored above ground biomass yield. Generally, FP and TWOI stress environment in different varieties also found that the production of AGB yield was lower than under the SAT, PD1, and PD2 water regimes (Table 5). Rice is sensitive to drought stress and even mild drought stress can result in a significant yield reduction (Guan et al., 2010). Blum (2009) reported that the production of biomass and grain yield is closely linked to the capture of soil moisture for transpiration under conditions of drought stress.

3.5.3. Harvest index (HI)

Table 5 shows the effect of different water regimes with rice varieties on the harvest index. The combination of the PD2 water regime with the V5 variety had the highest HI (0.413) while FP with the variety V1 had the lowest HI (0.302). This result showed that the water stress treatment (FP and TWOI) with rice varieties had a significantly lower harvest index compared with non-stress water regimes (PD1 and PD2) with rice varieties. Non-stress water regimes (SAT, PD1, and PD2) treatments with different rice varieties had shown non-significant difference HI in

Table 3. Water balance components and volume of water (300 m^2) withdrawn from the reservoir during each irrigation year.

Variables	2017						
	TVW (m^3)	SATD (m^3)	ETc (m^3)	SP (m^3)	PD (m^3)	ERF (m^3)	NI (m^3)
SAT	62.66	28.6	34.06	0	0	13.16	49.50
PD1	71.96	28.6	34.06	6.3	3	13.16	58.8
PD2	84.26	28.6	34.06	12.6	9	13.16	71.1
	2018						
SAT	62.66	28.6	34.06	0	0	11.26	51.40
PD1	71.96	28.6	34.06	6.3	3	11.26	60.70
PD2	84.26	28.6	34.06	12.6	9	11.26	73.00

SAT, transplanted and irrigating to saturation; PD1, transplanted and ponding to 1 cm water; PD2, transplanted and ponding to 3 cm water; TVW, the total volume of water in m^3; SATD, saturation depth in m^3; ETc, evapotranspiration losses; SP, seepage and percolation losses m^3; PD, ponding depth in m^3, ERF, effective rainfall in m^3; NI, net irrigation volume in m^3.

Table 4. Seasonal water use in 300 m^2 across different water regimes (mm).

Water Regimes	Year					
	2017			2018		
	S RF (mm)	NI (mm)	SWS (mm)	SRF (mm)	NI (mm)	SWS (mm)
FP	1118	NOI	1118	1222.6	NOI	1222.6
TWOI	1118	NOI	1118	1222.6	NOI	1222.6
SAT	1118	165.0	1283.0	1222.6	171.0	1393.6
PD1	1118	196.0	1314.0	1222.6	202.3	1424.9
PD2	1118	237.0	1355.0	1222.6	243.33	1465.9

FP, farmers practice; TWOI, transplanted but not irrigated; SAT, transplanted and irrigating to saturation; PD1, transplanted and ponding to 1 cm water; PD2, transplanted and ponding to 3 cm water; SRF, seasonal rainfall in mm; NI, net irrigation in mm; SWS, seasonal water use in mm; NOI, no irrigation.

Table 5. Generally, a higher harvest index was found under the combined effect of water regimes with varieties compared with water stress regimes (FP and TWOI) with rice varieties. Effective use of water in water-limited conditions during the period of reproductive structure may also be attributed to a higher HI and yield of the crop (Blum, 2009).

Similarly, Bueno and Lafarge (2009) and Ju et al. (2009) reported that efficient water management that could enhance the remobilization of assimilates from vegetative tissues to grains during the grain-filling period usually leads to a higher HI of the crop. Water stress at booting and flowering stages cause lower HI, which could be the damaging effect of the translocation of assimilates to the grains filling process (Rahman et al., 2002).

3.5.4. Irrigation water productivity (WP_{IR})

The combined effect of water regimes with rice varieties on irrigation water productivity is summarized and presented in Table 6. Irrigation water productivity (rainfall + supplemental irrigation) varied between water regimes x varieties from as low as 1.84kg grain $mm^{-1}ha^{-1}$ for V3 under FP as high as the yield of 3.07kg grain $mm^{-1}ha^{-1}$ for V1 and V4 under PD2. The interaction effect of PD2 with V1 and PD2 with V4 varieties had 67% WP_{IR} over FP with V3 (Table 6). Tuong et al. (2005) noted that the water productivity of rice concerning total water input (irrigation plus rainfall) ranges from 0.2 to 1.2 kg grain m^{-3} water. Similar observation reported by Pascual and Wang (2017) rice water productivity of irrigation plus rainfall water input ranges from 0.16 to 0.63 kg grain m^{-3} water. Smith et al. (1985) reported that water stress occurs at crop anthesis, which causes decreasing water productivity.

Under dryland situations where crops depend on unpredictable seasonal rainfall and moisture stress which is in lower water use efficiency (Blum, 2005). Under dryland situations, crops depend on unpredictable seasonal rainfall and moisture stress which is in lower water use efficiency.

This study indicated that the low WP_{IR} of farmers' fields (FP) with rice varieties compared with well managed and irrigation supported (PD1 and PD2) in line with rice varieties plots had higher irrigation water productivity.

Table 5. The interaction effect of water regimes x varieties on yield, above-ground biomass, and harvest index of rice at Fogera Plain, Ethiopia.

Parameter		Water regime (Main plot)				
	Variety (Subplot)	FP	TWOI	SAT	PD1	PD2
GY (t/ha)	V1	2.34ijkl	2.41ijkl	2.73fgh	3.78bcd	4.35a
	V2	2.23kl	2.48hijk	2.87fg	3.10ef	3.50de
	V3	2.12l	2.27jkl	2.61ghij	2.98fg	3.00fg
	V4	2.67ghij	2.91fg	3.65cd	4.015abc	4.22a
	V5	2.35ijk	2.42ijkl	3.45de	3.62cd	4.08ab
	$LSD_{0.05}$	0.4255				
	CV (%)	10.32				
		FP	TWOI	SAT	PD1	PD2
AGB (t/ha)	V1	5.41efg	5.18fghi	6.06cd	6.48ab	6.78a
	V2	4.27n	4.75jklm	5.11fghij	5.26fgh	5.26ef
	V3	4.45mn	4.30nm	4.36mn	4.66jklm	5.00ghijk
	V4	4.67jklm	5.28fgh	5.17fghi	5.79cde	6.26bc
	V5	4.54klmn	5.0ghijk	4.88hijk	5.32fgh	5.78de
	$LSD_{0.05}$	0.4027				
	CV (%)	6.27				
		FP	TWOI	SAT	PD1	PD2
HI	V1	0.302j	0.318ij	0.312j	0.37defgh	0.39bcde
	V2	0.342hi	0.343hi	0.358efg	0.373defg	0.388abcde
	V3	0.325ij	0.345ghi	0.377bcdef	0.388abcde	0.375dcdef
	V4	0.362defgh	0.358fgh	0.411a	0.408ab	0.403abc
	V5	0.342hi	0.327ij	0.411a	0.405ab	0.413a
	$LSD_{0.05}$	0.0285				
	CV (%)	5.72				

GY, grain yield t/ha; AGB, above-ground biomass t/ha; HI, Harvest index; FP, farmers practice; TWOI, transplanted but not irrigated; SAT, transplanted and irrigating to saturation level; PD1, transplanted and ponding to 1 cm water; PD2, transplanted and ponding to 3 cm water; V1, X-Jigna; V2, Edget; V3, Hiber; V4, Fogera-1; V5, Nerica-4. Means in the Table for the same parameter followed by the same letter(s) are not significantly different from each other at a 5% level of significance.

Table 6. The interaction effect on water regimes and varieties of irrigation water productivity/WP_{IR}/(kg grain ha^{-1} mm^{-1}).

Variety (Subplot)	Water regimes (Main plot)				
	FP	TWOI	SAT	PD1	PD2
V1	2.00jkl	2.06hijkl	2.05jk	2.76bcde	3.07a
V2	1.89kl	2.11hijk	2.14hijk	2.26ghi	2.47fg
V3	1.84l	1.93jkl	1.95jkl	2.17hij	2.12hijk
V4	2.29gh	2.50fg	2.72cdef	2.93abc	3.00ab
V5	2.01ijkl	2.061hijkl	2.56ef	2.64def	2.88abcd
LSD0.05 = 0.2617					
CV(%) = 12.07					

FP, farmers practice; TWOI, transplanted but not irrigated; SAT, transplanted and irrigating to saturation; PD1, transplanted and ponding to 1 cm water; PD2, transplanted and ponding to 3 cm water; V1, X-Jigna; V2, Edget; V3, Hiber; V4, Fogera-1; V5, Nerica-4.

Table 7. The effect on water regime and varieties on incremental irrigation water productivity (IWP_{IR}) (kg grain ha^{-1} mm^{-1}).

Varieties	Farmers practice			Transplanted but not irrigated		
	SAT-FP	PD1-FP	PD2-FP	SAT- TWOI	PD1- TWOI	PD2- TWOI
V1	2.32	7.23	8.36	1.91	6.88	8.07
V2	3.81	4.37	5.28	2.33	3.12	4.24
V3	2.91	4.12	3.50	2.03	3.57	2.95
V4	5.84	6.73	6.44	4.41	5.3	5.45
V5	6.55	6.38	7.19	6.08	5.98	6.90

FP, farmers practice; TWOI, transplanted but not irrigated; SAT, transplanted and irrigation to saturation; PD1, transplanted and ponding to 1 cm water; PD2, transplanted and ponding to 3 cm water; V1, X-Jigna; V2, Edget; V3, Hiber; V4, Fogera-1; V5, Nerica-4; SAT-FP, SAT over FP; PD1-FP, PD1 over FP; PD2 over FP; SAT-TWOI, SAT over TWOI; PD1-TWOI, PD1 over TWOI; PD2-TWOI, PD2 over TWOI.

Table 7 shows that the incremental irrigation water productivity **(**IWP_{IR}) data showed the additional grain yield increase over farmers' practice (dry planted rainfed rice) and transplanted but not irrigated across varieties per unit water applied. The IWP_{IR} varied between irrigation x varieties from the lowest of 1.91 kg ha^{-1} mm^{-1} for the SAT over TWOI (SAT-TWOI with V1) to the highest yield of 8.36 kg ha^{-1} mm^{-1} for PD2 over FP (PD2-FP with V1). V1 grown under PD2 gave the highest (8.36 kg ha^{-1} mm^{-1}) IWP_{IR} which is 4 times higher than the values for V1, V2, and V3 grown under TWOI and the value V1 grown under FP (Table 7). IWP_{IR} is an increase in the amount of the product (compared with no irrigation) over the volume of supplementary irrigation water (Cabangon et al., 2003). The present result implies that the primary factors for water productivity on the two production systems (farmer practice) and (transplanted but not irrigated) were a shortage of water during the terminal stage of the crop due to dry spell occurrence rather than other environmental factors in Fogera Plain.

3.6. Partial budget analysis

The partial budget analysis was conducted to evaluate the economic feasibility of the two years average of the different water regimes with rice varieties over two years of field price data. The results of the partial budget analysis showed that the highest net benefit (65, 550ETB) was obtained from the application of PD2 with V1, followed by PD1 withV4 had a medium level net benefit (NB) (60,750 ETB ha^{-1}) while TWOI with V3 gave the lowest net benefit (33, 500 ETB ha^{-1}) (Table 8). If the crop cycle is longer than 4–5 months and the proposed practice is new to farmers for a treatment to be considered meaningful to farmers with 100% the minimum acceptable rate of return (CIMMYT, 1988). The water regimes of rice varieties combination of FP with V4, SAT with V4, PD1 with V1, PD1 with V4, PD2 with V1 had met the requirement. However, the highest MRR (2000%) was recorded from the application of PD1 with V4, followed by PD2 with V1 had a medium MRR (300%) whereas SAT with V4 gave relatively low MRR (28%) (Table 8). As

Table 8. Partial budget analysis for water management and rice varieties in rice averaged for two years at Fogera Plain, Ethiopia.

Treatment	AGY (t/ha)	TVC (ETB ha^{-1})	NB (ETB ha^{-1})	MRR (%)	Treatment	AGY (t/ha)	TVC (ETB ha^{-1})	NB (ETB ha^{-1})	MRR (%
FPV1	2.11	1800	40400		SATV5	3.11	10825	51375	D
FPV3	1.92	2100	36100	D	SATV2	2.58	10850	40750	D
FPV5	2.12	2325	40075	D	PD1V1	3.40	11450	56550	138
FPV2	2.01	2400	37800	D	PD1V3	2.68	11550	42050	D
FPV4	240	3000	45000	283	PD1V4	3.62	11650	60750	2000
TWOIV1	2.17	7200	36200	D	PD1V5	3.26	11675	53525	D
TWOIV3	2.04	7300	33500	D	PD1V2	2.79	11700	44100	D
TWOIV4	2.62	7400	45000	D	PD2V1	3.92	12850	65550	300
TWOIV5	2.19	7425	36375	D	PD2V3	2.68	12950	40650	D
TWOIV2	2.23	7450	37150	D	PD2V4	3.80	13050	62950	D
SATV1	2.43	10600	38000	D	PD2V5	3.67	13075	60325	D
SATV3	2.35	10700	36300	D	PD2V2	3.15	13100	49900	D
SATV4	3.29	10800	55000	28					

described by CIMMYT (1988), the recommendation is not (necessarily) based on the highest MRR. As long as the MRR between two treatments exceeds the minimum acceptable rate of return, the change from one treatment to the next should be attractive to farmers. Thus, as presented in Table 8, PD2 with V1 has shown the highest net benefit (65,550 ETB) with an acceptable level of MRR (300%) and best recommended for rice production in Fogera Plain. Moreover, PD1 with V4 treatment could be also recommended as an alternative technology for local farmers. In line with this result, Sharma et al. (2010) reported that water harvesting and supplementary irrigation are economically viable and possibly increase by 50% for crop production.

ETB, Ethiopian Birr; AGY, adjusted grain yield; TVC, total variable cost; NB, net benefit; MRR, marginal rate of return; D, dominated treatments; FP, farmers practice; TWOI, transplanted but not irrigated; SAT, transplanted and irrigation to saturation; PD1, transplanted and ponding to 1 cm water; PD2, transplanted and ponding to 3 cm water; V1, X-Jigna; V2, Edget; V3, Hiber; V4, Fogera-1; V5, Nerica-4.

4. Conclusions

Insufficient rainfall during the reproductive growth stages limits rice production across the rice ecosystem in Fgera Plain. The present study shows that combination effect water regimes (PD2 and PD1) and rice varieties had a significant increase in grain yield, above-ground biomass, harvest index, and irrigation water productivity (WP_{IR}) compared with farmers practice (FP) and with rice varieties. Moreover, a combination of 3 cm ponding water regime with X-Jigna (V1) and 1 cm ponding water regime with that of Fogera-1 (V4) rice varieties was found to be a higher net benefit and marginal rate of return identified for dry spell stress environment implying that the profitability is captured. Therefore, the identified irrigation period from mid of September to the first week of October should be applied in the form of supplemental irrigation at the reproductive stages of rice. The system of rice supplemental irrigation and a minimum depth of water aims to make rainfed rice cultivation more sustainable and profitable, as it not only enhances grain yield and net income but also saves considerable amounts of water. It is concluded that for efficient water management and minimization of dry spell risks, ponding to 3 cm ponding depth (PD2) with X-Jigna (V1) and 1cm ponding depth with Fogera-1 (V4) rice varieties at reproductive growth stages are recommended for study areas. However, a few more years' data over locations data are needed to see the combined effect of irrigation with rice varieties response on grain and biomass yield, profitability, and irrigation water productivity of rice.

Declarations

Author contribution statement

Tesfaye Molla: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Kindie Tesfaye; Firew Mekbib; Tamado Tana; Tilahun Taddesse: Conceived and designed the experiments; Analyzed and interpreted the data.

Funding statement

This work was funded by the Ministry of Education and Debre Tabour University, Ethiopia. Special thanks to Ethiopia National Meteorological Service Agency for providing climate data and Fogera National Rice Research and Training Centre, Ethiopia for supporting necessary research facilities.

Data availability statement

Data associated with this study has been deposited at IR + Institutional Repository ETD Electronic thesis dissertation.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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