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Research Article

Determination of Water Requirements and Irrigation Scheduling for Major Cereal Crops Grown in Welmera District, Central Highland of Ethiopia

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Abstract

Determination of crop water requirements and appropriate irrigation scheduling is important to prevent over or under-irrigation. The study was conducted to determine the crop water requirement and irrigation scheduling of the selected cereal crops grown under irrigated conditions at Holeta, Central Highland of Ethiopia. The crops include wheat, maize, and barley. By using the 30-years climatic data, the crop evapotranspiration (ETc), reference crop evapotranspiration (ETo), and irrigation water requirement for each crop were determined by using the CROPWAT model which is based on FAO-Penman Monteith equation. The results indicated that, the CWR for the early January sown wheat, maize, and barley was 380.2mm, 433.2mm, and 399.2mm respectively. The seasonal gross irrigation requirement was estimated to be 633.67 mm, 722 mm, and 665.33 mm for wheat, maize, and barley respectively. for 1st January sown wheat, maize, and barley, irrigation should be given nine times for wheat (1-Jan, 10-Jan, 21-Jan,5-Feb, 16-Feb, 26-Feb, 11-Mar, 25-Mar, and last irrigation on 10-Apr), with GIR application of 50.3mm, 28.1mm, 34.6mm, 48.2mm,56.6mm,67.2mm,69.5mm, 66.2mm, and 72.3mm depth respectively. Seven times for maize (1-Jan, 19-Jan, 5-Feb, 19-Feb, 6-Mar, 21-Mar, and last irrigation on 10-Apr) with GIR of 54.1mm, 51.2mm, 73mm, 89.8mm,96.9mm, 97.7mm, and 100.8mm depth respectively and eight times for barley (1-Jan, 11-Jan, 25-Jan, 6-Feb, 16-Feb, 1-Mar, 15-Mar and last irrigation on 30-Mar) with GIR amount of 42.5mm, 29mm, 39.6mm, 54.1mm, 60mm, 61.6mm, 63.1mm, and 64.1mm depth at each irrigation date respectively. This study might be useful in preventing over or under-irrigation and planning water management strategies in the district for the selected crops.

Keywords

Cropwat 8.0, Crop Water Requirement, Irrigation Water Requirement, Irrigation Scheduling and Cereal Crops

1. Introduction

Irrigation scheduling involves deciding when and how much water to apply to a field. Good scheduling will apply water at the right time and in the right quantity in order to optimize production and minimize adverse environmental impacts. Bad scheduling will mean that either not enough water is applied or it is not applied at the right time, resulting in under-watering, or too much is applied or it is applied too soon resulting in over-watering. Under or over watering can lead to reduced yields, lower quality and inefficient use of nutrients [14].

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The proper amount of water for irrigation and the proper timing of irrigation are determined by irrigation scheduling. For scheduling of any crops exact quantity of water and correct timing of application is very much essential component [5]. Different agronomic techniques and irrigation scheduling under diverse geographical and climatic conditions have a big impact on getting the optimum yield [11, 2, 19].

CROPWAT 8.0 CROPWAT is a modern tool that is developed by land and water division of FAO (Food and agriculture organization) is a significant practice used by various researchers such as [3, 6-9, 15, 12, 18], have applied the CROPWAT model worldwide to efficiently investigate the crop water requirement, irrigation water requirement, as well as irrigation scheduling.

Currently, irrigated agriculture is widely expanded in the welmera district. Farmers can irrigate crops based on traditional know-how causing nutrient leaching, water logging, and severe water shortage problems in the study area. Wheat and maize is the most dominantly cultivated cereal crop under furrow irrigation in the district while barley is the newly practiced cereal crop by farmers under irrigation. However, crop water requirements and irrigation schedules of these crops were not done in the study site. Therefore, the present study was carried out to determine the crop water requirement, irrigation water requirement, and irrigation scheduling for wheat, maize and barley crops grown in the district using the CROPWAT model based on climatic, crop, and soil data.

2. Materials and Methods

2.1. Study Area

Welmera district is one of the special zones of Oromia National state surrounding Shaggar City, Ethiopia. The district is located 34 km to the west of Addis Ababa and it lies between 08°50′ – 09°15' N and Longitude 38°25'– 38°45' E at an average altitude of 2400m above sea level. The total geographical area of the district is 1046 km^2 and the average annual rainfall is 1034 mm. The soil which is predominant in this area is Red clay soils. The district consists of highland and mid-highland agro-climatic zones that cover about 61% and 39% of the total area respectively.

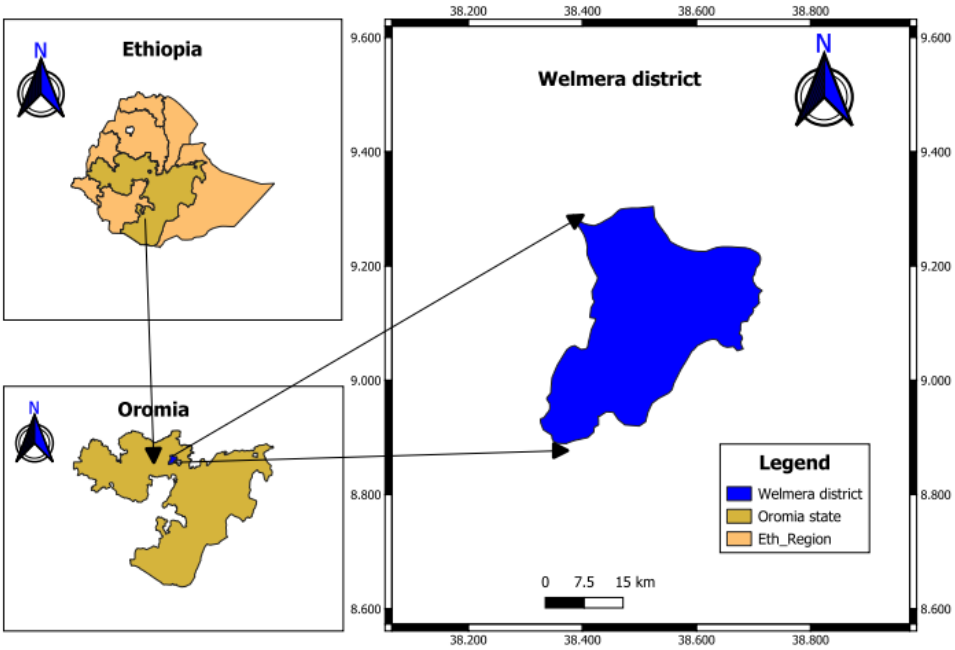

Figure 1. *Geographical location of the study area.*

As shown in Figure 2 the monthly evapotranspiration was higher than the monthly rainfall starting from June to September. In the remaining month of the year, evapotranspiration exceeds rainfall this implies that rainfall by itself does not meet the crop water need therefore the adoption of irrigation practices is desirable in the study area to replace the water loss through evapotranspiration for the irrigated crop production and agricultural sustainability.

June to September is the main rainy season, which accounts for 70% of the total rainfall.

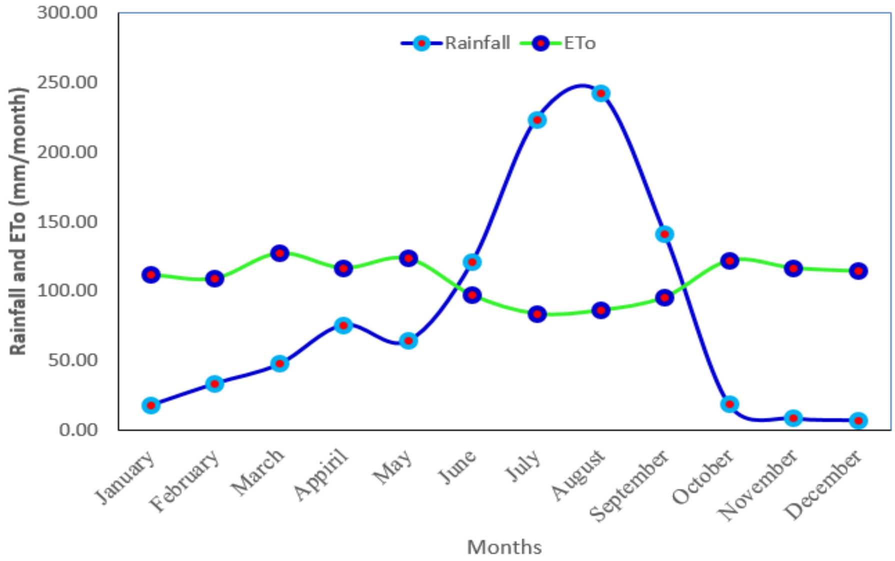

Figure 2. *Relationship between rainfall and evapotranspiration of the study area.*

2.2. Model Description

CROPWAT model [17] is a decision supporting tool developed by the water development division of FAO in computer programming language for calculating crop water requirements, irrigation water requirement, and irrigation scheduling using soil, crop, and climatic data.

2.3. Input Data for the Model

The model required initial input data of soil, crop, and climatic for the determination of crop water requirement and irrigation scheduling [10]. After all these data were correctly fed as input into the system, the software gives some important outputs, such as reference evapotranspiration, effective rainfall, net irrigation requirement, gross irrigation requirement, and irrigation scheduling.

2.3.1. Climate Data

To calculate reference crop evapotranspiration (ETo), the Holeta Agricultural Research Center meteorological station data for 30 years (1993 to 2023) was collected and used in this study.

The input climatic parameters for this model includes: average monthly minimum and maximum air temperature in ^{o}C, average monthly relative humidity in %, average monthly sunshine hours in the hr /day, average monthly precipitation in mm, average monthly wind speed at 2m height in m/s were used for estimation of reference evapotranspiration. ETo was calculated using Penman-Monteith equation as described in FAO publications [4]. Equation can be represented as:

$$ETo = \frac{0.408\Delta[Rn-G]+\left(\frac{900}{T+273}\right)u2(es-ea)}{\Delta+\gamma[1+0.34U2]} \qquad (1)$$

Where; ETo = Reference crop evapotranspiration (mm day^{-1})

Δ =Slope of the saturation vapor pressure curve (kPa^{-1})

Rn = Net radiation at the crop surface (MJm^{-2} day^{-1})

G = Soil heat flux density (MJ m^{-2} day^{-1})

T = Mean daily air temperature at 2 m height (℃)

U2 = Wind speed at 2 m height (m/s)

es = Saturation vapor pressure (kPa)

ea = Actual vapor pressure (kPa)

γ = Psychrometric constant (kPa^{-1})

2.3.2. Crop data

To estimate crop water requirement and irrigation scheduling for each crop the model requires crop data like:- planting date, harvesting date, length of plant growth stages, KC values (initial, development, mid-season, and late season), rooting depth, critical depletion, and yield response factor. This information was obtained from FAO manual 56 and adapted to the local climate conditions. In Table 1, the details of crop information, including sowing date, crop coefficient, and duration of growth stages, were described.

Table 1. *Crop coefficient and growing period of wheat, maize and barley.*

Crop		Wheat	Maize	Barley
Date of sowing		**1 Jan**	**1 Jan**	**1 Jan**
Crop coefficient (Kc)	Initial	0.3	0.3	0.3
	Mid	1.15	1.2	1.10
	Late	0.3	0.35	0.15
Growing pe-	Initial	30	20	20

Crop		**Wheat**	**Maize**	**Barley**
Date of sowing		**1 Jan**	**1 Jan**	**1 Jan**
riod (days)	Development	30	35	30
	Mid-season	40	40	50
	Late season	20	30	30
Total growing days		120	125	130

2.3.3. Soil Data

The Cropwat model requires some general soil data such as total available soil moisture, maximum infiltration rate, maximum root depth, initial soil moisture depletion, and initial available soil moisture. This information was obtained from FAO Manual 56 and the laboratory results of the Holeta Agricultural Research Center. The infiltration rate was measured using the double-ring infiltrometer as described by [16].

2.3.4. Rain Data

To determine the portion of the rainfall that effectively contributes to cover crop water requirement, the rainfall data recorded from the Holeta Agro meteorological station for the last 30 years (1993 to 2023) was used and applied in CROPWAT software to obtain effective rainfall. The effective rainfall is a portion of rainfall which is effectively used by the plants. This effective rainfall was used to determine the irrigation requirement. The effective rainfall was determined based on the Food and Agriculture Organization of the United Nations /Water Resources Development Management Service (FAO/AGLW), which is expressed as:

$$Pe=0.6*P-10 \text{ for month } \leq 70mm \quad (2)$$

$$Pe=0.8*P-24 \text{ for month } \geq 70mm \quad (3)$$

Where Pe is the effective rainfall (mm) and P is rainfall (mm/month).

2.4. Crop Water Requirement, Net and Gross Irrigation Requirement

The amount of water needed by each crop as the depth to meet the water loss through evapotranspiration can be referred as CWR. The Crop water requirement (ETc) is calculated by multiplying reference crop evapotranspiration (ETo) values with the Crop coefficients (Kc). The Kc values for wheat, maize, and barley at the different growth stages (initial, development, mid, and late stage) are obtained from the FAO-56 crop manual. The crop water requirement (CWR) was determined using the CROPWAT program based on the FAO Penman-Monteith method [4] as:

$$ETc=ETo\times Kc \quad (4)$$

Where ETc is crop evapotranspiration in mm, Kc is crop factor in fraction and ETo is reference crop evapotranspiration in mm per month.

The net irrigation requirement was calculated using the following equation.

$$NIR=ETc-Pe \quad (5)$$

Where NIR is net irrigation water requirement (mm), ETc is crop water requirement (mm) and Pe is effective rainfall (mm).

The gross irrigation requirement was obtained by dividing the net irrigation requirement by irrigation application efficiency. In this study, Ea of 60% for surface irrigation was used to estimate the gross irrigation requirement using equation [6].

$$GIR= (NIR/Ea)\times 100 \quad (6)$$

Where GIR is gross irrigation requirement (mm), NIR is net irrigation requirement (mm) and Ea is application efficiency (%). Ea, represents application efficiency of irrigation operation which depends on the characteristics of the adopted irrigation methods.

2.5. Irrigation Scheduling

Irrigation scheduling allows the users to decide when to irrigate and how much water to be applied in each irrigation. In the CROPWAT software, many irrigation scheduling options are available for selecting irrigation timing, irrigation application, and irrigation efficiency. In this study case for all the three selected cereals crops, the irrigation scheduling can be done at 55% depletion level as irrigation application time as indicated in FAO 56, and the irrigation application option of refilling soil to field capacity at 100% was selected. An irrigation efficiency of 60% was considered due to furrow irrigation being the main irrigation application method for the study area.

2.6. Data Analysis

The long-term mean monthly climatic data were used in the CROPWAT 8.0 model to determine the ETo for the study area. The ETo data obtained was further used to calculate the ETc. The flowchart showing the methodology for estimating crop water requirements and irrigation scheduling using the CROPWAT model is shown in Figure 3.

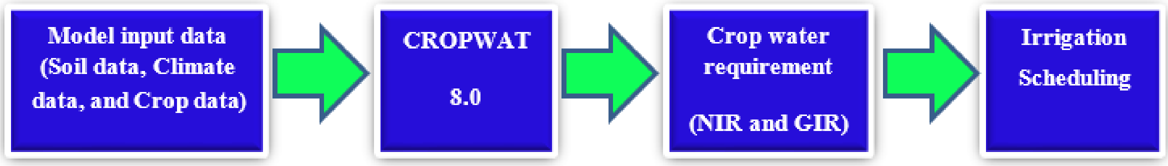

Figure 3. *Flow chart for the estimation of irrigation demand and scheduling using CROPWAT model.*

3. Results and Discussion

3.1. Analysis of Soil Data

Crop performance and efficient use of the available water can be optimized by determining the water holding capacity of the soil, the water requirements, and the response of each crop grown, using an effective soil moisture monitoring system and irrigation scheduling. The Holeta Agricultural Research Center's physical soil analysis revealed that the texture of the soil changed as it got deeper in the soil profile. The topsoil 0-30 cm is sandy clay in texture, while the 2nd layer (30-60cm) and the 3rd layer (60-90cm) were sandy clay loam and clay respectively. The average moisture content on a volume basis at Field Capacity (FC) and Permanent Wilting Point (PWP) were 36.85% and 26.61%, respectively. Table 2 shows that the average volumetric Total Available Water (TAW) was 133.12 mm/m and had a bulk density of 1.3 cm^{-3}.

Table 2. *Soil physical and chemical properties of experimental field.*

Soil properties	**Soil depth (cm)**			**Average**
	0-30	**30 -60**	**60- 90**	
Particle size distribution				
Sand (%)	47.49	48.46	12.8	36.25
Silt (%)	11.3	17.95	34	21.06
Clay (%)	41.19	33.69	53.2	42.69
Textural class	Sandy Clay	Sandy Clay loam	Clay	Clay
Bulk density (g/cm^3)	1.29	1.30	1.31	1.3
Field capacity (weight basis %)	35.64	37.54	37.38	36.85
Permanent wilting point (weight basis %)	25.15	27.52	27.17	26.61
Total available water (mm/m)	135.32	130.26	133.75	133.12

3.2. Reference Evapotranspiration (ETo)

The reference evapotranspiration (ETo) for the district was calculated from the Penman-Montieth equation using agro-climatic data. The ETo ranged from 2.6 mm/day to 4.2 mm/day, and it was found at its maximum in February and March, and its minimum in July (Figure 4). The results show that ETo was lowest during the rainy season, but higher during the dry season. As the trend of ETo is affected by climatic factors such as temperatures, solar radiation, and rainfall as well as wind, and relative humidity of the air consequently ETo is a climatic parameter. A significant variation in ETo between seasons can be caused by variations in these parameters. The results obtained in this study are similar to [1, 13] which showed that ETo was lowest during the peak of the rainy season to highest during the peak of the dry season.

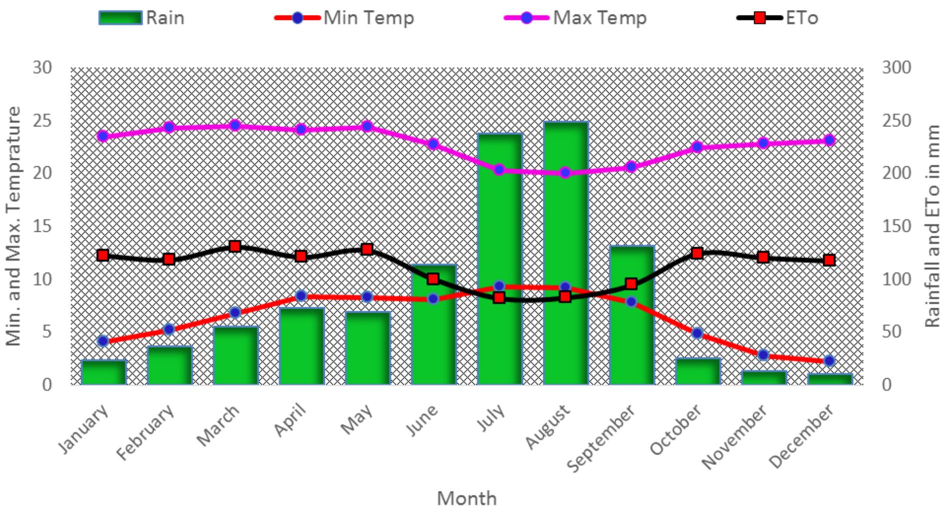

Figure 4. *Mean monthly rainfall, evapotranspiration, minimum and maximum temperature of the study area*

3.3. Rainfall and Effective Rainfall

The effective rainfall (Peff) for the district was calculated using the USDA-SCS method and it ranged from 0 to 175mm. The effective rainfall was zero in November and December, which indicates that a large quantity of irrigation water will be required to replenish the soil with moisture. The effective rainfall values were found to be satisfactory during the summer season. Figure 5 represents the month-wise total and effective rainfall of the region. Maximum effective rainfall of 175 mm was observed in August, while effective rainfall was zero in November and December. It shows that November and December are the driest months in the study area, during which crops need irrigation without considering rainfall. The study result found that the total average effective rainfall is 597.6 mm, which is 57.8% of the average annual rainfall of 1034.3 mm.

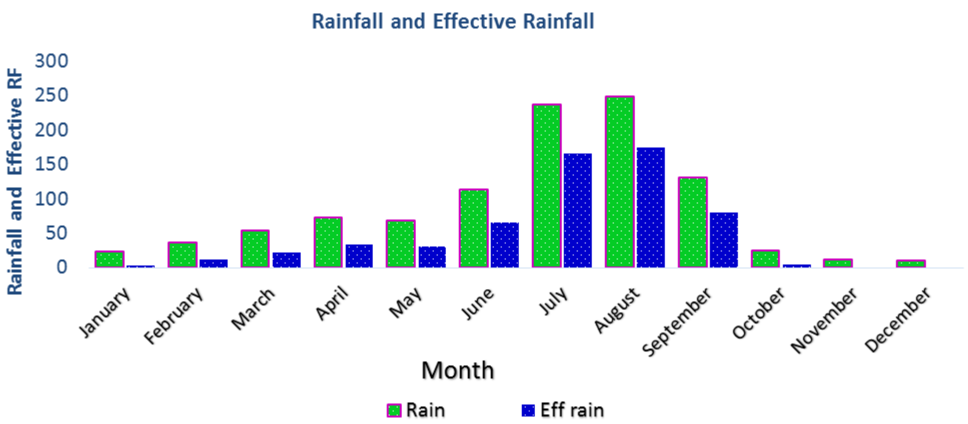

Figure 5. *Rainfall and effective rainfall of the district.*

3.4. Crop Water Requirement

Estimation of the CWR was carried out by calling up successively the appropriate climate and rainfall data sets, together with soil and crop data files and the corresponding planting dates. Based on the data, fed to the CROPWAT model the crop water requirement has been determined for each crop. The water requirement of wheat, maize, and barley was 380.2mm, 433.2mm, and 399.2mm respectively (Tables 3, 4 and 5). The determined above crop water requirements for each crop are within the range indicated in the FAO 66 [20] which are (200 to 500 mm for wheat, < 500 to > 800 mm for maize, and 100 to 500 mm for barley).

Table 3. *Crop water Requirement for wheat.*

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Jan	1	Init	0.3	1.17	11.7	0.8	10.8
Jan	2	Init	0.3	1.18	11.8	1.2	10.6
Jan	3	Deve	0.3	1.22	13.4	2.2	11.3
Feb	1	Deve	0.49	2.01	20.1	3.1	17
Feb	2	Deve	0.77	3.27	32.7	3.9	28.8
Feb	3	Deve	1.03	4.35	34.8	5.1	29.7
Mar	1	Mid	1.16	4.89	48.9	6.4	42.5
Mar	2	Mid	1.16	4.88	48.8	7.6	41.3
Mar	3	Mid	1.16	4.82	53	8.9	44.1
Apr	1	Mid	1.16	4.75	47.5	10.6	36.9
Apr	2	Late	0.93	3.73	37.3	12.1	25.2
Apr	3	Late	0.49	2	20	11.5	8.5
Total					380.2	73.2	306.9

Table 4. *Crop water Requirement for maize.*

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Jan	1	Init	0.3	1.17	11.7	0.8	10.8
Jan	2	Init	0.3	1.18	11.8	1.2	10.6
Jan	3	Deve	0.46	1.85	20.3	2.2	18.2
Feb	1	Deve	0.73	3.03	30.3	3.1	27.2
Feb	2	Deve	1	4.2	42	3.9	38.2
Feb	3	Mid	1.2	5.06	40.4	5.1	35.3
Mar	1	Mid	1.22	5.13	51.3	6.4	44.9
Mar	2	Mid	1.22	5.12	51.2	7.6	43.6
Mar	3	Mid	1.22	5.05	55.6	8.9	46.7
Apr	1	Late	1.18	4.8	48	10.6	37.5
Apr	2	Late	0.92	3.69	36.9	12.1	24.8
Apr	3	Late	0.63	2.53	25.3	11.5	13.8
May	1	Late	0.41	1.66	8.3	4.8	3.6
Total					433.2	78	355.2

Table 5. *Crop water Requirement for barley.*

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Jan	1	Init	0.3	1.11	11.1	0.8	10.3
Jan	2	Init	0.3	1.1	11	1.2	9.8
Jan	3	Deve	0.46	1.72	18.9	2.2	16.8
Feb	1	Deve	0.73	2.81	28.1	3.1	25.1
Feb	2	Mid	0.99	3.9	39	3.9	35.1
Feb	3	Mid	1.08	4.37	35	5.1	29.9
Mar	1	Mid	1.08	4.48	44.8	6.4	38.4
Mar	2	Mid	1.08	4.58	45.8	7.6	38.2
Mar	3	Mid	1.08	4.49	49.4	8.9	40.5
Apr	1	Mid	1.08	4.4	44	10.6	33.4
Apr	2	Late	0.91	3.63	36.3	12.1	24.2
Apr	3	Late	0.6	2.41	24.1	11.5	12.6
May	1	Late	0.29	1.17	11.7	9.5	2.2
Total					399.2	82.8	316.5

Where, Dev = Development stage, Mid = Middle stage and Init = Initial stage

3.5. Irrigation Scheduling

The irrigation scheduling can be done at critical depletion timing and the irrigation application option is to refill soil to above or below field capacity at FAO recommended allowable depletion level for each crop.

The result indicated that in the study area, the total growing days (from sowing to harvesting) for wheat sown on 1st January took 120 days. irrigation should be given nine times (1-Jan, 10-Jan, 21-Jan,5-Feb, 16-Feb, 26-Feb, 11-Mar, 25-Mar, and last irrigation on 10-Apr) with a gross irrigation water amount of 50.3mm, 28.1mm, 34.6mm, 48.2mm,56.6mm,67.2mm,69.5mm, 66.2mm, and 72.3mm depth respectively (Table 6).

For 1st January sown maize the total growing days (from sowing to harvesting) took 125 days. irrigation should be given seven times (1-Jan, 19-Jan,5-Feb, 19-Feb, 6-Mar, 21-Mar, and last irrigation on 10-Apr) with a gross irrigation water amount of 54.1mm, 51.2mm, 73mm, 89.8mm,96.9mm, 97.7mm, and 100.8mm depth respectively (Table 7).

Similarly, for barley sown on 1st January, the total growing days (from sowing to harvesting) took 130 days. irrigation should be given eight times (1-Jan, 11-Jan, 25-Jan, 6-Feb, 16-Feb, 1-Mar, 15-Mar, and last irrigation on 30-Mar) with a gross irrigation water amount of 42.5mm, 29mm, 39.6mm, 54.1mm, 60mm, 61.6mm,63.1mm, and 64.1mm depth respectively (Table 8).

Table 6. *Irrigation requirement and irrigation scheduling of early January planted wheat.*

Date	Day	Stage	Net Irr mm	Gr. Irr Mm	Flow l/s/ha
1-Jan	1	Init	30.2	50.3	5.83
10-Jan	10	Init	16.9	28.1	0.36
21-Jan	21	Init	20.8	34.6	0.36
5-Feb	36	Dev	28.9	48.2	0.37

Date	Day	Stage	Net Irr mm	Gr. Irr Mm	Flow l/s/ha
16-Feb	47	Dev	34	56.6	0.6
26-Feb	57	Dev	40.3	67.2	0.78
11-Mar	70	Mid	41.7	69.5	0.62
25-Mar	84	Mid	39.7	66.2	0.55
10-Apr	100	Mid	43.4	72.3	0.52
30-Apr	End	End			

Table 7. *Irrigation scheduling of early January planted maize.*

Date	Day	Stage	Net Irr Mm	Gr. Irr Mm	Flow l/s/ha
1-Jan	1	Init	32.5	54.1	6.26
19-Jan	19	Init	30.7	51.2	0.33
5-Feb	36	Dev	43.8	73	0.5
19-Feb	50	Dev	53.9	89.8	0.74
6-Mar	65	Mid	58.2	96.9	0.75
21-Mar	80	Mid	58.6	97.7	0.75
10-Apr	100	End	60.5	100.8	0.58
5-May		End			

Table 8. *Irrigation scheduling of early January planted barley.*

Date	Day	Stage	Net Irr mm	Gr. Irr Mm	Flow l/s/ha
1-Jan	1	Init	25.5	42.5	4.91
11-Jan	11	Init	17.4	29	0.34
25-Jan	25	Dev	23.7	39.6	0.33
6-Feb	37	Dev	32.4	54.1	0.52
16-Feb	47	Dev	36	60	0.69
1-Mar	60	Mid	37	61.6	0.55
15-Mar	74	Mid	37.9	63.1	0.52
30-Mar	89	Mid	38.5	64.1	0.49
10-May		End			

4. Conclusion

The Crop water requirement (CWR), growth irrigation requirements (GIR), and irrigation scheduling of wheat, maize, and barley were estimated using CROPWAT 8.0 for the Welmera district. The results of this study reveal that the total seasonal crop water requirement for wheat, maize, and barley was 380.2mm, 433.2mm, and 399.2mm respectively. The gross irrigation requirement considering 60 % irrigation application efficiency for furrow irrigation method was estimated to be 633.67 mm, 722 mm, and 665.33 mm for wheat, maize, and barley respectively.

for 1st January sown wheat, maize, and, barley, irrigation should be given nine times for wheat (1-Jan, 10-Jan, 21-Jan,5-Feb, 16-Feb, 26-Feb, 11-Mar, 25-Mar, 10-Apr) with a gross irrigation water amount of 50.3mm, 28.1mm, 34.6mm, 48.2mm,56.6mm,67.2mm,69.5mm, 66.2mm, and 72.3mm depth respectively. seven times for maize (1-Jan, 19-Jan, 5-Feb, 19-Feb, 6-Mar, 21-Mar, 10-Apr) with a gross irrigation water amount of 54.1mm, 51.2mm, 73mm, 89.8mm,96.9mm, 97.7mm, and 100.8mm depth respectively and eight times for barley (1-Jan, 11-Jan, 25-Jan, 6-Feb, 16-Feb, 1-Mar, 15-Mar and 30-Mar) with a gross irrigation water amount of 42.5mm, 29mm, 39.6mm, 54.1mm, 60mm, 61.6mm,63.1mm, and 64.1mm depth at each irrigation date respectively.

The findings obtained from this study can be used by water resource planners for future planning, thereby helping to save water in meeting the crop water requirement and it can be used as a guide for the farmers to adopt water-saving practices by applying the required amount of water at a required time for the crops being studied.

Abbreviations

CWR	Crop Water Requirement
ETo	Reference Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
FC	Field Capacity
GIR	Gross Irrigation Requirement
Hr	Hour
Kc	Crop Coefficient
NIR	Net Irrigation Requirement
Peff	Effective Rainfall
PWP	Permanent Wilting Point
TAW	Total Available Water

Author Contributions

Nigusie Abebe: Conceptualization, Data collection, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Mohammed Temam: Data collection, Investigation, Supervision, Visualization, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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