academicresearchJournals

Vol. 7(6), pp. 333-340, September 2019
DOI: 10.14662/ARJASR2019.100

ISSN: 2360-7874
http://www.academicresearchjournals.org/ARJASR/Index.htm

Academic Research Journal of Agricultural Science and Research

Full Length Research

Determination of optimal irrigation scheduling and water productivity for wheat (*Triticum aestevum L.*) at Kulumsa, Arsi Zone, Ethiopia

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Accepted 31 July 2019

This study was conducted at Kulumsa Agricultural Research Center, Arsi zone, Ethiopia, for two consecutive years (2015/16 and 2016/17) to evaluate the response of wheat to irrigation regime (when and how much water to irrigate) and to determine its water requirement and productivity. The experiment was arranged in a Randomized Complete Block Design (RCBD) with three replications. The treatments included five levels of irrigation regime, which were selected based on their level of soil moisture depletion (60%, 80%, 100%, 120% and 140% of Allowable Soil Moisture Depletion Level (ASMDL)). The result revealed that ASMDL significantly (*p*<0.05) affected the grain yield, above ground total biological yield and water productivity of wheat. The highest grain (4,959 kg ha^{-1}) and above ground total biological (10,734 kg ha^{-1}) yields were obtained at 60% of ASMDL. However, these results were statistically similar to the control treatment (100% ASMDL). The minimum grain (3,823 kg ha^{-1}) and above ground total biological (8,555 kg ha^{-1}) yields were recorded at 140% and 120% of ASMDL, respectively. The highest water productivity (1.17 kg m^{-3}) was obtained at 60% of ASMDL, which was statistically similar to the control treatment whereas the lowest water productivity (0.98 kg m^{-3}) was recorded at 140% of ASMDL. The result further revealed that increasing the soil moisture depletion level from 60% to 140% of the FAO recommendation had no effect on plant height, hectoliter weight, kernel weight and harvesting index of wheat. Having considered the non-significant difference between the control treatment (100% of ASMDL) and 60% of ASMDL with respect to wheat yield and its water productivity, irrigation at 100% of ASMDL has been recommended for wheat production at the study area and other areas with similar agro-ecology and soil type due to the fact that the irrigation interval of the 100% of ASMDL is longer compared to the 60% of ASMDL.

Keywords: irrigation scheduling, soil moisture depletion, water productivity and wheat

Cite this article as: Samuel L., Bakasho I., Mehiret H., Kassu T., Wubengida A. (2019). Determination of Optimal Irrigation Scheduling and Water Productivity for Wheat (*Triticum aestevum* L.) at Kulumsa, Arsi Zone, Ethiopia. Acad. Res. J. Agri. Sci. Res. 7(6): 333-340

INTRODUCTION

Water is essential for crop production and the best use of available water must be made for efficient crop production and high yields. This requires a proper understanding of the effect of rainfall and irrigation on crop growth and yield under different growing conditions (FAO, 1986). Irrigation can be defined as replenishment of soil water storage in the plant root zone through methods other than natural precipitation. Irrigation is seen to have found its roots in the history of mankind since earliest beginning. It helps to reduce the uncertainties, particularly the climatic variability in agricultural practices. The problem of irrigation consists of when and how much water to irrigate.

Crop water requirements (CWR) encompass the total amount of water used in evapotranspiration. FAO (1986) defined crop water requirements as the depth of water needed to meet the water loss through evapotranspiration of a crop, being disease free, growing in large fields under non restricting soil conditions, including soil water and fertility, and achieving full production potential under the given growing environment. The irrigation water requirement represents the difference between the crop water requirement and effective precipitation. The irrigation water requirement also includes additional water for leaching of salts where available and water to compensate for non-uniformity of water application. For the calculations of the CWR, the crop coefficient approach is used (Allen et al., 1998).

Water shortage in country demands to develop new technologies and methods of irrigation that can be helpful to utilize this precious input in an effective way. In addition, there is also a need to carry out practices of irrigation water management to achieve high water use efficiency (WUE).

Wheat (*Triticum aestivum L.*) is one of the most important staple food crops in the world. Ethiopia is the major producer of wheat in Eastern Africa accounting for over 70% of the total wheat area coverage in the region (Gebre-Mariam, 1991). The two major species of wheat grown in Ethiopia are tetraploid durum and hexaploid bread wheat (Tesemma and Jemal, 1982). Since annual crops including wheat are moderately to highly sensitive to water stress and the inadequate supply of irrigation water influences the growth and yield (Alderfasi and Nielsen, 2001; Mishra et al., 1995). Under semi-arid conditions, water resources are usually scarce and hence a limiting factor for crop production. Soil moisture deficit (SMD) at a particular magnitude may occur either continuously over the total growing period of the crop or it may occur during any individual growth period. However, different crops have different requirements and respond differently to SMD under different climatic conditions. Therefore, information on optimal irrigation water management and the adverse effects of soil moisture depletion levels at different growth stages of wheat and its yield performance is essential for decision making in irrigation water management. Research results have confirmed that some deficit irrigation is successful in increasing the WUE for various crops without causing severe yield reduction (Geerts and Dirk, 2009).

The water shortage stresses rescheduling of irrigation which should not affect grain yield significantly but can reduce the water applied to the crop. Water requirements of wheat vary from 180 to 420mm (Balasubramaniyan and Palaniappan, 2001). Thus, there is sufficient room to carry out research to find out what minimum amount of water should be applied to have maximum yield per millimeter of water applied. Study of soil moisture contents and the patterns of moisture depletion as the crop grows could help to sort out a suitable irrigation schedule for this objective. Lots of scientific works in this respect have been documented. Mohamed (1994)reported that irrigation at 60% available soil moisture depletion (ASMD) gave the highest grain yield and harvest index in wheat while WUE was the highest with 85% ASMD. Ahmad et al. (1996) observed that increasing ASMD from 50% to 75% markedly reduced total yield. Karim et al. (1997) observed that irrigation at 35% ASMD gave highest yield (4.71 t ha^{-1}) with the application of 120 kg N ha^{-1} while irrigation at 65% ASMD produced satisfactory yield (4.13 t ha^{-1}) with highest WUE (196.5 kg ha^{-1} cm^{-1}) with application of 80 kg N ha^{-1}. Similarly, Aydin et al. (2000) reported that irrigation at 66% ASMD was the most effective in terms of grain yield in wheat. Tahmasabi and Fardad (2000) applied irrigation at 10, 25, 50 and 75% ASMD and observed that grain yields were 3384, 3050, 3094 and 2273 kg ha^{-1}, while WUE was 1.13, 1.05, 0.82 and 0.86 kg m^{-3}, respectively. Narang et al. (2000) found that yield of all wheat cultivars studied decreased with increasing levels of ASMD. WUE was the highest with 60% ASMD.

Water is needed to carry out normal physiological activities of the plant. However, the actual water requirement is the quantity of water required to meet the demands of evapotranspiration and the metabolic activities of the plant i.e., consumptive use (CU). Since the water used in actual metabolic processes is insignificant (about 1%), water requirement is usually equal to evapotranspiration or CU. Observation in the study area indicated that there has been a practice of wheat production under full or supplementary irrigation. However, review of the available literature indicated that there were very few information regarding the optimum irrigation regime for wheat and its effect on the water productivity. Therefore, the objectives of the current study were (1) to evaluate the response of wheat to irrigation regime (when and how much water to irrigate) and (2) to determine the crop water requirement of wheat crop for highest water productivity.

MATERIALS AND METHODS

Description of the Study Area

The study was conducted at Kulumsa Agricultural Research Center, Tiyo district of Arsi Zone Oromia regional state, Ethiopia. The study area lies between 8°00’59’’ latitude, 39°09’25’’ longitude and situated at an elevation of 2200m a.s.l. The dominant soil type of the study area is characterized as vertic Luvisol (IUSS Working Group WRB, 2014) whereas the soil texture isclay loam. The bulk density was 1.25 g cm^{-3}. The field capacity and permanent wilting point at the experimental site were 33.60% and of 21.8%, respectively, which has the total available water of about 11.80%. The area is characterized by uni-modal rainfall pattern with mean annual rainfall of 809 mm. The mean maximum and minimum air temperature of the study area are 23.08°C and 9.90°C, respectively. The summarized climatic information of the study area is shown in the Table 1.

Table 1: Long term (1979-2009) climatic data of Kulumsa area

Year	RF (mm)	Max T (oc)	Min T (oc)	RH (%)	WS (m/s)	SS (hr)	ETo (mm)
Jan	17.09	23.36	8.21	56.49	4.96	8.18	191.36
Feb	37.66	24.37	9.35	52.89	5.23	8.35	173.18
Mar	79.53	25.07	10.33	50.73	4.36	7.65	182.63
Apr	84.15	24.41	11.50	58.35	4.18	7.23	161.08
May	88.13	24.80	11.16	57.26	4.74	7.28	179.89
Jun	87.04	23.50	10.64	80.58	4.71	6.53	133.03
Jul	124.22	21.16	10.64	76.41	4.84	4.94	128.55
Aug	131.07	20.94	10.38	77.37	3.87	4.96	105.58
Sep	97.86	21.51	9.94	75.38	2.87	5.57	99.01
Oct	42.09	22.75	10.17	60.91	4.98	7.65	192.32
Nov	10.16	22.56	8.70	53.98	5.71	8.75	198.98
Dec	10.15	22.53	7.71	54.23	6.11	9.00	179.27
Total	809.15						1924.87
Average		23.08	9.90	62.88	4.71	7.17	

Table 2: Climatic data of Kulumsa area during cropping season (2015/16-2016/17)

Year	Months	Rainfall (mm)	Effective RF (mm)	RH (%)	Sun Shine Hour (hr)	T_{max} (^oC)	T_{min} (^oC)	Wind Speed (m/s)
2015	November	28.40	7.04	58.33	8.04	23.68	12.15	2.20
	December	0.30	-9.82	62.06	7.56	23.12	11.43	2.16
2016	January	20.90	2.54	64.58	8.89	24.73	11.95	1.44
	February	1.90	-8.86	52.21	7.03	26.47	11.30	2.17
	November	12.20	-2.68	56.65	7.51	23.52	11.20	1.76
	December	0.00	-10.00	55.39	8.96	22.60	10.42	2.35
2017	January	0.00	-10.00	44.57	8.94	24.08	9.14	2.39
	February	29.10	7.46	60.86	6.98	24.67	10.70	1.58

Effective Rainfall (P_{eff}) is calculated by Dastane N.G., 1974 empirical equation for design purposes at 80% probability of exceedance as follows:

$$P_{eff} = 0.6 * P_{Total} - 10 \quad for\ P_{Total} < 70mm \qquad 1$$
$$P_{eff} = 0.8 * P_{Total} - 24 \quad for\ P_{Total} > 70mm$$

Crop management practice

Wheat (cv *king bird*) was sown to the experimental plots and was well-watered to have suitable germination and favorable plant stand. The plot size was 4m by 4.5m. The spacing between ridges was 0.40m. Seeds were sown at a rate of 125 kg ha^{-1} and drilled along the furrows by hand in double rows with 0.20m spacing at the right and left sides with in each ridge. The distances between plots and replications were 1m and 1.5m, respectively. Recommended rate of N and P (73-30 kg N-P ha^{-1}) were applied from di-ammonium phosphate and urea, respectively. Half dose of N and full does of P were applied during sowing as basal application while the remaining half dose of N was applied at tillering stage.

Furrow irrigation method was used to deliver water to the sown crop and the amount of water applied was measured using parshall flume. The crop water requirement was calculated based on the Penman monteith equation (Allen et al., 1998) using the FAO CROPWAT 8.0 computer program (Martin, 1996). The irrigation scheduling was done based on soil water depletion replenishments. The soil water content was monitored using the gravimetric method in such a way that soil samples were taken by metallic cylinders with a volume of 100cm^{-3} just before irrigation and 24hrs after full irrigation to maintain the soil water between allowable depletion level and field capacity, respectively. The recommended practices for wheat crop production were conducted from sowing to harvesting.

Experimental Design

The experiment was conducted for two consecutive years (2015/16 to 2016/17) during the off season. The irrigation treatments included five levels of soil water depletions based on the FAO 33 guideline. The five treatments were available soil moisture depletion level (ASMDL) of 60%, 80%, 100%, 120 % and 140%. Irrigation scheduling was based on the percentage depletion of the available soil water in the root zone. The experimental treatments were laid out in randomized complete block design (RCBD) with three replications. With the aid of the CROPWAT computer program, the crop water requirement of wheat was calculated for the various growth stages. The treatment setup is described as follow in Table 3.

Table 3: Treatment setting for the field experiment

Treatment No	Treatment code	Treatment description
T_1	$ASMD_1$	60% of ASMDL
T_2	$ASMD_2$	80% of ASMDL
T_3	$ASMD_3$	100% of ASMDL
T_4	$ASMD_4$	120% of ASMDL
T_5	$ASMD_5$	140% of ASMDL

Data Collection

The input data collected for the CROPWAT 8.0 computer program were daily climatic data; soil physical properties and crop data. Among the collected soil physical properties were soil texture, field capacity, permanent wilting point, available water and infiltration capacity of the studied soil. Whereas the crop data included: information on growth stages along with their periods, effective rooting depth and days to maturity. The water requirement of the studied crop, wheat, for the study area is summarized in the Table 3.

The yield and yield components data collected (computed) included plant height, hectoliter weight (HLW), thousand kernel weight (TKW), harvesting index (HI), above ground total biological yield and grain yield. The water productivity was estimated as the ratio between grain yield to the total irrigation water applied during the growing season (equation 1).

$$\text{Water productivity}\left(\frac{kg}{m^3}\right) = \frac{Grain\ yield\ (kg)}{Crop\ water\ use\ (m^3)} \quad 2$$

The effect of water stress on wheat yield was quantified by using the yield response factor (K_y) relationship (Simonne EH., 2010) (equation 2).

$$K_y = \frac{\left[1 - \left(\frac{Y_a}{Y_m}\right)\right]}{\left[1 - \left(\frac{ET_a}{ET_m}\right)\right]} \quad 3$$

Where K_y is yield response factor, Y_a is actual harvested yield, Y_m is maximum harvested yield, ET_a is actual evapotranspiration, ET_m is maximum evapotranspiration,

Statistical Data Analysis

The collected data were subjected to analysis of variance using the statistical analysis system (SAS) software version 9.0 with the General Linear Model (GLM) procedure (SAS Institute Inc., 2002). Mean separation was employed using the least significant difference (LSD) at 5% probability level to compare the differences among the treatments means.

RESULT AND DISCUSSION

Water requirement of wheat

Analysis of 31 years rainfall data indicated that the period from November to April is considered as dry season in the study area (Table 1). This implies that the seasonal precipitation during the aforementioned period in the experimental area is very low. Hence, it demands application of irrigation water for the crop production to be conducted since the precipitation could not satisfy the wheat crop water requirement.

The calculated water and net irrigation requirements of wheat in the study area were 654.61 and 425.50 mm, respectively (Table 4).

Table 4: Water and net irrigation requirements of wheat at Kulumsa

Growing stage	Length of growing period (days)	ETc (mm day^{-1})	Net irrigation requirement (mm)	Crop water requirement (mm)
Initial	30	1.62	48.9	75.23
Development	30	4.50	135.0	207.69
Mid	40	4.35	174.0	267.69
Late	20	3.38	67.6	104.00
Total	**120**		**425.5**	**654.61**

Yield components

The analysis of variance showed that the plant height, hectoliter weight, thousand kernel weight and harvest index of wheat were not affected by various levels of soil moisture depletion (Table 4). The recorded plant height ranged from 64.17 to 71.67 cm at ASMDL of 80% and 60%, respectively. The hectoliter liter weight obtained varied from 230.57 to 232.03 kg hl^{-1} at ASMDL of 140% and 60%, respectively. The thousand kernel weight of wheat varies from 38.04 to 42.83 g at 80% and 60% of ASDL. The harvesting index of wheat differs from 43.89 to 48.05% at ASMDL of 140 and 100%, respectively (Table 4). The non-significant result of harvest index of wheat in the current study is in agreement with Elias et al. (2017), who reported that different levels of moisture stress had no influence on the harvesting index of wheat. Similar finding due to soil moisture stress was also reported by Khakwani et al. (2011) despite the different wheat varieties showed dissimilar harvesting index.

Grain and above ground total biological yields

The analysis of variance revealed that grain the yield of wheat was significantly (p<0.05) affected by the different levels of soil moisture depletion (Table 4). The highest grain yield of wheat (4,959 kg ha^{-1}) was obtained from the application of irrigation water at 60% of ASMDL. However, this result was statistically similar to the grain yield of wheat obtained when irrigation was scheduled at 100% of ASMDL (p=0.55; Allen et al., 1998) (4,800 kg ha^{-1}). The lowest grain yield of wheat (3,823 kg ha^{-1}) was obtained when irrigation water was applied after the crop depleted 140% of the ASMDL. However, this result was statistically similar to the 80% (3,945 kg ha^{-1}) and 120% (3929 kg ha^{-1}) of ASMDL treatments (Table 4). The current result implies that wheat grain yield could be increased when irrigation water was applied after the crop depleted 60% of the ASMDL on a clay loam textured soil. The result further infers that the application of irrigation water at the FAO recommended value for wheat (p=0.55 or 100% of ASMDL) Decreased the frequency of irrigation compared to the 60% of ASMDL treatment. Adoption of 100% of ASMDL for wheat in the study area and other areas with similar agro-ecology has been found better in terms of longer irrigation interval, which minimizes irrigation frequency and labor cost in comparison with the 60% of ASMDL treatments.

The analysis of variance further indicated that application of irrigation water at different levels of available soil moisture depletion significantly (p<0.05) influenced the above ground total biomass yield of wheat. The highest above ground total biological yield of wheat (10,734 kg ha^{-1}) was recorded when irrigation was scheduled at 60% of ASMDL. This result was statistically different from all treatments except for 100% of ASMDL (p=0.55). The lowest above ground total biological yield of wheat (8,554 kg ha^{-1}) was obtained from the plots that received irrigation water at 120% of ASMDL. However, this result was statistically similar to application of irrigation water at 80% and 120% of ASMDL (Table 5).

Narang *et al*. (2000) reported that the yield of wheat cultivars decreased with increasing levels of soil moisture depletion level, which agrees well with the current result. Panda et al (2003) reported that above ground dry matter followed a similar trend as that of grain yield, which is also in line with the findings of the current study. They also observed that when the irrigation was scheduled at a depletion level of less than or equal to 45% MAD, there was no significant change in the above ground dry matter yield. However, a reduction in the above ground dry matter yield was observed when irrigation was scheduled at 60% to 75% MAD because soil moisture was depleted sufficiently and affected the root water extraction. Similar trend was observed during all the three depletion levels, which FAO recommend 60% depletion level for production of grass species (FAO 1998). This might be due to the optimum depletion level of the lemongrass required is 60% of the total available water (TAW) both for optimum water and air circulation in the root depth. This could be as soil gets dried beyond 60% of TAW, the crop experienced stress in the growing season due to photosynthesis interruption as a consequence of shortage of water supply (Makino, 2011).

Table 5: ANOVA table for the influence of various levels of soil moisture depletion on the yield and yield components of wheat at Kulumsa

Treatments	plant height (cm)	Hectolite r weight (kg hl^{-1})	Thousand kernel weight (gm)	Harvest index (%)	Grain yield (kg ha^{-1})	Biomass yield (kg ha^{-1})
60% of ASMDL	71.67	232.03	42.83^{a}	46.21	4959^{a}	10734^{a}
80% of ASMDL	64.17	231.91	38.04^{b}	44.10	3945^{bc}	8750^{b}
100% of ASMDL	70.00	231.18	39.29^{ab}	48.05	4800^{ab}	9950^{ab}
120% of ASMDL	65.67	231.50	39.51^{ab}	44.29	3929^{bc}	8554^{b}
140% of ASMDL	68.83	230.57	40.13^{ab}	43.89	3823^{c}	8668^{b}
$LSD_{0.05}$	ns	ns	ns	ns	9.47	16.11
CV (%)	9.87	3.34	7.61	8.51	18.42	14.33

Note: Means followed by the same letters in each column are not significantly different at α = 0.5

Water Productivity

Scheduling irrigation at various levels of ASMDL resulted in statistically significant (p<0.05) differences with respect to water productivity in wheat. The highest water productivity of wheat (1.17 kg m^{-3}) was recorded from scheduling irrigation at 60% of ASMDL (Table 6). This result was not statistically different from application of irrigation water at 100% of ASMDL (1.13 kg m^{-3}). The lowest water productivity of 0.89 kg m^{-3} was recorded when wheat was irrigated after 140% of the available soil moisture depleted from the soil. This result was statistically similar to scheduling irrigation at 120% (0.92 kg m^{-3}) and 80% (0.93 kg m^{-3}) of ASMDL. Compared to application of irrigation water at 100% ASMDL, scheduling irrigation of wheat at 60% of ASMDL improved water productivity by 3% (Table 6). Improving water productivity is an increasing concern through different irrigation practices to enhance yield of crop per unit of irrigation water used. Many studies on a variety of crops revealed that water productivity could be improved using different irrigation practice such as determination of the optimal soil moisture depletion level through field experiments. As there was no significance yield reduction between 60% and 100% of ASMDL treatments, it has been recommended to schedule irrigation of wheat in the study area and other areas with similar agro-ecologies for the fact that that latter could save labor cost.

Table 6: The effect of scheduling irrigation at different available soil moisture depletion level on the water productivity in wheat at Kulumsa

Treatments	Irrigation water applied in		Grain yield (kg ha^{-1})	Yield reduction (%)	Water productivity (kg m^{-3})
	mm	m^3			
60% of ASMDL	425.5	4255	4959	-	1.17^{a}
80% of ASMDL	425.5	4255	3945	20.45	0.93^{bc}
100% of ASMDL	425.5	4255	4800	-	1.13^{ab}
120% of ASMDL	425.5	4255	3929	18.15	0.92^{bc}
140% of ASMDL	425.5	4255	3823	2.7	0.90^{c}
$LSD_{0.05}$					0.22
CV (%)					18.42

CONCLUSION AND RECOMMENDATION

Water is one of the essential inputs for crop production and the best use of the available water resources must be made for increasing yields in the context of an exploding population pressure. This requires a proper understanding of the effect of water (rainfall or irrigation) on crop growth and yield under different growing conditions. Soil water monitoring is also important for proper irrigation water management. Field experiment was, therefore, conducted at Kulumsa Agricultural Research Center, Arsi zone, Ethiopia to evaluate the response of wheat to irrigation regime (when and how much irrigation water to be applied) and determine the crop water requirement of wheat. Five levels of irrigation scheduling (60%, 80%, 100%, 120% and 140% available soil moisture depletion level (ASMDL) of the FAO recommendation for wheat) were tested in line with the aforementioned objectives. Results showed that scheduling irrigation at various ASMDL had significant effect on wheat grain yield, above ground total biological yield and water productivity. The result further revealed that no significant effects were obtained on plant height, hectoliter weight, thousand kernel weight and harvest index of wheat. The highest grain yield (4,959 kg ha^{-1}), above ground total biomass yield (10,734 kg ha^{-1}) and water productivity (1.17 kg m^{-3}) were obtained from scheduling irrigation at 60% of ASMDL. However, these results were found statistically similar with application of irrigation water at 100% ASMDL. The lowest grain yield (3,823 kg ha^{-1}) and water productivity (0.89 kg m^{-3}) were recorded at 140% of ASMDL. Since the yield and water productivity obtained from scheduling of irrigation at 60% of ASMDL had no statistically significant difference compared to the FAO 33 recommendation (100% of ASMDL), the adoption of the latter has been recommended due to the fact that it increased the irrigation interval, which minimizes irrigation frequency labor consumption. Therefore, scheduling irrigation at 100% ASMDL (p=0.55) has been recommended for increasing wheat production in the study area and other areas with similar agro-ecology and soil type.

ACKNOWLEDGMENT

The authors are grateful to Ethiopian Institute of Agricultural Research for providing funds for the execution of this experiment. The authors are also very grateful to Kulumsa Agricultural Research Center for the provision of logistics during the conduct of the experiment. We are also greatly indebted to Mr. Mengistu M., Alemayehu W., Dawit T. and all staff members of natural resources management research process for the provision of technical support, suggestion and guidance thorough the execution of the experiment.

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