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Determination of Crop Water Requirements and Irrigation Scheduling of Wheat Using Cropwat at Koga and Rib Irrigation Scheme, Ethiopia

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Abstract: Population growth, high water competition, and the effect of climate change have caused water shortage problems in the Nile basin, Ethiopia. Proper water management improves water efficiency and determining the water requirement of field crops are options for improving water productivity. In this study, the CROPWAT 8.0 model, local climate, and soil data were used to determine crop water requirement (CWR) and irrigation scheduling of wheat at Koga and Rib irrigation scheme, Nile basin. The Penman-Monteith and United States Department of Agriculture (USDA) soil conservation service methods were used to compute the reference evapotranspiration (ETo) and effective rainfall. Five levels of water depth (50%, 75%, 100%, 125%, and 150%) of the model and two irrigation intervals (14 and 21 days) were arranged in a Randomized Completely Block Design. The Koga, irrigating 75% of CROPWAT simulated water depth (9.3 , 22.9 , 44.1 and 25.8 mm at initial, development, middle and late-stage respectively) gave 3.37 t ha^{-1} wheat yield and 1.01 kg m^{-3} water productivity. The result at Rib showed that irrigating 75% of the model (9.1, 23.6, 47.2, and 34.2 mm at initial, development, middle, late-stage, respectively) gave 4.27 t ha^{-1} yield and 1.81 kg m^{-3} water productivity of wheat. The reference evapotranspiration varied from 4.86 to 3.14 mm day^{-1} at Koga and from 4.67 to 2.36 mm day^{-1} at Rib scheme. The irrigation requirement of wheat at Koga was 376.9 mm dec^{-1} while at Rib was 379.9 mm dec^{-1}. The CROPWAT model is an important tool to compute the crop water requirement of field crops in irrigated agriculture.

Keywords: Irrigation scheduling, Crop water requirement, Wheat, Koga, Rib

Water is the main production inputs in agriculture to maintain the development of irrigation agriculture and Irrigated agriculture plays an important role in food security, poverty reduction, and economic growth, thus effective management is an important issue in an irrigation system. Comprehensive irrigation water management practices are essential to improve water management and eliminate the associated problems. Agriculture is the backbone of Ethiopia but most of the cultivated land is under a rain-fed agriculture system. Even though Ethiopia has abundant water resources from precipitation, surface and subsurface source, it suffered from severe drought, high temporal and spatial variations of water resources for the last four decades. Farmers in Ethiopia produce crops under high spatial and temporal variation of rainfall which causes cop production failures. The population is growing rapidly and is expected to continue grow, which inevitably leads to increased food demand. Farmers in Ethiopia face challenges including high competition for water, unpredictable rainfall, limited financial capacity, and climate change. By realizing such challenges, the government of Ethiopia takes initiation and allocating huge investments for irrigation infrastructure development during the last two decades. Tana Beles, Megech, Koga, and Rib are some of the irrigation projects located in the Blue Nile Basin, Ethiopia. Appropriate water (crop water requirement) application in crops production can improve nutrient availability, prevent land degradation, improve crop yield and water use efficiency. Soil moisture conditions affect nutrient availability to the crops. Good irrigation management is critical for wheat productivity, a significant grain yield and tillers were observed using optimal and suboptimal crop water requirements. The proper amount and timing of irrigation water applications is a crucial decision for a farm manager to prevent yield loss and maximize the irrigation water use efficiency. Crop water requirements are the depth of water needed to meet the water loss through evapotranspiration, being disease-free, growing in large fields under non-restricting in soil, water, and fertility, and achieving full production potential under the given growing environment. Several empirical methods were developed around the world from the simplest and oldest (Blaney Criddle method) to the most recent and accurate (FAO Penman-Monteith method) to determine crop water requirement ranging. The Penman-Monteith method has been recommended as the appropriate combination method to determine reference evapotranspiration (ETo) based on climatic data. CROPWAT is a tool developed by FAO used for irrigation planning and management and is widely used to estimate reference evapotranspiration (ETo) and crop water requirement. It allows for the development of improved irrigation practices, planning of irrigation schedules, and assessment of production under rained/irrigation conditions. Irrigation agriculture is widely expanded in the Blue Nile basin like Koga and Rib irrigation schemes. Farmers can irrigate crops based on traditional know-how causing nutrient leaching, waterlogging, and severe water shortage problems in the study area. Wheat is the most dominantly cultivated cereal crop under irrigation in the Koga irrigation command area while at Rib is the newly introduced cereal crop by farmers. However, crop water requirements and irrigation schedules of wheat were not done in the study site (Koga and Rib) irrigation scheme. Therefore, the objectives of this study were to determine the crop water requirement and irrigation scheduling of wheat using the CROPWAT model for optimal resource allocation and to increase yield and water productivity.

MATERIAL AND METHODS

Study Area

Koga irrigation scheme is located in the Tana Basin under Mecha district, south of the Amhara Region, Ethiopia. It lies between 11° 20' to 11° 32' North Latitude and 37° 02' to 37° 11' East Longitude. Koga irrigation scheme is located 41 km to the West of Bahir Dar city and 543 km to the North of the capital city, Addis Ababa at 37° 7' 29.72" Easting and 11° 20' 57.85" Northing and 1953 m a.s.l. The average annual rainfall of the area is 1124 mm. The mean maximum and minimum temperatures are 26.8 ^{0}C and 9.7 ^{0}C respectively (Fig. 1). Rib irrigation scheme is located inside Tana Basin in Fogera district Northwest of Ethiopia, 60 kilometers to the East of Bahir Dar city and 648 km North of the capital city, Addis Ababa at 37°25' to 37°58' Easting and 11°44' to 12°03' Northing and an altitude of 1803 m a.s.l. It receives 1400 mm mean annual rainfall. The mean daily maximum and minimum temperature of the area is 30°C and 11.5°C.

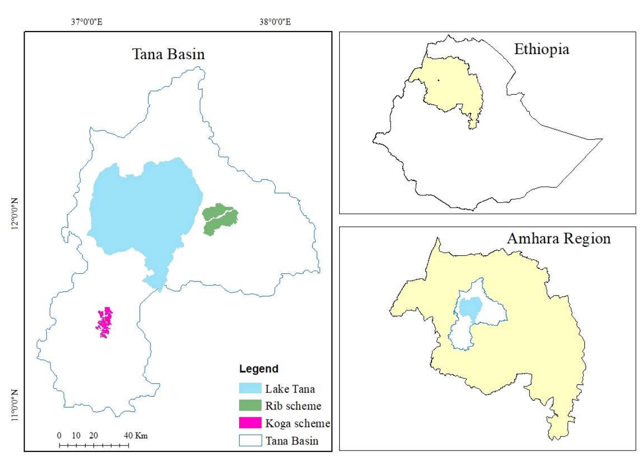

Fig. 1. Location of the study site

To verify the CROPWAT model generated water depth, field experiments were carried out for two consecutive years (2015 and 2016) at both locations. The field experiments were arranged in a randomized complete block design (RCBD) with three replications. The crop wheat variety of TAY was used and planted on 0.2 m spacing between rows with 150 kg ha^{-1} seed rate. The planting date under irrigation in the study area was started in mid-November. DAP was applied at a rate of 100 kg ha^{-1} at planting and 138 kg ha^{-1} Urea (half at planting and a half at 45 days after planting) were applied. All the agronomic practices were applied equally for all treatment as per agronomic recommendation. Local rainfall data, reference evapotranspiration (ETo), soil data, and crop data have used as an input for the CROPWAT model. Crop water requirement and irrigation water requirement were computed using the CROPWAT 8.0 model. Climate data for sixteen years (2000-2016) for the Koga irrigation scheme were taken from Koga and Bahir Dar meteorological stations while for the Rib irrigation scheme Addis Zemen meteorological station was used. The crop data for wheat (root depth, crop coefficient, critical depletion, yield response factor, and length of plant growth stage) was obtained from FAO irrigation and drainage paper 56. Information on soil properties i.e., field capacity (FC), permanent wilting point (PWP), infiltration rate, initial soil moisture depletion were done at Adet Agricultural Research Center soil laboratory using the gravimetric method. Reference evapotranspiration (ETo), the crop evapotranspiration (ETc), and irrigation water requirement (IWR) were estimated using FAO penman-Monteith method; equations 1, 2 and 3 respectively. The United States Department of Agriculture (USDA) Soil Conservation Service method was used for the estimation of effective rainfall.

$$ETo = \frac{0.408\,\Delta(Rn - G) + \gamma\,\dfrac{900}{T + 273}U2(es - ea)}{\Delta + \gamma(1 + 0.34U2)} \quad ....(1)$$

Where: ETo = reference evapotranspiration [mm day-1], Rn = net radiation at the crop surface [MJ m^{-2} day^{-1}], G = soil heat flux density [MJ m^{-2} day^{-1}], T = mean daily air temperature [°C], U2 = wind speed at 2 m height [m s^{-1}], es = saturation vapour pressure [kPa], ea = actual vapour pressure [kPa], es-ea = saturation vapour pressure deficit [kPa], Δ = slope vapour pressure curve [kPa °C^{-1}], γ = psychrometric constant [kPa °C^{-1}] The crop water requirement (CWR) is the water lost from a cropped field through evapotranspiration (ET) and it is expressed as the rate of ET in mm/day. The CWR is derived from crop evapotranspiration (ETc) and estimated by the following equation. The differences in crop evapotranspiration (ETc) during the growth stages, crop coefficient (Kc) for wheat was varied over the development stage (initial development, mid-season, and late-season). Irrigation scheduling determines when and how much irrigate the specific field crop.

$$ETc = ETo \times Kc \quad \text{(eqn. 2)}$$

Where,

ETc = Crop Evapotranspiration (mm day^{-1}),

ETo = Reference Crop Evapotranspiration (mm day^{-1})

Kc = Crop coefficient

The irrigation requirement (IR) is the main parameter for the planning, design, and operation of irrigation and water resources systems. It is important to the optimal allocation of water resources for policy and decision-maker during the operation and management of irrigation systems. Missed management of irrigation requirements may lead to inappropriate capacities storage reservoirs, low water use efficiency, reduction of the irrigated area, and increased development costs. The irrigation requirement is therefore determined by the following equation.

$$IRn = ETc - (Pe + Ge + Ws) + LR \quad \text{(eqn 3)}$$

Where, IRn = Net irrigation requirement (mm), ETc = Crop evapotranspiration (mm), Pe = Effective dependable rainfall (mm), Ge = Groundwater contribution from water table (mm), Ws = Water stored in the soil at the beginning of each period (mm) and LR = Leaching requirement (mm)

Field experiment: The on-farm trial was conducted in the dry season (November to April) with ten treatments. Two fixed irrigation intervals of 14 and 21 days and five water depths 50, 75,100,125 and 150 % of CROPWAT 8.0 generated were arranged in Randomly Completed Block Design (Table 1). During crop water requirement determination 70 % application efficiency was applied at both locations.

Table 1. Treatment setup of the experiments

Treatment	Depth and interval CWR at 14 days	Treatment	Depth and interval CWR at 21 days
T1	50%	T6	50%
T2	75%	T7	75%
T3	100%	T8	100%
T4	125%	T9	125%
T5	150%	T10	150%

RESULTS AND DISCUSSION

The soil sample was taken before the planting of wheat takes place and analyzed using laboratory procedure. The particle size of the sample was determined using the hydrometer method. The result as shown the soil texture was varied in the study site (Table 2). It shown that the texture was laid under the clay soil texture class at Koga according to and the other physical characteristics were similar with . The soil analysis at Rib has shown that a light clay classification and has high alluvial deposited that comes from a mountainous area upstream of the Rib River (Table 2). Data of wheat planting and harvesting date, critical depletion level, root depth, crop growing period (Table 3) and soil characteristics of the study area (Table 2) were used to compute crop evapotranspiration.

The reference evapotranspiration (ETo) obtained using the input data at the Koga irrigation scheme was high between February and June (4.0-4.86 mm day^{-1}) due to the high temperature (Table 4). It decreases after July and the lowest value was 3.14 mm day^{-1} in August due to low temperature in the area. The average reference evapotranspiration was 3.88 mm day^{-1} (Table 4). The reference evapotranspiration value at Rib irrigation scheme shown that, a high evaporation rate was observed in March (4.67 mm day^{-1}) while the lowest evaporation (2.36 mm day^{-1}) was recorded in July (Table 5). The June, July, August, and September are the rainy seasons. The lowest rainfall and effective rainfall was during November to May (Table 6). The average rainfall of the last sixteen years (2000 – 2017) was used as input and the USDA soil conservation service was applied to estimate effective rainfall and to compute the wheat water requirement and irrigation scheduling. The average annual rainfall at Koga and Rib irrigation scheme

Table 2. Soil characteristics of the study area

Site	FC (%)	WP (%)	Sand (%)	Silt (%)	Clay (%)
Koga	30.8±1.7	18.9±1.2	20.2±4.8	22.4±2.7	57.3±4.5
Rib	59.0±1.3	21.0±1.4	24.0±2.4	36.0±3.5	40.0±5.2

Table 3. Input data for CROPWAT model in the study area

Crop	Planting and harvesting date	Root depth (m)	Depletion fraction (P)	Yield response factor (K_y)			
				Initial	Development	Middle	Late
Wheat	Mid-November	0.6 - 1.5	0.55	0.20	0.60	0.50	0.50

were 874.3 mm and 1032.0 mm while the effective rainfall was 539.2 mm 623.1 mm respectively (Table 6). The monthly reference evapotranspiration (ETO) exceeds the monthly rainfall from January to May and from November to December on both locations (Fig. 2, 3). These indicate that irrigation water is substantial during these months in the study area.

Crop water requirement: The monthly water requirement and irrigation requirement of wheat planted in mid-November shown that crop water demand in both locations was varied within the same month. The maximum crop water requirement was in February was 46.3 mm dec^{-1} at Koga and 50.2 mm dec^{-1} at Rib irrigation scheme (Table 7, 8). This variation comes from high-temperature variation between the two study sites (Table 5, 4).

Net irrigation requirement and irrigation scheduling: The farmers applied irrigation water through furrow irrigation (dominantly) and flooding irrigation (minor) systems. The application efficiency in the study area was taken as 70 % to determine irrigation requirements. The total gross and net irrigation water requirement for wheat at the Koga irrigation scheme was 529.2 mm and 370.5 mm respectively while at the Rib irrigation scheme was 635.8 mm and 445 mm respectively (Table 9).

Table 4. Climate characteristics of Koga irrigation scheme

Month	Temperature (°C)		Relative humidity (%)	Wind speed (km day^{-1})	Sunshine hours	Radiation ($MJ/m^2 day^{-1}$)	ETo (mm day^{-1})
	Min	Max					
January	8.2	27.1	48	61	9.5	20.9	3.45
February	10	29.1	43	69	9.7	22.6	4.01
March	12.7	30.1	41	86	9.2	23.3	4.56
April	14.4	30.3	42	95	9.1	23.6	4.86
May	15.2	29.7	52	86	8.5	22.3	4.62
June	14.2	27.8	66	86	6.9	19.5	4.00
July	14	24.4	76	69	4.6	16.2	3.21
August	13.9	24.8	84	69	4.6	16.4	3.14
September	13.4	25.8	73	69	6.3	18.8	3.57
October	13.7	26.8	64	69	8.7	21.4	3.96
November	11.2	26.9	57	61	9.7	21.4	3.72
December	8.5	26.8	52	61	9.7	20.6	3.41
Average	12.4	27.5	58	73	8	20.6	3.88

Table 5. Climate characteristics of Rib irrigation scheme

Month	Temperature (°C)		Relative humidity (%)	Wind speed (km day^{-1})	Sunshine hours	Radiation ($MJ/m^2 day^{-1}$)	ETo (mm day^{-1})
	Min	Max					
January	9.8	27.7	67	156	8.3	19.1	3.57
February	10.8	29.5	63	156	9.3	21.9	4.25
March	11.8	29.7	60	147	9.2	23.2	4.67
April	12.1	29.2	59	130	8.3	22.3	4.57
May	12.1	29.5	71	156	6.8	19.8	4.12
June	12.0	26.8	86	156	5.6	17.7	3.37
July	12.1	23.7	94	104	2.0	12.4	2.36
August	12.0	24.0	95	86	2.2	12.8	2.40
September	11.6	25.2	91	104	6.7	19.4	3.38
October	10.8	27.2	82	138	8.4	20.9	3.69
November	10.3	27.2	77	138	9.1	20.4	3.56
December	10.3	27.6	71	112	8.8	19.2	3.40
Average	11.3	27.3	76	132	7.1	19.1	3.61

The crop needs optimal moisture conditions to achieve maximum yield. The total available moisture (TAM) and readily available moisture (RAM) (Fig. 4, 5) are media that the plant can get from the root zone with no water stress. The crop water requirement of wheat varies in place, month, and growth stage in the study area. In general optimal irrigation application considering soil water holding capacity and crop water requirement (especially during critical stages of wheat) is essential to improve water shortage problems and to enhance yield and water productivity of the study area.

Yield and water productivity of wheat: The yield and water productivity of wheat for irrigation interval and depth has significantly affected at both locations. The optimal yield of 3.37 t ha^{-1} and 1.01 kg m^{-3} water productivity of wheat were obtained under 75 % CWR within 14-day irrigation interval at Koga (Table 11). The yield showed an increasing trend with the increase of water depth. However, a further increase in irrigation level hurt the grain yield of wheat. The production was low compared to other productive areas of northwestern Amhara this is due to the soil condition (acidic soil) of Koga command area. Besides, the soil at Koga has very low organic matter content and available phosphorus as

Table 6. Rainfall and effective characteristics of the study irrigation scheme

Month	Rainfall (mm)		Eff. Rainfall (mm)	
	Koga	Rib	Koga	Rib
January	0.0	6.0	0.0	5.9
February	0.0	2.0	0.0	2.0
March	0.1	0.0	0.1	0.0
April	0.0	11.0	0.0	10.8
May	7.3	32.0	7.2	30.4
June	122.0	110.0	98.2	90.6
July	314.8	355.0	156.5	160.5
August	274.4	319.0	152.4	156.9
September	137.9	129.0	107.5	102.4
October	17.8	51.0	17.3	46.8
November	0.0	13.0	0.0	12.7
December	0.0	4.0	0.0	4.0
Total	874.3	1032.0	539.2	623.1

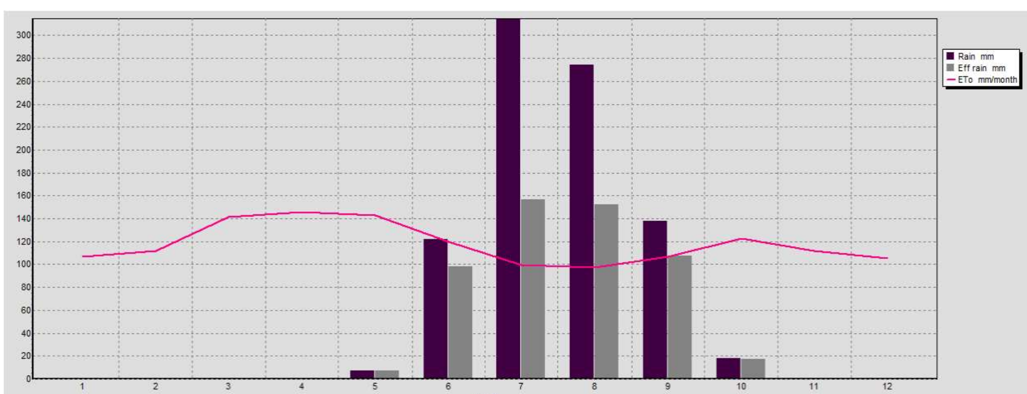

Fig. 2. Reference evapotranspiration (ETo), rainfall and effective rainfall at Koga scheme

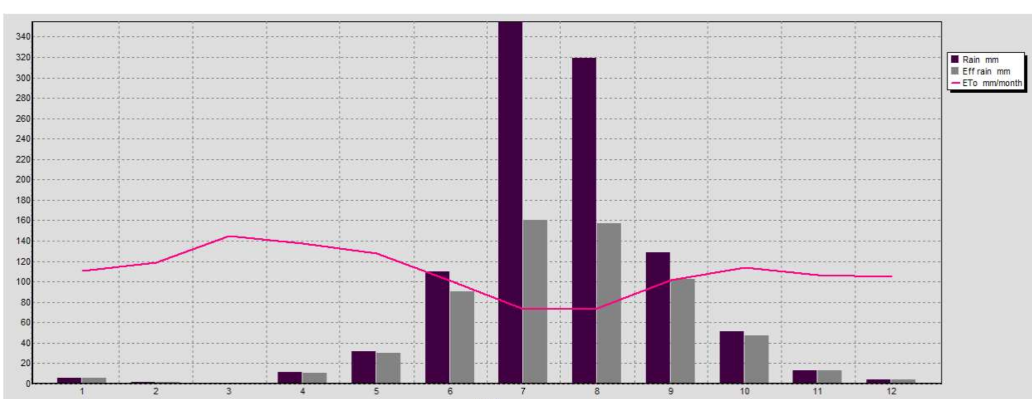

Fig. 3. Reference evapotranspiration (ETo), rainfall and effective rainfall at Rib scheme

Table 7. Crop water requirement and irrigation requirement of wheat at Koga irrigation scheme

Month	Decade	Stage	Kc (Coeff.)	ETc (mm day^{-1})	ETc (mm dec^{-1})	Eff rain (mm dec^{-1})	Irr. Req. (mm day^{-1})
November	2	Init	0.30	1.12	6.7	0	6.7
November	3	Init	0.30	1.09	10.9	0	10.9
December	1	Init	0.30	1.05	10.5	0	10.5
December	2	Dev	0.36	1.23	12.3	0	12.3
December	3	Dev	0.64	2.20	24.2	0	24.2
January	1	Dev	0.94	3.24	32.4	0	32.4
January	2	Mid	1.15	3.96	39.6	0	39.6
January	3	Mid	1.16	4.21	46.3	0	46.3
February	1	Mid	1.16	4.42	44.2	0	44.2
February	2	Mid	1.16	4.63	46.3	0	46.3
February	3	Late	1.08	4.53	36.2	0	36.2
March	1	Late	0.83	3.62	36.2	0	36.2
March	2	Late	0.54	2.47	24.7	0	24.7
March	3	Late	0.34	1.60	6.4	0	6.4
Total					377	0.1	376.9

Table 8. Crop water requirement and irrigation requirement of wheat at Rib irrigation scheme

Month	Decade	Stage	Kc (Coeff.)	ETc (mm day^{-1})	ETc (mm dec^{-1})	Eff rain (mm dec^{-1})	Irr. Req. (mm day^{-1})
November	2	Init	0.30	1.07	6.4	1.9	4.9
November	3	Init	0.30	1.05	10.5	2.5	8.0
December	1	Init	0.30	1.04	10.4	2.0	8.4
December	2	Dev	0.36	1.23	12.3	0.9	11.4
December	3	Dev	0.65	2.25	24.8	1.2	23.6
January	1	Dev	0.96	3.38	33.8	1.9	31.8
January	2	Mid	1.17	4.18	41.8	2.2	39.6
January	3	Mid	1.18	4.48	49.3	1.7	47.6
February	1	Mid	1.18	4.75	47.5	1.1	46.5
February	2	Mid	1.18	5.02	50.2	0.6	49.6
February	3	Late	1.10	4.85	38.8	0.4	38.4
March	1	Late	0.84	3.82	38.2	0.0	38.2
March	2	Late	0.55	2.57	25.7	0.0	25.7
March	3	Late	0.34	1.60	6.4	0.0	6.3
Total					396.1	16.5	379.9

Table 9. Irrigation scheduling of wheat at Koga irrigation scheme

Date	Day	Stage	Rain (mm)	Ks (fract.)	Eta (%)	Depl (%)	Net Irr (mm)	Deficit (mm)	Loss (mm)	Gr. Irr (mm)
28-December	44	Dev	0	1	100	56	58.0	0	0	82.8
18-January	65	Mid	0	1	100	56	70.7	0	0	101.0
04-February	82	Mid	0	1	100	57	71.9	0	0	102.7
20-February	98	Mid	0	1	100	58	72.8	0	0	104.0
20-March	126	End	0	1	100	77	97.1	0	0	138.7
24-March	End	End	0	1	0	4				

Table 10. Irrigation scheduling of wheat at Rib irrigation scheme

Date	Day	Stage	Rain (mm)	Ks (fract.)	Eta (%)	Depl (%)	Net Irr (mm)	Deficit (mm)	Loss (mm)	Gr. Irr (mm)
28-November	14	Init	0	0.82	92	64	45.1	0	0	64.5
12-December	28	Init	0	1	100	26	24.3	0	0	34.7
26-December	42	Dev	0	1	100	29	33.5	0	0	47.9
09-January	56	Dev	0	1	100	37	50.4	0	0	72.0
23-January	70	Mid	0.9	1	100	40	57.9	0	0	82.6
06-February	84	Mid	0	1	100	44	63.0	0	0	90.0
20-February	98	Mid	0	1	100	48	68.6	0	0	98.0
06-March	112	End	0	1	100	43	61.3	0	0	87.6
20-March	126	End	0	1	100	28	40.9	0	0	58.5
24-March	End	End	0	1	0	3				

Table 11. Result of yield and water productivity in the study area

Treatment	Yield (ton ha^{-1})		Water productivity (kg m^{-3})	
	Koga	Rib	Koga	Rib
14D x 50%	2.06	3.67	0.92	1.88
14D x 75%	3.37	4.25	1.01	1.47
14D x 100%	3.54	3.99	0.66	1.04
14D x 125%	3.61	4.54	0.64	0.95
14D x 150%	3.33	4.13	0.62	0.72
21D x 50%	2.94	3.98	1.02	2.38
21D x 75%	3.36	4.27	1.07	1.81
21D x 100%	2.87	4.14	0.68	1.34
21D x 125%	2.95	4.03	0.96	0.95
21D x 150%	2.09	3.96	0.33	0.91
CV	8.9	5.2	7.6	7.4
LSD (5%)	**	**	ns	*

Note: D = Day, * = significant, ns = no significant and ** = highly significant

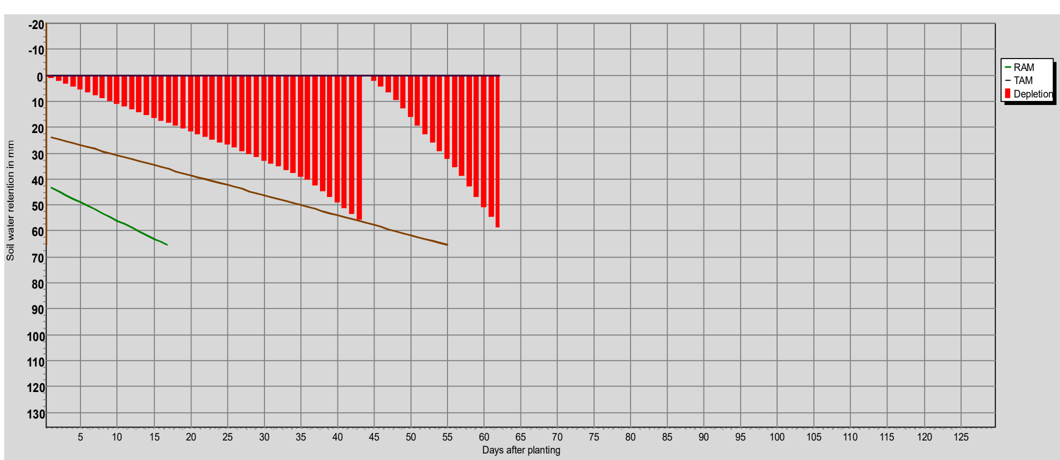

Fig. 4. Irrigation scheduling of wheat at Koga irrigation scheme

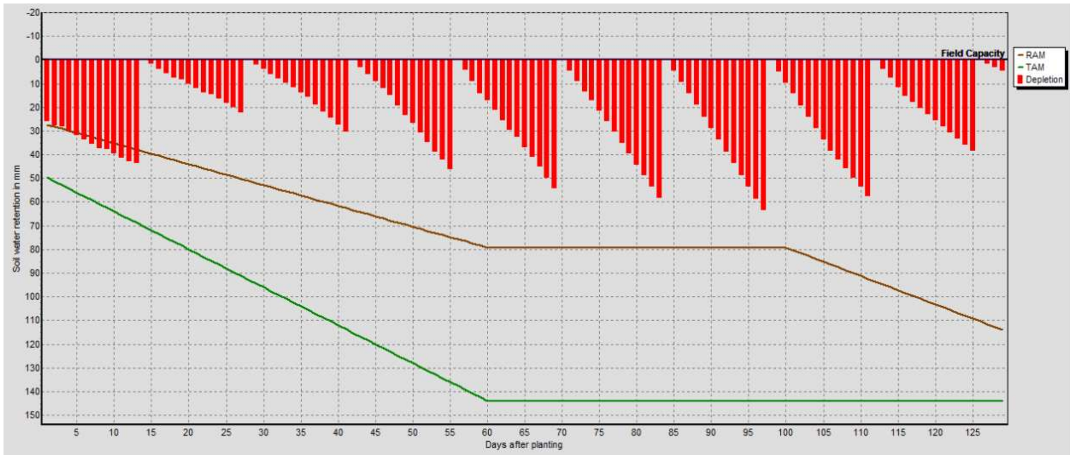

Fig. 5. Irrigation scheduling of wheat at Rib irrigation scheme

categorized by. The yield of wheat at Rib was 4.54 t ha^{-1} of wheat yield and 0.95 kg m^{-3} of water productivity was obtained at 125 % CWR within 14 days irrigation interval (Table 11). However, at Rib scheme 4.27 t ha^{-1} yield and 1.81kg m^{-3} of water productivity was achieved using 75% of CROPWAT generated depth within 21 days irrigation interval. Therefore, application of the CROPWAT generated depth of irrigation water within 21 days of irrigation interval is another option for the study area. The soil at Rib is alluvial deposited which comes from the upper catchments which has good nutrient content results the yield of wheat at Rib was higher than at Koga scheme.

CONCLUSION

Monthly crop water requirement and irrigation water requirement of wheat have high spatial and temporal variation. Simulation of crop water requirement and scheduling of wheat using the CROPWAT model was specific to the study area owing to a high seasonal and spatial variation. At Koga, irrigating 75 % CWR with 14 day interval gave optimal yield and water productivity while at Rib, irrigating 75 % CWR within 21 days irrigation interval gave better yield and water productivity. This study showed that the CROPWAT generated water depth is a good tool to determine crop water requirement of field crops. The study will help to improve the management of water resources and the productivity of wheat. CROPWAT tool can help to assess crop water requirement and irrigation scheduling of field crops in areas where water resource is limited. This study may a reference for decision-making for future planning.

Author contributions: D.T. and A.A. were responsible for Methodology, Software, Validation, Formal Analysis, Investigation, and the Original Manuscript Preparation. A.T. was responsible for Review and Editing, Discussions, Visualization, and writing the final draft. A.E. and M.W. was responsible for data collection, Editing and Discussion.

Conflicts of Interest: The authors declare there is no conflict of interest.

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