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EFFECTS OF IRRIGATION REGIME AND FREQUENCY ON SOIL PHYSICAL QUALITY, WATER USE EFFICIENCY, WATER PRODUCTIVITY AND ECONOMIC RETURNS OF PADDY RICE

S. T. Abu and W. B. Malgwi,
Department of Soil Science, Faculty of Agriculture/Institute for Agricultural Research, Ahmadu Bello University, Samaru-Zaria, Nigeria
E-Mail: abufa12003@yahoo.com

ABSTRACT

Talata Mafara is located in a semi-arid region in Sudan Savanna agroecosystem of Nigeria and regularly faces widespread drought. Given current water scarcity, the limited available water should be used as efficient and productive as possible. The influence of five regulated deficit irrigation regimes involving water application depths of 100, 85, 70, 55 and 40 % of total available water (TAW) capacity equivalent, referred to as TAW, 85 % TAW, 70 % TAW, 55 % TAW and 40 % TAW and irrigation intervals of 4, 8, 12 and 16 days on soil physical quality as well as paddy rice yield, water use efficiency, water productivity and economic return was studied. The study was conducted at Talata Mafara irrigation research station of the Institute for Agricultural Research, Samaru-Zaria. Water was conveyed from field ditches into each basin through a pair of polyvinyl chloride pipes using surface irrigation method. Routine methods of soil physical quality analysis were employed. Results showed that application of water depths of 85 % TAW and 8 days frequency significantly enhanced soil organic carbon (OC) content, and consequently, promoted macroaggregate stability measured by mean weight diameter and microaggregate stability measured by aggregated silt and clay and clay flocculation index as well as infiltration rate. However, yield, water use efficiency, water productivity and net revenue as well as gross profit rate were highest on application of 85 % TAW and irrigation at 8 days interval. Therefore, given the deterioration of soil physical quality on application of higher water depth, regular replenishment of soil organic matter is essential for sustainable use of the soil for production of rice and other irrigated crops.

Keywords: irrigation regime, irrigation interval, soil physical properties, water use efficiency, economic return, paddy rice.

INTRODUCTION

Soil properties vary in vertical and lateral directions and such variation follow systematic changes as a function of the landscape position (slope), soil forming factors, and/or soil management practices (land use) (Amusan *et al.*, 2006; Mbagwu and Auerswald, 1999). Nigerian savanna is made up of four ecological zones namely: Southern Guinea (SG), Northern Guinea (NG), Sudan (Su) and Sahel (SA) Savanna covering an area of about 700, 000 km^2 corresponding to about three quarters of Nigeria's total land area. Sudan and Sahel savanna are located in the semi-arid and arid part of Nigeria where water is becoming economically scarce resource (IPCC, 2001). The 60s and 70s were characterized among others by a poor performance of the agricultural economy and problems of drought (Adams, 1991). An important concern of the local peasantry was therefore to overcome a shortfall in rain and to have an alternative source of available water (Beckman, 1984) to boost agricultural production.

In order to cope with the problems of aridity, rainfall variability and the lack of food self sufficiency, FAO (1969) recommended the development of Bakolori irrigation project (BIP) and a relatively modest dam and irrigation scheme at Talata Mafara on the River Sokoto (Figure-1) as part of a comprehensive basin development plan and for soil and water resources study. The traditional land use long-term before the construction of BIP was the practices of extensive flood-recession agriculture by the farmers and was well adapted to the annual flood regime. The construction of the Bakolori dam altered the pattern of the natural runoff of the Sokoto River significantly and the farmers encountered severe problems. This was particularly true for the 1978-81 periods, when the dam was first closed and the whole runoff was used for filling the reservoir. Later it was partly released in out-of-season artificial floods in order to have storage capacity for the wet season and by this to extend the annual length of construction time in the irrigation area (Adams, 1993). In contrast to the initial design which intended almost exclusively surface irrigation, the irrigation system was later modified to 15, 000 hectares of much more expensive sprinkler irrigation and only 7, 500 hectares of gravity irrigation (Kebbeh, 2003). However, the sprinkler heads were broken down more than 2 decades ago and not operational anymore. Thus, only 7, 500 hectares with surface irrigation are currently used.

Small-scale farmers own 90 % of the BIP land and grow rice in more than 80 percent of the irrigated area while suffering from declining yields over the years (Kebbeh *et al.*, 2003). In addition, poor operation and management of the water facilities at BIP resulted in environmental and ecological problems, like waterlogging, salinity and weed infestation covering more than 50 % of the available area under gravity surface irrigation and are

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capable to turn the BIP into a barren land in the foreseeable future (Kolawole, 1993).

Farmers face the problem of knowing the exact amount (or optimum amount) of water to apply, which amount to apply in areas of abundance and areas of scarcity. Because rice receives more irrigation water than other grain crops, water-saving irrigation technologies for rice are seen as a key component in any strategy to deal with water scarcity (Qadir, 2003; Li and Barker, 2004). The need to produce more food with less water poses vast challenges to reassign existing water supplies, encourage more efficient use and promote natural resource protection (Hussain *et al.*, 2007). One of the water conserving irrigation scheduling techniques is deficit irrigation which provides a means of reducing water consumption while minimizing adverse effects on yield and the environment (Mugabe and Nyakatawa, 2000; Ghinassi and Trucchi, 2001; Kirda, 2002; Mao *et al.*, 2003; Panda *et al.*, 2003; and Zhang *et al.*, 2004). Many investigators have concluded that deficit irrigation can increase net farm income (English, 1990; Martin *et al.*, 1989; Fardad and Golkar, 2002; and Zhang *et al.*, 2002).

This research was aimed at (1) determining the effects of deficit irrigation regimes and intervals on soil physical quality and (2) investigating the effects of various irrigation regimes and intervals on yield, water use efficiency, water productivity and economic return from investment on production of paddy rice.

MATERIALS AND METHODS

Description of site

The experiment was conducted for 2 consecutive dry seasons (2009 and 2010) at the Irrigation Research Farm of the Institute for Agricultural Research at Talata Mafara, Nigeria (12^o 37.212$^/$ N and 06^o 1.382$^/$ E and 309 m above sea level). The location is in the northern Sudan savanna ecology, in an environment described as semi-arid. Tropical wet and dry climate prevails in the area. Rainfall distribution is monomodal and most rains fall from June to September with an annual precipitation of about 650 mm. In some years, rainfall may be prolonged while there may be delayed onset in some other years. Maximum and minimum annual mean temperatures are 34 and 16°C, respectively. The area is geomorphologic ally plain and nearly flat with gentle slope and characterized by sparse vegetation of Sudan savanna types. The data in Table-1 present information on physical and chemical properties of the soil of the experimental site. Predominantly sandy clay loam in texture, the soil had moderate bulk density and total porosity. The aggregated silt and clay is low with high clay dispersion index and dispersion ratio. The pH is moderately acidic in reaction with low in total nitrogen, available phosphorus, CEC and exchangeable bases.

Table-1. Physico-chemical composition of the soils at the irrigation research farm, Talata Mafara.

Soil properties	Characteristics
Sand (%)	65.6
Silt (%)	12.4
Clay (%)	22.0
Bulk density (g/cm^3)	1.53
Total porosity (%)	42.4
Macroporocity (%)	15.66
Microporosity (%)	26.72
SOC (g/kg)	5.02
MWDw (mm)	0.28
Aggregated silt and clay (%)	4.0
Clay flocculation index (%)	9.6
Dispersion ratio (%)	89.9
Clay dispersion index (%)	90.2
Saturation percentage (%)	42.2
Field capacity (%)	20.8
Permanent wilting point (%)	10.6
Available water (%)	10.2
pH in H_2O	5.92
pH in 0.01M $CaCl_2$	4.90
ECe	0.083
Total nitrogen (g/kg)	0.124
Available phosphorus (mg/kg)	7.25
CEC (cmol/kg)	8.2
Exchangeable bases (cmol/kg):	8.6
Ca	3.24
Mg	2.02
K	1.10
Na	1.26

Field study

The treatments include five regulated deficit irrigation regimes involving water application depths of 100, 85, 70, 55 and 40 % of total available water (TAW) capacity equivalent, referred to as TAW, 85 % TAW, 70 % TAW, 55 % TAW and 40 % TAW and irrigation intervals of 4, 8, 12 and 16 days. The treatments were laid out in randomized complete block design (RCBD) with split plot arrangement and replicated thrice. The total available water capacity of the soil was determined before imposing irrigation regime treatments. For this purpose, soil samples were collected at the experimental site. Field water capacity (FC), permanent wilting point (PWP), bulk density (ρ) and available water (AW) capacity were then determined from core samples collected to 60 cm depth at 15 cm interval thus: the soil moisture of dry weight (W) at field capacity (W_{FC}) and permanent wilting point (W_{PWP})

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were converted to volumetric (Θ) moisture content at same field capacity (ΘFC) and permanent wilting point (ΘPWP) by multiplying the former values by ρ at the corresponding soil depths. The soil total available water (TAW) across the rooting depth (RD) was computed using the following equation:

$$\Theta_{FC} = W_{FC}*\rho*d; \quad (1)$$

$$\Theta_{PWP} = W_{PWP}*\rho*d \quad (2)$$

$$TAW = \sum_{i=0}^{n}[(\Theta_{FCi} - \Theta_{PWPi})RDi] \quad (3)$$

where, d = depth of soil layer; Θ_{FCi} = volumetric moisture content at field capacity within ith layer; Θ_{PWPi} = volumetric moisture content at permanent wilting point within ith layer; RD_i = soil layers within rooting depth.

Surface irrigation method was used in conveying water into each basin. A pair of 5 cm diameter PVC pipes of 40 cm length was used to let water from field ditches into each basin. These pipes were installed to give a free orifice flow. Stage guages were placed at the water inlet of each basin to measure the depth of water flowing through the pipes. Thus the discharges through the pipe into the basins were computed and the depth of water applied was monitored using a stop watch. Soil moisture status was determined one day before and after 4, 8, 12 and 16 days intervals using soil moisture resistance devices (gypsym blocks) installed at 0-30 cm depth for determination of water deficit.

The irrigation regimes were assigned to the main plot whereas irrigation intervals were placed in the subplots. Soil samples were collected at the experimental site to 30 cm depth from each treatment for laboratory analysis.

Infiltration characteristics of the soil were measured using cylinder infiltrometer as described by Walker and Skogerboe (1987).

Basal compound fertilizers (N-P-K 15-15-15) at the rate of 200 kg/ha was incorporated into the soil. Rice (Wita 1 or Tox 3118-6-E2-3) was direct seeded at the rate of 60 kg/ha by dibbling method at a spacing of 20 cm between plants and rows. It was followed by a light irrigation. Urea (46 % N) fertilizer was applied as top dressing at the rate of 200 kg/ha Urea in two equal split, a half of the rate broadcasted 30 days after 3-4 leaves stage and another half at ear initiation. The plots were manually weeded 2 times in the season.

At physiological maturity, crops were harvested from 8 m^2 selected in the center of each experimental plot by cutting the aboveground dry matter and weighed. The harvested rice was then threshed and weighed to obtain the grain weight. The grain moisture content at threshing was determined in the laboratory and was about 13.5 %.

Water use efficiency (WUE) was determined as follows:

$$WUE = \frac{Grain\ Yield,\ \ kg\ ha^{-1}}{WU,\ \ mm}\ \ (Kg\ ha^{-1}\ mm^{-1}) \quad (4)$$

where: WU is the amount of water applied in a season.

Water productivity (WP) was determined using the following equation:

$$WP = \frac{\left(\frac{\$}{kg}\right)(\text{Grain Yield},\ \ \text{kg ha}^{-1})}{\text{WU},\ \ \text{mm}}\ \ (\$\ \text{mm}^{-1}) \quad (5)$$

The Value to Cost Ratio (VCR) was used to determine the profitability which was computer as follows:

VCR = Total Revenue / Total Cost of inputs (6)

Total Revenue = Yield * Price of 1 kg of grain (7)

Total Cost of inputs = Qty of each inputs * Price of each input (8)

The formula below was used to calculate gross profit rate:

Gross Profit Rate = (Gross profit/Total revenue)*100 (9)

Laboratory study

Soil Organic Carbon (OC) was determined by the Walkley-Black method (Nelson and Sommer, 1982). Samples for MWD were air-dried and passed through a 4.75 mm sieve while those for micro aggregate stability indices, water retention and organic carbon were sieved with a 2 mm sieve after air-drying. Particle size distribution was determined by the hydrometer method (Gee and Or, 2002). For micro aggregate stability, this involved the determination of the amounts of silt and clay in calgon-dispersed as well as water-dispersed samples using Bouyoucos hydrometer method of particle size analysis described by Gee and Or (2002). Mean weight diameter (MWD) was determined by the wet-sieving method of Kemper and Rosenau (1986). MWD of water stable aggregates was calculated as:

$$MWD = \sum_{i=0}^{n} XiWi \quad (10)$$

where X_i is the mean diameter of the ith sieve size and W_i is the proportion of the total aggregates in the ith fraction.

The core samples were used for the determination of the following parameters: *Bulk Density* (ρd) - using the core method as described by Anderson and Ingram (1993); Total porosity (P_t) was calculated from ρd values as follows:

$$P_t = [1-(\rho d / P_D)] \times 100 \quad (11)$$

where P_D = particle density (P_D)

Water retention

Water retained at field capacity (FC) and permanent wilting point (PWP) was determined using the saturation water percentage-based estimation models of Mbagwu and Mbah (1998):

FC = 0.79 (SP)-6.22 (r = 0.972); (12)

PWP = 0.51 (SP)-8.65 (r = 0.949), (13)

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where: FC and PWP are the field capacity (%) and permanent wilting point (%), respectively and SP is the saturation water (%).

Available water (AW) was computed as the difference between moisture retained at FC and PWP; *Macroporosity* (P_{mac}) *and microporosity* (P_{mic}) were computed as follows:

$$P_{mac} = P_t - FC; \quad (14)$$

$$P_{mic} = P_t - P_{mac}. \quad (15)$$

Statistical analysis

The data collected were subjected to factorial analysis of variance (ANOVA) and significant differences among treatments were compared by the Tukey-Kramer Multiple Comparison Test using NCSS computer statistical program (Hintze, 2004). Linear regression analysis was done to determine the response of grain yield and yield attributes to irrigation regime and interval and the relationship between the grain yield and yield attributes of the paddy rice. All the significant responses were expressed by the regression equation:

$$Y = a + bX \quad (17)$$

where, Y = paddy rice grain yield

X = the yield attributes

a and b = regression coefficients

RESULTS AND DISCUSSIONS

Particle size distribution

Results on irrigation regime and frequency effects on particle size distribution (Table-2) showed that sandiness was significantly ($p = 0.0330$) higher on irrigation with water depth of TAW (64.8 %). Treatments irrigated with 55 and 40 % TAW got significantly ($p = 0.0043$) higher silt content (16.1 %), while clay content was higher ($p = 0.0265$) on irrigation at water depth of 40 % TAW (27.4 %). Considering irrigation frequency, the highest sand and lowest silt and clay contents was recorded on irrigation at 4 days frequency. The textural class under all the treatments was sandy clay loam (medium coarse). According to Esteban (2000), coarse-textured soils lack both nutrient and water holding capacities, while fine-textured soils often have structural and infiltration problems. The occurrence of sandy clay loam texture implies that the study site may have moderate to moderately slow infiltration (Landon, 1991).

Soil organic carbon and aggregate stability

Irrigation regime and frequency effects on soil organic carbon/matter (SOC/SOM) are presented in Table-3, showing that treatments irrigated with water depths of 85, 70, 55 and 40 % TAW were statistically equivalent but significantly ($p=0.0100$) differed from TAW treatment. An increasing trend in SOC content was observed as the water deficit level increased up to 85% TAW which further decreased inconsistently. The highest value recorded in treatment irrigated with water depth of 85 % TAW. Significantly higher SOC was recorded on irrigation at 4 days frequency which showed decreasing pattern with decrease in irrigation frequency.

Loveland and Webb (2003) reported a threshold of 34 g kg^{-1} (19.7 34 g kg^{-1}) SOM (SOC) for most soils below which decline in soil quality is expected to occur. Based on this, all the treatments showed tendency of physical quality decline due to the low (<10/17.2 g kg^{-1}) SOC/SOM content. The present findings are in conformity with the low SOC/SOM earlier reported by Esu (1983, 1989) for savanna soils.

The trend of irrigation regime and frequency effects on wet mean weight diameter (MWDw) indicate an increasing pattern up to 85 % TAW and 8 days irrigation frequency under which the highest mean values were recorded (0.434 and 0.419 mm, respectively). However, further deficit in water depth and extention of irrigation interval resulted to drop in MWDw value. The treatments effects on aggregated silt and clay (ASC) and clay flocculation index (CFI) followed similar trend as MWD with 85 % TAW treatments having significantly ($p<0.0001$) higher ASC (9.1 %) and CFI (25.3 %). Conversely, soil dispersion ratio (DR) and clay dispersion index (CDI) were higher with treatments supplied with water depth equivalent to TAW and irrigated at 16 days frequency. The differences observerd among the treatments in MWD as well as ASC and CFI could be explained by the amount and frequency of water application in association with the differences in SOC/SOM they possessed. This probably resulted to the collapse of macro aggregates into micro aggregates in the other treatments. In support of the present findings, some researchers (Suwardji and Eberbach, 1998) also reported that inter annual and seasonal variability in aggregate stability results from seasonal wetting and drying interacting with the accumulation of plant and microbial debris associated with the growing plant. Other researchers (Igwe, 2004; Oguike and Mbagwu, 2009; Igwe *et al*., 1995; Malgwi and Abu, 2011) reported numerous positive correlations between soil organic matter content and water stable aggregation (macro aggregation). Moreover, Levy and Miller (1997) and Scalenghe *et al.* (2004) associated such low macro aggregate stability with decrease in macro-porosity and production of finer particles and micro aggregates.

The implication of the lower MWD as well as ASC and CFI seen with some of the treatments is that the treatments possess low macro- and micro aggregate stability to water erosion compared to those with higher values. Hence, sustainable use of such soil with low MWD requires replenishment of the soil with organic matter since clay (silt) interacts with SOC to form stable micro aggregates.

Soil bulk density and porosity

The results presented in Table-4 revealed that treatments supplied with water depth of TAW and irrigated at 4 days frequency had significantly higher bulk density (ρd), (1.62 and 1.61 g cm^{-3}) which consistently decreased with increase in deficit water level and irrigation frequency. The reports of Abdelaty and Gamal (2009) were in conformity with our finding. The increment of soil bulk density under high irrigation level may be due to applied irrigation at short irrigation frequencies coupled with decrease in SOC/SOM which led to rearrangement of soil particles and reorientation of soil pores. The present finding is in concurrence with the findings of Pikul and Zuzel (1994) and Franzuluebbers (2002), who reported that soil organic C (soil humus content) has a direct impact on the bulk density (or inversely on the porosity) of soil. The ρd values in all the treatments were moderate (1.54-1.62 g cm^{-3}), implying that the soil was slightly compacted and could restrict root development (Evanylo and McGuinn, 2000). Ikpe and Powell (2002) observed that low soil bulk density enhanced access to soil moisture and increased nutrient uptake resulting in higher crop yield.

Contrasting the trend of effects of the irrigation regimes and frequency on ρd, total porosity (P_t) decreased with increasing water application depth (38.8 % under TAW and 41.9 % under 40 % TAW) and decreasing irrigation frequency (39.2 % at 4 days and 41.3 % on irrigation at 16 days frequency). The influence of the various water application depths on macro- (P_{mac}) and microporosity (P_{mic}) was significant ($p<0.0001$), the highest values being recorded with 40% TAW (14.9 and 27.0 %, respectively). Significant differences were not found among the investigated irrigation frequencies in P_{mac} values but were found in P_{mic}, thus increasing with increase in irrigation frequency.

The reduced P_t, P_{mac} and P_{mic} observed as the water application depth increased and irrigation frequency decreased could be explained by the increase in soil compaction level as indicated by relatively higher bulk density. Hillel (1982) reported that soil total porosity range from 30 to 60 % is considered good for root development. Pagliai (1984) also reported that a soil is considered compact when the total P_{mac} (> 50 μm) is < 10 %. Since the P_t and P_{mac} values were generally closer to the lowest limit proposed by these authors, the soils in the site could be considered as tending toward compaction which could restrict root development.

Water retention properties and infiltration rate

Regarding the water retention properties (Table-5), they depicted significant response to both the irrigation regimes and frequencies. Increasing soil moisture stress led to significant increase in soil field capacity (FC), permanent wilting point (PWP) and available water capacity (AWC). The report of Abdelaty and Gamal (2009) is in conformity with our finding which showed that increased soil moisture stress resulted to increase in AWC.

According to Ellerbrock *et al*. (2005), soil organic carbon/matter interacts with other soil properties to influence water behavior in soils. Thus, the higher soil moisture retained at SP, FC, PWP and AWC as observed in treatments supplied with comparatively higher water deficit and larger irrigation frequencies is a reflection of production of generally low SOC (SOM) content and higher clay contents under those conditions. Oguike and Mbagwu (2004) and Mbagwu *et al*. (1994) reported that high water retention in soils with high SOC/SOM manifests the affinity of SOC (SOM) for water.

The treatments significantly influenced soil infiltration rate, with the highest rate recorded on irrigation at the depth of 40% TAW (0.543 cm/min.) and 16 days frequency (0.525 cm/min). The values consistently decreased on increasing water application depth (Figure-2) and decreasing irrigation frequency (Figure-3). The comparatively higher infiltration rate recorded in treatments irrigated with water defict levels and larger frequencies compared to TAW and 4 days irrigation frequency could also be associated with the lower bulk density observed in these treatments. This is supported by reports by Carter and Stewart (1996) and Franzluebbers (2002). The irrigation regime and frequency, and consequently, their influence on SOC production acconted for 97.6 and 99.7 %, respectively variation in the infiltration rate of the soil.

Yield attributes

The response of yield attributes of paddy rice to the irrigation regimes and frequency were significant as seen in Table-6. The results showed that the highest number of panicle per square meter, number as well as weight of grains per panicle and per plant were produced by treatments supplied with water depth of 85 % TAW and irrigated at 8 days frequency. The comparison of the mean values of 1000 grain weight showed that treatments supplied with water depth of TAW and irrigated at 4 days frequency had the highest values, which consistently decreased with deficit water application depth and increase in irrigation frequency. This corroborates the reports by Thomas *et al.* (2003) which showed that as the applied water depth was increased, 1000 grain weight significantly increased. Blank grain percentage was found to significantly and consistently increase with deficit water application depth from TAW to 40 % TAW and increase in irrigation frequency. This could be due to soil moisture stress which might have induces sterility during anthesis. In conformity with our findings, Islam and Mondal (1992) reported that filled grain percentage was seriously affected by moisture stress at the later part of crop growth.

Paddy rice yield, water use, water use efficiency and water productivity

Data in Table-7 present information on the effects of irrigation regime and frequency on paddy rice yield, water use (WU), water use efficiency (WUE) and water productivity (WP), showing that the investigated irrigation regimes and frequencies significantly affected grain yield, WU at less than 1 % level, WUE at 5 % level and WP at less than 1 % level of significance. Irrigation at the depth of 85% TAW and 8 days frequency gave the highest grain yield (4772.0 and 4442.3 kg ha^{-1}), WUE (5.8 and 6.4 kg $ha^{-1}mm^{-1}$) and WP (3.43 and 3.79 US$ mm^{-1},

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respectively). This shows that water depth of 85 % TAW and irrigation at 8 days frequency satisfied almost the full moisture requirement at all the growth stages of the crop, resulting in moderate WUE. This is in agreement with results reported by Damdroth and Bramm (1979), Mbagwu and Osuigwe (1985) and Morgado and Rao (1985). Nour *et al.* (1997) reported significant decrease in WUE as the irrigation frequency increased. Hussaini *et al*. (1998) also reported that prolonging the period of irrigation to 9 days frequency adversely affected paddy yield in sandy loam soil, but was not so in clay loam soil.

Results on the effects of irrigation regime and frequencies on water use (WU) shows that treatments with water application depth of TAW and 4 days frequency had the highest WU (1077.5 and 1348.9 mm, respectively). Mean water saving, ranging from 161.9 to 646.4 mm, was recorded within an irrigation season due to reduction in water application depth and increase in frequency. Terjung *et al*. (1985) reported that 1000 mm of water was needed to attain optimum yield (between 6000-10,000 kg/ha) in north central china, while 500 mm water depth was required to achieve the same yield in southern part of the country. The reasons for grain yield reduction with water stress mainly were decreases in the number of filled spikelets per panicle and 1000 grain weight. Similar results were reported by Beser (1997).

Regression analyses

Simple linear regression analysis between paddy rice grain yield and yield attributes (Table-8) showed that weight of grains per plant had the most effect on paddy rice grain yield (R^2=0.944). The results of stepwise regression analysis showed that, weight of grains per plant (R^2=0.944) and 1000 grain weight (R^2=0.021) had the largest proportion in paddy rice grain yield variation (Tables 9 and 10). This could explain the higher yield obtained in treatments irrigated with water depth of 85 % TAW and at 8 days frequency compared to the other treatments. It is apparent from this result that maintaining soil moisture regime close to or at saturation is required for increased number and weight of grains. This observation is similar to those earlier made by Yoshida (1981). The other yield attributes had little effects on the grain yield of the paddy rice, thus contributing only 3.5 % in the grain yield variation.

Economic return

The benefit-cost analysis revealed that treatments supplied with water depth of 85 % TAW and 8 days frequency gave the highest net revenue (US$ 1905.0 and US$ 1739.2) (Figures 4 and 5), value-cost ratio (3.08 and 2.96) and gross profit rate (67.5 and 66.2 %) (Figures 6 and 7, respectively). The analysis show that 79.3 and 74.4 % of the net revenue achieved is explained by the irrigation regime and frequency, respectively. Similarly, 84.6 and 80.8 % of the gross profit rate is explained by the irrigation regime and frequency, respectively.

Table-2. Particle size distribution as influenced by irrigation regime and interval in Talata Mafara, Nigeria

Treatment	Sand	Silt	Clay	Textural class
	…………………… % …………………………………			
Irrigation regime				
TAW	64.8a	12.6b	21.8b	SCL
85 % TAW	62.7ab	13.7ab	23.7ab	SCL
70 % TAW	59.5ab	14.8ab	25.7ab	SCL
55 % TAW	57.8ab	16.3a	26.1ab	SCL
40 % TAW	56.6b	16.1a	27.4a	SCL
MSD	8.0487	3.0368	5.0467	-
P (0.05)	0.0330	0.0043	0.0265	-
Irrigation interval				
4 days	66.3a	12.1b	21.1b	SCL
8 days	61.7ab	14.2ab	24.2ab	SCL
12 days	57.4b	16.1a	26.5a	SCL
16 days	55.7b	16.5a	27.9a	SCL
SE	6.7562	2.5491	4.2362	-
P (0.05)	0.0006	0.0001	0.0007	-

Note: TAW = Water application depth of soil total available water equivalent; SCL = Sandy clay loam; All means followed by the same letter within a column are not significantly different at 5% probability level using the Tukey-Kramer Multiple-Comparison Test.

Table-3. Soil organic carbon and aggregate stability as influenced by irrigation regime and interval in Talata Mafara, Nigeria.

Treatment	SOC ..g/kg..	MWDw ..mm..	ASC	CFI	DR	CDI
			……………………… % ……………………			
		Irrigation regime				
TAW	4.07b	0.327d	6.5c	12.3c	86.2a	87.7a
85 % TAW	5.88ab	0.352c	6.5c	14.2bc	82.8a	85.8ba
70 % TAW	5.96a	0.365c	7.5bc	21.4ab	78.5b	78.5bc
55 % TAW	5.99a	0.394b	9.0ab	25.0a	77.2b	75.0c
40 % TAW	6.26a	0.434a	9.1a	25.3a	74.7b	74.7c
SE	0.2231	0.0049	1.5053	1.4925	3.9737	7.4504
P (0.05)	0.0100	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
		Irrigation interval				
4 days	4.06ca	0.315d	7.1b	19.2ab	78.0bc	80.8ab
8 days	4.98bc	0.363c	8.9a	25.2a	75.9c	74.8b
12 days	6.26ab	0.401b	7.8ab	19.3ab	81.2ab	80.6ab
16 days	7.22a	0.419a	7.0b	14.9b	84.3a	85.1a
SE	1.5343	0.0172	1.2636	6.235	3.3355	6.254
P (0.05)	<0.0001	<0.0001	0.0007	0.0009	<0.0001	0.0010

Note: ASC=Aggregated silt and clay; CFI=Clay flocculation index; DR=Dispersion ratio; CDI=Clay dispersion index: MWDw=Wet mean weight diameter; TAW = as explained in Table-2; All means followed by the same letter within a column are not significantly different at 5% probability level using the Tukey-Kramer Multiple-Comparison Test.

Table-4. Soil bulk density and porosity as influenced by irrigation regime and interval in Talata Mafara, Nigeria.

Treatment	Bulk density ..g/cm..	Total porosity	Macroporosity	Microporosity
		……………………. % ………………………….		
	Irrigation Regime			
TAW	1.62a	38.8e	14.4bc	24.4c
85 % TAW	1.60b	39.5d	14.3c	25.2b
70 % TAW	1.59c	40.1c	14.5bc	25.6b
55 % TAW	1.56d	41.1b	14.6b	26.5a
40 % TAW	1.54e	41.9a	14.9a	27.0a
SE	0.0173	0.6526	0.2875	0.5983
P (0.05)	<0.0001	<0.0001	< 0.0001	<0.0001
	Irrigation Interval			
4 days	1.61a	39.2c	14.6a	24.7c
8 days	1.59b	40.0b	14.4a	25.6b
12 days	1.58b	40.6b	14.6a	26.0b
16 days	1.55c	41.3a	14.6a	26.7a
SE	0.0145	0.5478	0.2414	0.5022
P (0.05)	<0.0001	<0.0001	NS	<0.0001

Note: TAW = as explained in Table-2; All means followed by the same letter within a column are not significantly different at 5% probability level using the Tukey-Kramer Multiple-Comparison Test.

Table-5. Water retention properties, infiltration rate and paddy rice yield of soil as influenced by Irrigation regime and interval.

Treatment	Saturation percentage	Field capacity	Permanent wilting point	Available water
	……………………… …….% …………………………………….			
Irrigation regime				
TAW	38.8c	24.4c	11.1c	13.3c
85 % TAW	39.7b	25.2b	11.6b	13.6b
70 % TAW	40.3b	25.6b	11.9b	13.7b
55 % TAW	41.4a	26.5a	12.5a	14.0a
40 % TAW	42.0a	27.0a	12.8a	14.2a
MSD	0.7573	0.5983	0.3862	0.2120
P (0.05)	<0.0001	<0.0001	<0.0001	<0.0001
4 days	39.1c	24.7c	11.3c	13.4c
8 days	40.3b	25.6b	11.9b	13.7b
12 days	40.8b	26.0b	12.1b	13.8b
16 days	41.7a	26.7a	12.6a	14.1a
MSD	0.6357	0.5022	0.3242	0.0516
P (0.05)	<0.0001	<0.0001	<0.0001	<0.0001

Note: TAW = as explained in Table-2; All means followed by the same letter within a column are not significantly different at 5% probability level using the Tukey-Kramer Multiple-Comparison Test.

Table-6. Effects of irrigation regime and frequency on yield attributes of paddy rice at the Irrigation research farm, Talata Mafara.

Treatment	Number of panicles/ m^2	Number of grains/ panicle	Grain weight/ panicle …………	Grain weight/ plant (g) ……..	1000 grain weight ………	Blank grain percentage (%)
Irrigation regime						
TAW	534.0b	116.0b	2.01b	4.64b	25.03a	15.0d
85 % TAW	544.8a	120.3a	2.11a	4.86a	24.94a	16.0c
70 % TAW	522.3b	112.3c	1.96c	4.58b	23.96b	16.9b
55 % TAW	509.0c	107.3d	1.91d	4.30c	23.50bc	17.4b
40 % TAW	494.5d	102.5e	1.82e	4.18c	23.02c	18.1a
SE	3.931	0.855	0.011	0.040	0.209	0.174
P (0.05)	0.000	0.000	0.000	0.000	0.000	0.000
Irrigation frequency						
4 days	537.8b	115.4b	2.01b	4.68b	24.75a	13.0d
8 days	558.4a	118.0a	2.07a	4.85a	25.28a	15.2c
12 days	518.4c	109.4c	1.92c	4.25c	23.69b	17.9b
16 days	469.0d	108.6c	1.84d	4.26c	22.68c	20.1a
SE	3.516	0.765	0.010	0.048	0.157	0.133
P (0.05)	0.000	0.000	0.000	0.000	0.000	0.000

Note: All means followed by the same letter within a column are not significantly different at 5% probability level using the Tukey-Kramer Multiple-Comparison Test.

Table-7. Effects of irrigation regime and frequency on paddy rice yield, water use, water use efficiency and water productivity at the irrigation research farm, Talata Mafara.

Treatment	Yield ..kg ha^{-1}..	Water use .. mm ..	Water use efficiency ..kg $ha^{-1}mm^{-1}$..	Water productivity ..US$ mm^{-1}..
Irrigation regime				
TAW	4039.7b	1077.5a	4.1b	2.45c
85 % TAW	4772.0a	915.6ab	5.8a	3.43a
70 % TAW	3404.6c	755.4b	4.9a	2.94bc
55 % TAW	2675.4d	592.4c	4.5ab	2.91ab
40 % TAW	2080.2d	431.1cd	5.5a	3.27ab
SE	204.2	69.57	0.237	0.150
P (0.05)	0.010	0.000	0.049	0.000
Irrigation frequency				
4 days	4068.0a	1348.9a	3.0c	1.79c
8 days	4442.3a	706.0b	6.4a	3.79a
12 days	2691.7b	513.4c	5.4b	3.17b
16 days	2375.5b	449.3c	5.4b	3.23b
SE	182.7	62.23	0.212	0.134
P (0.05)	0.000	0.000	0.000	0.000

Note: All means followed by the same letter within a column are not significantly different at 5% probability level using the Tukey-Kramer Multiple-Comparison Test.

Table-8. Grain yield regression equation and coefficient with yield attribute variables.

Variables	Regression equation	Regression Coefficient (R^2)
Number of panicles/m^2	Y= - 12187.1 + 29.9x	0.728
Number of grains/panicle	Y= - 15119.4 + 164.1x	0.862
1000 grain weight	Y= - 19289.5 + 941.7x	0.875
Grain weight/panicle	Y= - 1496.2 + 9370.1x	0.878
Grain weight/plant	Y= - 12597.1 + 3545.4x	0.944
Blank grain percentage	Y= 9783.2 - 382.9x	0.622

Table-9. Model parameter for relationship between paddy rice grain yield and yield attributes.

Variables	Parameter estimate	SE	t	sig.
Intercept	-15724.8	1221.5	-12.873	0.000
Grain weight/plant	2469.4	371.3	6.651	0.000
1000 grain weight	331.3	102.4	3.235	0.005

Fitted model 2: Y = -15724.8 + 24699.4 (grain weight/plant) + 331.3 (1000 grain weight)

Table-10. Summary of stepwise selection for paddy rice grain yield and yield attributes.

Step	Variable entered	Number of variable. In	Partial R^2	Cumulative R^2	F-value	Pr>F
1	Grain weight/plant	1	0.944	0.944	302.9	0.000
2	1000 grain weight	2	0.021	0.965	236.3	0.000

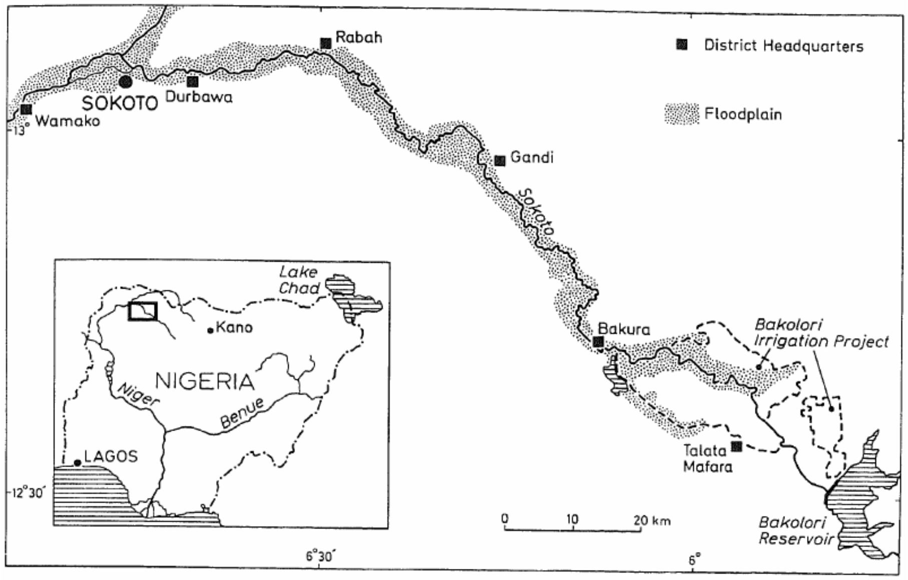

Figure-1. Location of the Sokoto River and the Bakolori irrigation project (Adams, 1993).

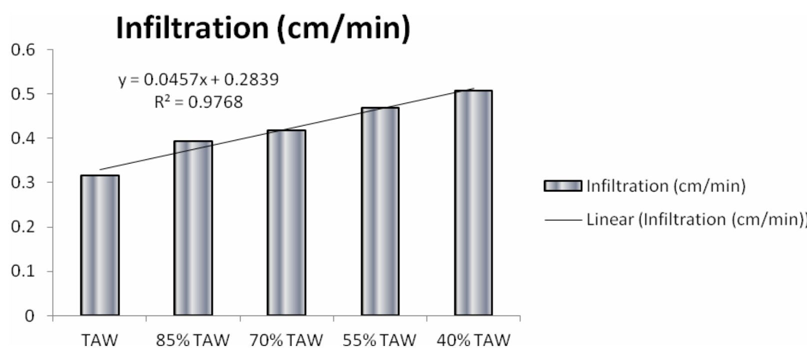

Figure-2. Infiltration rate of paddy rice field under various irrigation frequencies
TAW denotes total available water

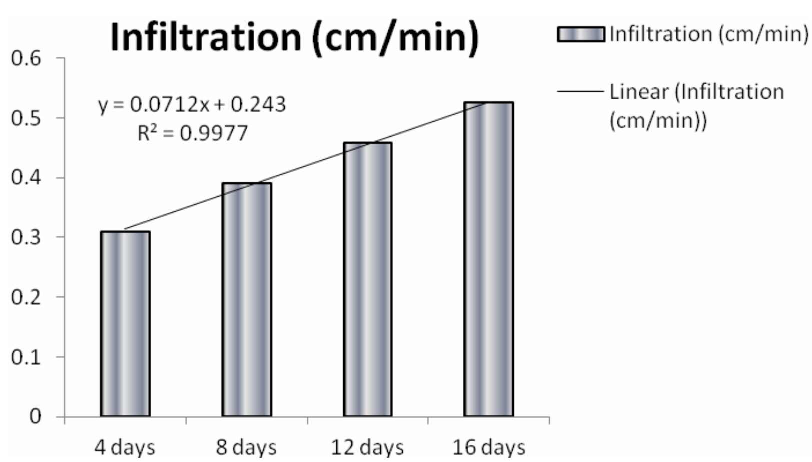

Figure-3. Infiltration rate of paddy rice field under various irrigation frequencies.

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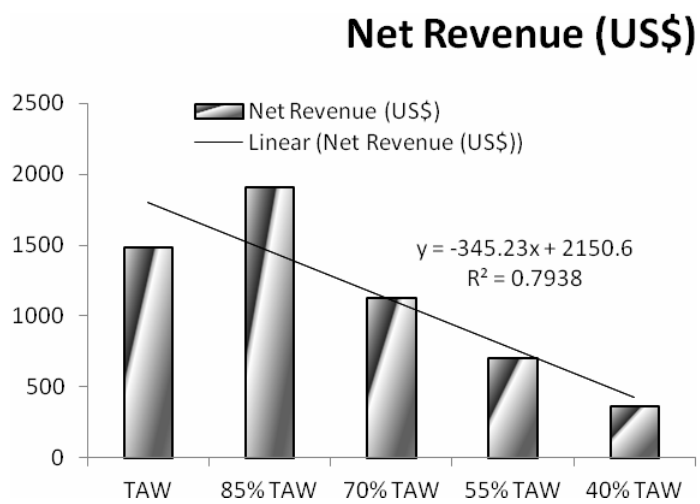

Figure-4. Net revenue obtained from sells of paddy rice produced under different irrigation regimes; TAW denotes total available water.

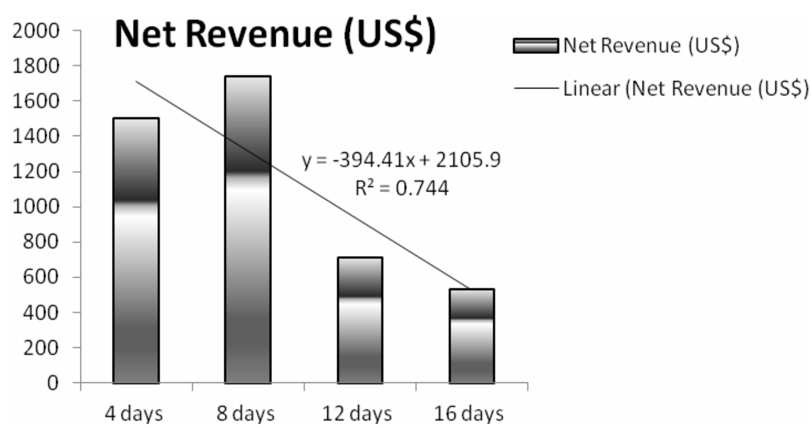

Figure-5. Net revenue obtained from sells of paddy rice produced under different irrigation frequencies.

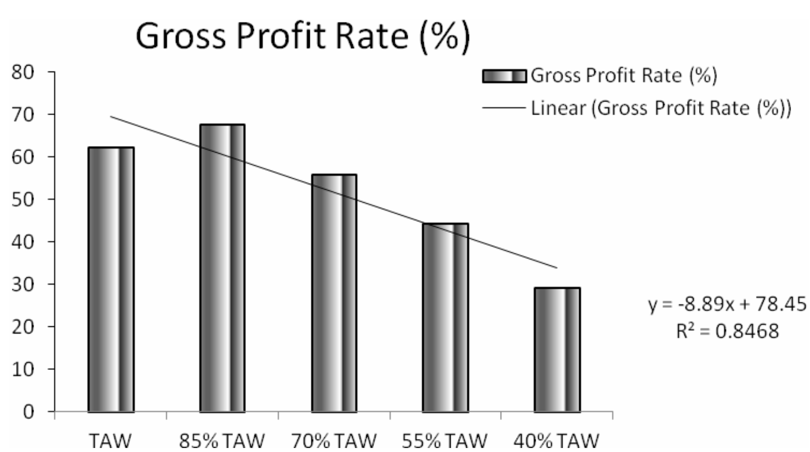

Figure-6. Gross profit rate of paddy rice obtained under different irrigation regimes.

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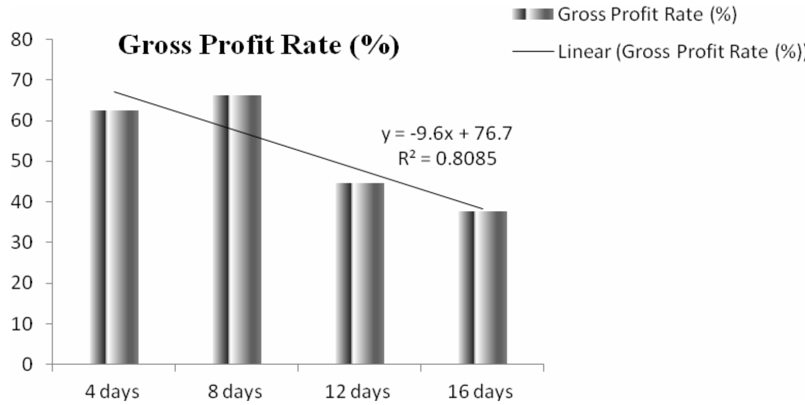

Figure-7. Gross profit rate of paddy rice obtained under different irrigation frequencies.

CONCLUSSIONS

From the results of the present study, it could be concluded that soil organic carbon content, mean weight diameter (wet) and clay flocculation index showed increasing pattern with deficit irrigation up to 85% TAW, but further water deficit resulted to decrease in these values. Pore size classes, water retained at saturation, field capacity, permanent wilting point and available for plant showed increasing pattern with increase in deficit water level up to 40 % TAW and irrigation frequency up to 16 days. However, increased water depth up to TAW and extreme water deficit (40% TAW) as well as more frequent (4 days interval) and prolonged irrigation (16 days) promoted soil dispersion as confirmed by the high clay dispersion ratio and clay dispersion index. Increased water depth and increased frequency favoured increase in soil bulk density. While higher water application depths and shorted irrigation frequencies were adversely affecting the soil physical quality, irrigation with water depth of 85 % TAW and 8 days frequency led to production of the highest paddy rice yield, water use efficiency, water productivity and economic return. Therefore, for this particular condition, given the deterioration of soil physical quality on application of higher water depth, it is advisable to replenish organic matter using resources such as crop residues and manure for attainment of high yield of both paddy rice as well as other crop and economic return while concurrently improving soil physical quality.

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