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Water Requirement and Irrigation Scheduling of Selected Vegetable Crops Grown in Welmera District, Central Highland of Ethiopia

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Abstract: Accurate quantification of irrigation water requirement at different physiological growth stages of crops is important to prevent over or under irrigation. A study was carried out to determine the crop water requirement and irrigation scheduling of the selected vegetable crops grown under irrigated conditions at Holeta, Central Highland of Ethiopia. The crops include, cabbage, and tomato. By using the 30-year climatic data, the crop evapotranspiration (ETc), reference crop evapotranspiration (ETo), and irrigation water requirement for each crop were determined using the CROPWAT model. The study shows that the total CWR of cabbage, and tomato was estimated to be 426.6mm, and 497.7mm respectively, and the total GIR of cabbage, and tomato was found to be 598.3 mm, and 691.7 mm respectively. for early January planted cabbage, irrigation should be given twelve times (1-Jan, 9-Jan, 16-Jan,24-Jan, 2-Feb, 11-Feb, 21-Feb, 5-Mar,15-Mar, 25-Mar, 2- Apr and last irrigation on 12-Apr) with a gross irrigation water amount of 59.8mm, 32.5mm, 31.5mm, 35.2mm,42.2mm,43.3mm,48.1mm, 52mm, 51.3mm, 49.5mm, 51mm, and 51.7mm depth respectively. Similarly for early January planted tomato, irrigation should be given twelve times (1-Jan, 5-Jan, 10-Jan, 16-Jan, 21-Jan, 29-Jan, 6-Feb, 15-Feb, 26-Feb, 12-Mar, 26-Mar, and the last irrigation on 10-Apr) with a gross irrigation water amount of 53.9mm, 19.3mm, 25.5mm, 30.7mm, 30.6mm, 36.4mm, 47.8mm, 58.5mm, 73.4mm, 83.5mm, 80.9mm, 80.7mm irrigation depth respectively. This study might be useful to prevent over or under irrigation which will help in effectively planning and management of irrigation water in the district.

Keywords: Cropwat, ETo, Water Requirement, Irrigation Scheduling, Cabbage and Tomato.

Research Paper

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INTRODUCTION

Water is the major limiting factor for crop diversification and production. More than 80% of water resources have been exploited for agricultural irrigation [16]. Inadequate irrigation application results in crop water stress and yield reduction. Excess irrigation application can result in pollution of water sources due to the loss of plant nutrients through leaching, runoff, and soil erosion. As a result, scheduling irrigation according to crop water needs minimizes the chances of under or over watering [14]. Likewise there is less crop failure and leaching of fertilizers beyond the root-zone, and more profit for growers under well-established crop water requirement reference [1].

Accurate quantification of crop water requirements of any crop is essentially required for irrigation scheduling and water management [21]. The proper irrigation scheduling by deciding the exact quantity of water and correct timing of application is very much essential component to prevent over or under irrigation [3]. The potential returns of irrigation scheduling are derived from three factors: increase irrigation efficiency, reduced cost of irrigation and opportunity cost of water [5-7]. CROPWAT 8.0 CROPWAT is a modern tool that is developed by land and water division of FAO (Food and agriculture organization). It is widely used all over the world, for determining crop water requirement, irrigation water requirement, as well as irrigation scheduling [6-19].

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. Cabbage and tomato is the most dominantly cultivated vegetables crop under furrow irrigation method in the district. 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 cabbage and tomato crops grown in the district by using the CROPWAT model based on local climatic, crop, and soil data.

MATERIALS AND METHODS

Study Area:

Welmera district is one of the special zones of Oromia National state surrounding Shaggar City, Ethiopia. The district is located at 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. 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 are Red clay soils. The district consist of highland and mid highland agro climatic zone that cover about 61% and 39% of the total area respectively.

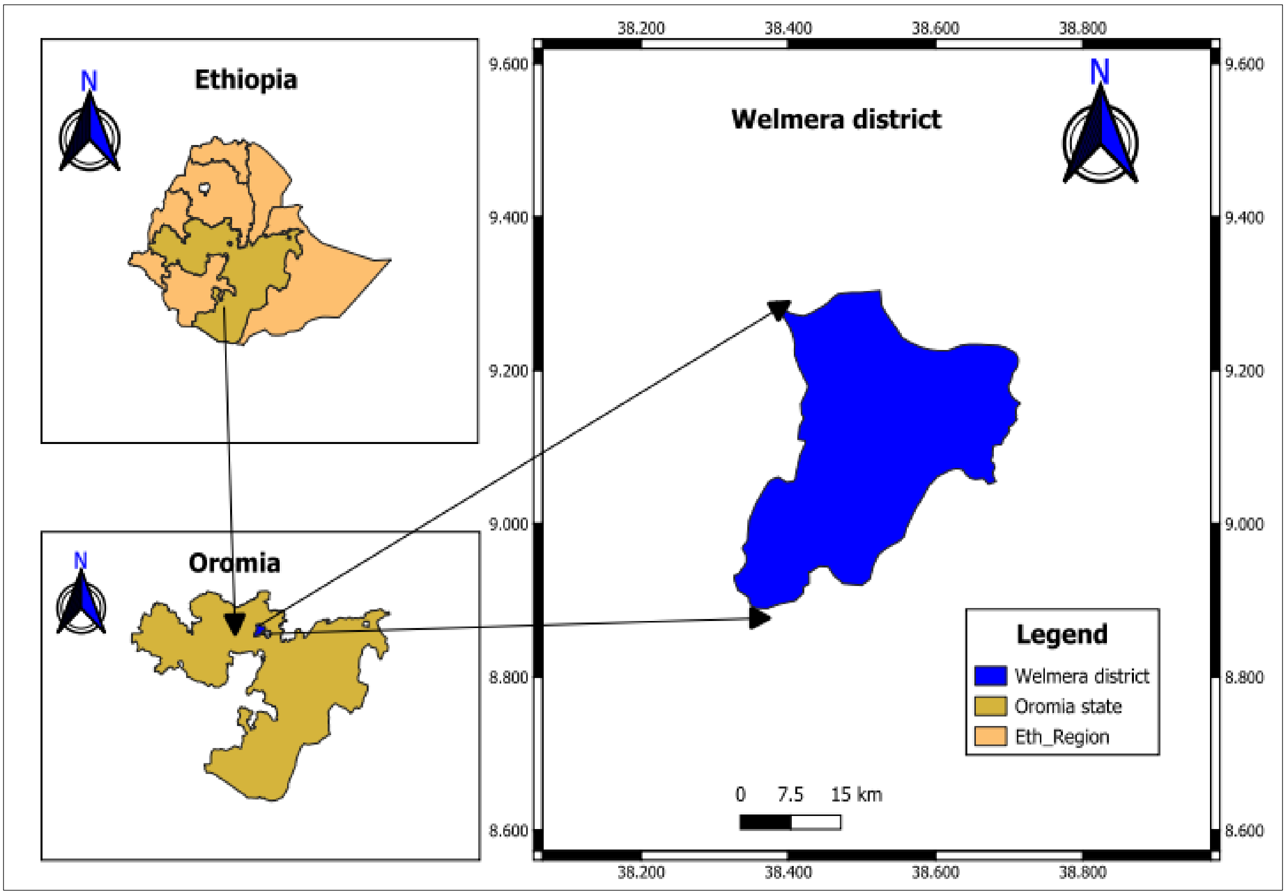

Fig. 1: Geographical location of the study area

Model Description:

CROPWAT model [18], is a decision supporting tool developed by water development division of FAO in computer programing language for calculating crop water requirement, irrigation water management, and irrigation scheduling using soil, crop and climatic data. The flowchart showing the methodology for estimating crop water requirements and irrigation scheduling using the CROPWAT model is shown in Figure 2.

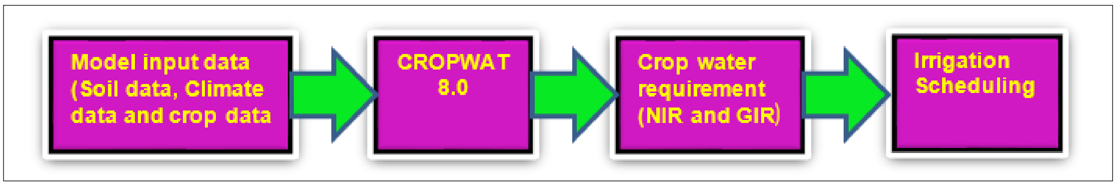

Fig. 2: Flow chart for the estimation of irrigation demand and scheduling using CROPWAT model

Data Input and Output for the Model:

The initial data that are needed for the model for the determination of crop water requirement and irrigation scheduling are Meteorological data, crop growth data & soil data [10]. After all inputs have been correctly introduced, the software gives some important outputs, such as reference evapotranspiration, effective rainfall, net irrigation requirement, gross irrigation requirement and irrigation scheduling.

Climate Data Collection and Reference Evapotranspiration Determination:

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. These data include: average monthly minimum and maximum air temperature in ° 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. The Penman-Monteith equation [2], was used to calculate the ETo. Equation can be represented as:

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

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 (°C)
U2 = Wind speed at 2 m height (m/s),
es = Saturation vapor pressure at a given period (kPa),
ea = Actual vapor pressure (kPa), and
γ = Psychrometric constant (kPa^{-1})

Crop Data:

The Cropwat software needs some information about wheat, maize and barley crops i.e. crop name, planting date, harvesting date, Crop coefficient (KC) values depending on the crop growth stages, duration of four main crop growth stages (initial, development, mid-season and late season), rooting depth, critical depletion and yield response factor. The information was obtained from FAO manual 56 and adapted to the local climate conditions. In Figure 3a and b, the details of crop information, including sowing date, crop coefficient, and duration of growth stages, were described.

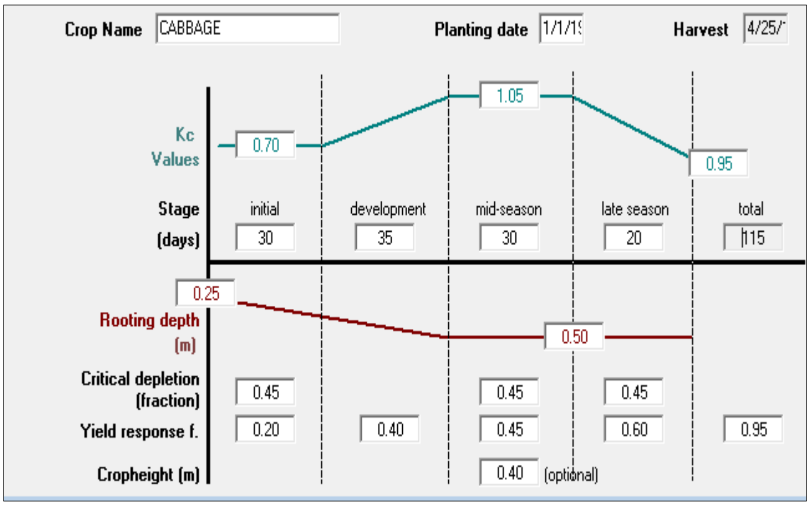

Fig. 3a: Cabbage crop information

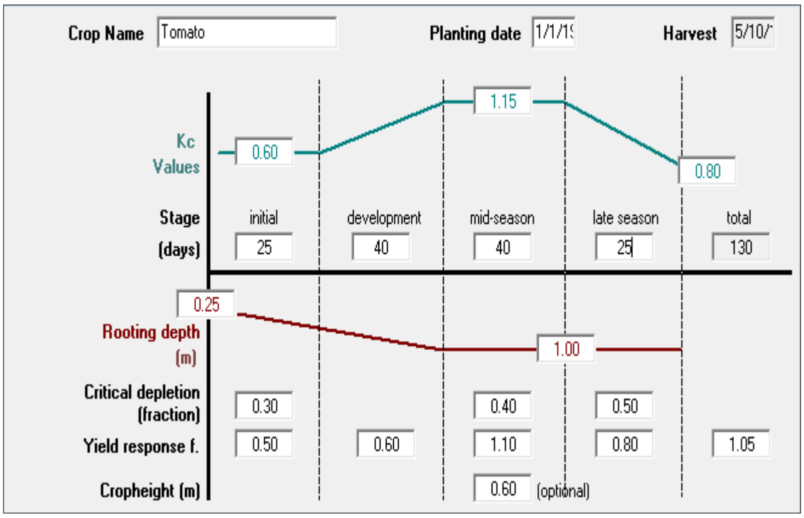

Fig. 3b: Tomato crop information

Soil Data:

The Cropwat model requires 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 Holeta Agricultural Research Center. The infiltration rate was measured using the double-ring infiltrometer as described by [17].

Rainfall and Effective Rainfall:

The rainfall data recorded from the 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:

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

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

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

Crop Water Requirement, Net and Gross Irrigation Requirement:

The crop water requirement is the amount of water equal to what is lost from a cropped field by the ET and is expressed by the rate of ET in mm/day. The Crop water requirement (ETc) is obtained by multiplying reference crop evapotranspiration (ETo) values with the Crop coefficients (Kc). The Kc values for cabbage, and tomato 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 [2] 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 using the following equation:

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

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. In this study Ea of 60% for surface irrigation was used to estimate the gross irrigation requirement using equation.

Irrigation Scheduling:

Irrigation scheduling determines the correct measure of water to irrigate and the correct time for watering. In the CROPWAT software, many irrigation scheduling options are available for selecting irrigation timing, irrigation application, and irrigation efficiency. In this study case for the two selected vegetable crops, the irrigation scheduling can be done at allowable depletion level of each crop as irrigation application time as indicated in FAO 56, and the irrigation application option of refill 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.

Data Analysis:

CROPWAT software version 8.0 used to data analysis. The data processing carried out in this software is in the form of the pattern of climate data, ETo (actual evaporation), and the relation between ETo and each of climate parameters (air temperature, duration of sunlight, humidity, rainfall, and average wind speed).

RESULTS AND DISCUSSION

Climate Characteristics of the Study Area

Temperature:

Temperature is an important element of weather in crop production. Several factors influence the temperature of an area including latitude, altitude, distance from large water bodies and direction of prevailing winds. According the long term climatic data of 30 years (1993 to 2023), mean maximum temperature of the area ranges from 19.73^{0}C in August to 23.97^{o}C in March with relative variation during the year. While the minimum temperatures also falling below 5^{o}C starting from October to February. In general, temperature regime would be suitable for irrigated crops adapted to the area. The mean monthly maximum and minimum temperature of Holeta Agricultural have been illustrated graphically in Figure 4.

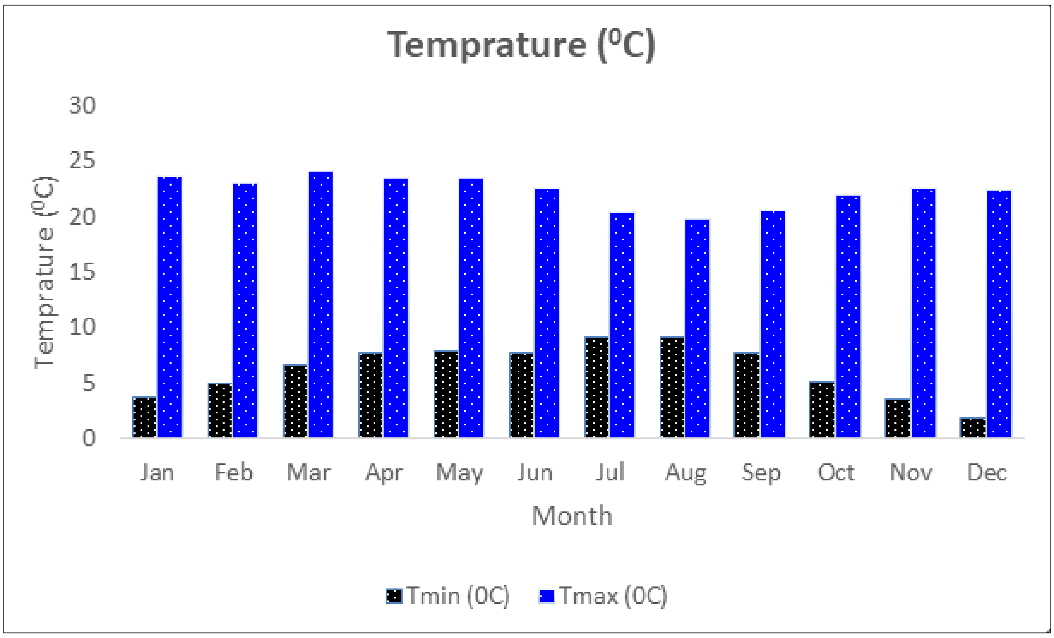

Fig. 4: Maximum and minimum mean monthly temperatures

Relative Humidity:

Relative humidity, the water vapor contained in the atmosphere, is expressed as the percentage of the ratio of actual to saturation vapor pressure. More evaporation takes place in a dry air than in air with high relative humidity. The average monthly relative humidity of the area ranges from a low of 48.9% in February to a high of 80.2% during the month of August (Figure 5). This shows that while temperature and solar radiation decreased at the onset of the rainy season, relative humidity increased in the study area.

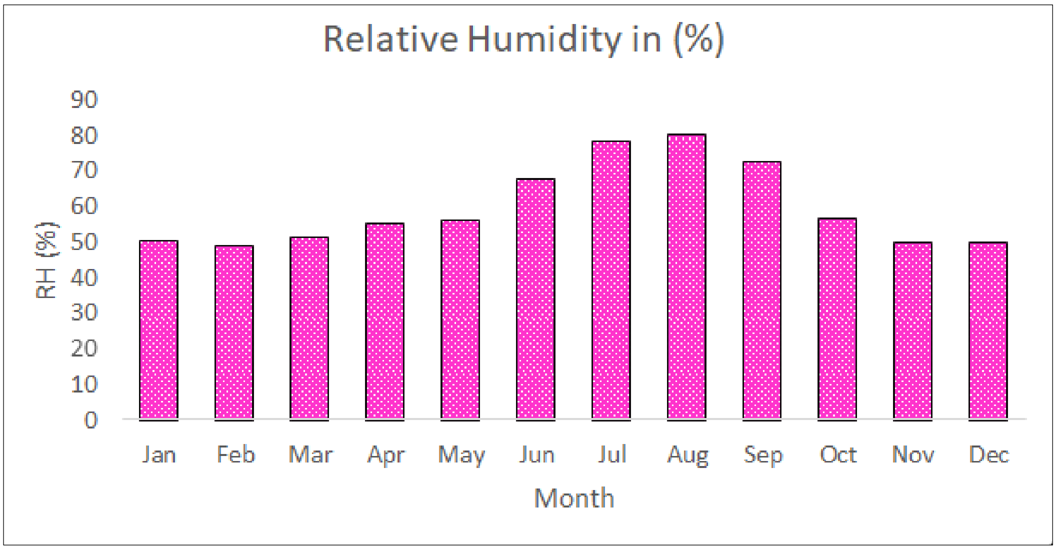

Fig. 5: Monthly Relative Humidity

Wind Speed:

Wind movement creates turbulence and replaces the air at the water surface with less moist air and thus increases evaporation. Hence, the higher the wind speed is, the more the evaporation. Wind movements from high pressure to low-pressure areas, accompanied by moisture sources, determine the wet and dry seasons in the study area. According to the long term climatic data, the mean monthly data, recorded at two meter height, varies from 0.7m/sec in August to 1.5m/sec in March. February to May are comparatively the windy months. The average monthly wind speed data of the district is presented illustrated in Figure 6.

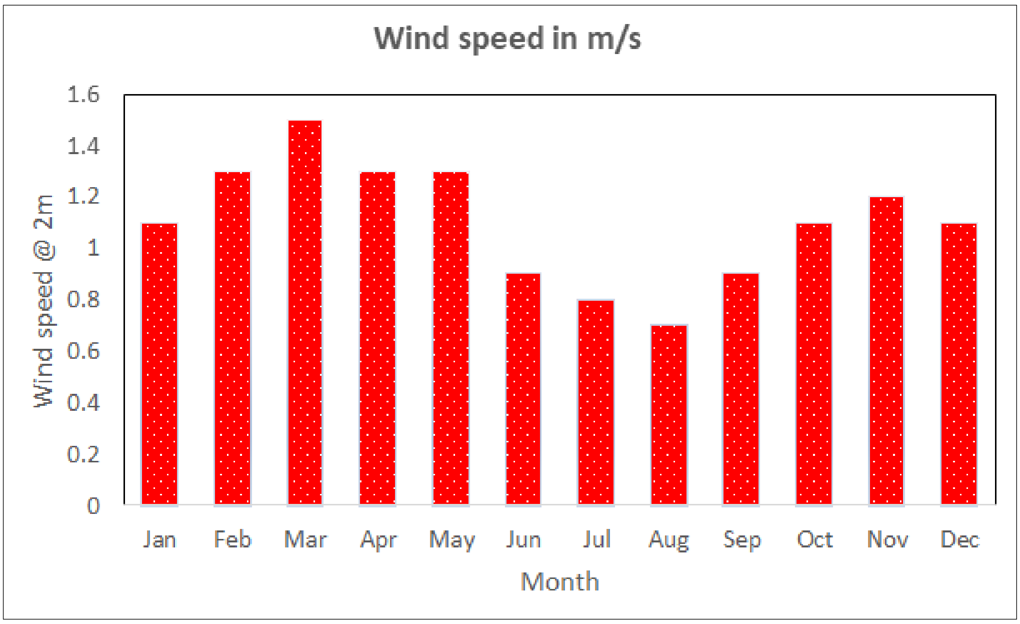

Fig. 6: Average Monthly Wind Speed

Sunshine Hours:

Solar radiation provides nearly all of the energy that reaches the earth's surface. Daily sunshine hour's duration is thus a factor that determines radiation and the potential evapotranspiration. The longer the sunshine hour is, the more evapotranspiration occurs. The average monthly sunshine hour's duration data of the study area shows the variation seasonally from 10.5 hours in January to 3.04 hours in July Figure 7. The duration is longer during the cool season while in the rainy season from June to September, the sunshine duration gets smaller.

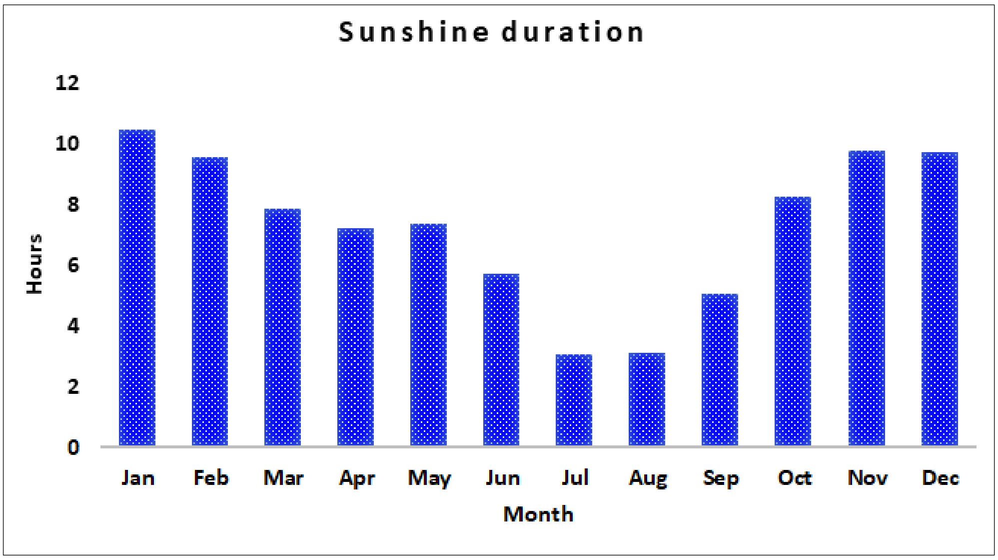

Figure 7: Monthly average daily sunshine hour's duration

Soil Characteristics of the Study Area:

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 1 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 1: 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

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 (Table 2). It is due to the high temperature. The results show that ETo was lowest during the rainy season, but higher during the dry season. A decrease in temperature accompanied by an increase in relative humidity can result in a decrease in evapotranspiration [12]. The results obtained in this study are similar to [8], who stated that the rate of evapotranspiration is strongly influenced by factors of temperature, solar radiation, and wind speed. The result are although in line with the findings of [1-11], which showed that ETo was lowest during the peak of the rainy season to highest during the peak of the dry season.

Table 2: Mean monthly rainfall, evapotranspiration, minimum and maximum temperature of the study area

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Average
ETo (mm/day)	3.9	4.2	4.2	4.0	4.1	3.3	2.6	2.7	3.2	4.0	4.0	3.8	3.7

Rainfall and Effective Rainfall:

Effective rain is the amount of rainfall that can be absorbed and utilized effectively by plants to meet the crop water requirement [13]. In this study**,** 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. Table 3 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 nil 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.

Table 3: Rainfall and effective rainfall of the district

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Avg (mm)
RF (mm)	23.6	36.6	54.6	72.8	68.5	113.5	237.3	248.8	131.1	24.7	12.6	10.2	**597.6**
Eff. RF (mm)	4.2	12	22.8	34.2	31.1	66.8	165.8	175	80.9	4.8	0	0	**1034.3**

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 the selected cereal crops. The water requirement of cabbage, and tomato was 426.6mm, and 497.7mm respectively (Table 4, and 5). The determined above crop water requirement for each crops are within the range indicated in the FAO 33 [14], and FAO 66 [20], which are (380 to 500 mm for cabbage, and 400 to 800 mm for tomato) respectively.

Table 4: Crop water Requirement for cabbage

Month	Decade	Stage	Kc	ETc	ETc	Eff rain	Irr. Req.	GIR
			Coeff	mm/day	mm/dec	mm/dec	mm/dec	mm/dec
Jan	1	Init	0.7	2.72	27.2	0.8	26.4	44.0
Jan	2	Init	0.7	2.76	27.6	1.2	26.4	44.0
Jan	3	Deve	0.7	2.83	31.1	2.2	29	48.3
Feb	1	Deve	0.77	3.17	31.7	3.1	28.6	47.7

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec	GIR mm/dec
Feb	2	Deve	0.87	3.67	36.7	3.9	32.8	54.7
Feb	3	Deve	0.96	4.06	32.5	5.1	27.3	45.5
Mar	1	Mid	1.05	4.4	44	6.4	37.6	62.7
Mar	2	Mid	1.06	4.46	44.6	7.6	37	61.7
Mar	3	Mid	1.06	4.4	48.3	8.9	39.5	65.8
Apr	1	Late	1.05	4.3	43	10.6	32.4	54.0
Apr	2	Late	1	4.04	40.4	12.1	28.3	47.2
Apr	3	Late	0.96	3.9	19.5	5.7	13.7	22.8
Total					**426.6**	**67.5**	**359.1**	**598.3**

Table 5: Crop water requirement for tomato

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec	GIR mm/dec
Jan	1	Init	0.6	2.33	23.3	0.8	22.5	37.5
Jan	2	Init	0.6	2.37	23.7	1.2	22.4	37.3
Jan	3	Deve	0.63	2.53	27.8	2.2	25.7	42.8
Feb	1	Deve	0.76	3.14	31.4	3.1	28.4	47.3
Feb	2	Deve	0.9	3.8	38	3.9	34.1	56.8
Feb	3	Deve	1.03	4.33	34.6	5.1	29.5	49.2
Mar	1	Mid	1.14	4.79	47.9	6.4	41.5	69.2
Mar	2	Mid	1.16	4.87	48.7	7.6	41.1	68.5
Mar	3	Mid	1.16	4.8	52.8	8.9	44	73.3
Apr	1	Mid	1.16	4.74	47.4	10.6	36.8	61.3
Apr	2	Late	1.14	4.58	45.8	12.1	33.8	56.3
Apr	3	Late	1.01	4.09	40.9	11.5	29.4	49.0
May	1	Late	0.87	3.53	35.3	9.5	25.8	43.0
Total					**497.7**	**82.8**	**415**	**691.7**

Where, Deve = Development stage, Mid = Middle stage, Init = Initial stage and GIR= Gross irrigation requirement

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 planting to harvesting) for cabbage planted on 1st January, took 115 days. irrigation should be given twelve times (1-Jan, 9-Jan, 16-Jan,24-Jan, 2-Feb, 11-Feb, 21-Feb, 5-Mar,15-Mar, 25-Mar, 2- Apr and last irrigation on 12-Apr) with gross irrigation water amount of 59.8mm, 32.5mm, 31.5mm, 35.2mm, 42.2mm, 43.3mm, 48.1mm, 52mm, 51.3mm, 49.5mm, 51mm, and 51.7mm depth respectively (Table 6).

Similarly, for tomato transplanted on 1st January, the total growing days (from transplanting to harvesting) took 130 days. irrigation should be given twelve times (1-Jan, 5-Jan, 10-Jan, 16-Jan, 21-Jan, 29-Jan, 6-Feb, 15-Feb, 26-Feb, 12-Mar, 26-Mar, and the last irrigation on 10-Apr) with a gross irrigation water amount of 53.9mm, 19.3mm, 25.5mm, 30.7mm, 30.6mm, 36.4mm, 47.8mm, 58.5mm, 73.4mm, 83.5mm, 80.9mm, 80.7mm respectively depth respectively (Table7).

Table 6: Irrigation requirement and irrigation scheduling of early January planted cabbage

Date	Day	Stage	Net Irr Mm	Gr. Irr mm	Flow l/s/ha
1-Jan	1	Init	35.9	59.8	6.92
9-Jan	9	Init	19.5	32.5	0.47
16-Jan	16	Init	18.9	31.5	0.52
24-Jan	24	Init	21.1	35.2	0.51
2-Feb	33	Dev	25.3	42.2	0.54
11-Feb	42	Dev	26	43.3	0.56
21-Feb	52	Dev	28.9	48.1	0.56
5-Mar	64	Dev	31.2	52	0.5
15-Mar	74	Mid	30.8	51.3	0.59
25-Mar	84	Mid	29.7	49.5	0.57

Date	Day	Stage	Net Irr	Gr. Irr	Flow
			Mm	mm	l/s/ha
2-Apr	92	Mid	30.6	51	0.74
12-Apr	102	End	31	51.7	0.6
25-Apr	End	End			

Table 7: Irrigation scheduling of early January planted tomato

Date	Day	Stage	Net Irr	Gr. Irr	Flow
			Mm	mm	l/s/ha
1-Jan	1	Init	32.4	53.9	6.24
5-Jan	5	Init	11.6	19.3	0.56
10-Jan	10	Init	15.3	25.5	0.59
16-Jan	16	Init	18.4	30.7	0.59
21-Jan	21	Init	18.4	30.6	0.71
29-Jan	29	Dev	21.9	36.4	0.53
6-Feb	37	Dev	28.7	47.8	0.69
15-Feb	46	Dev	35.1	58.5	0.75
26-Feb	57	Dev	44.1	73.4	0.77
12-Mar	71	Mid	50.1	83.5	0.69
26-Mar	85	Mid	48.6	80.9	0.67
10-Apr	100	Mid	48.4	80.7	0.62
10-May	End	End			

CONCLUSION

Cabbage, and tomato are among the principal crops widely cultivated by irrigation farmers in Welmera, and their crop water demand was evaluated using the FAO CROPWAT 8.0 model. From the results, it was evident that, the total seasonal crop water requirement for cabbage, and tomato was 426.6mm, and 497.7mm respectively. The gross irrigation requirement considering 60 % irrigation application efficiency for furrow irrigation was estimated to be 598.3 mm, and 691.7 mm for cabbage, and tomato respectively.

For 1st January planted cabbage, irrigation should be given twelve times (1-Jan, 9-Jan, 16-Jan,24-Jan, 2-Feb, 11-Feb, 21-Feb, 5-Mar,15-Mar, 25-Mar, 2-Apr and last irrigation on 12-Apr) with a gross irrigation water amount of 59.8mm, 32.5mm, 31.5mm, 35.2mm,42.2mm,43.3mm,48.1mm, 52mm, 51.3mm, 49.5mm, 51mm, and 51.7mm depth respectively. Similarly for 1st January transplanted tomato, irrigation should be given twelve times (1-Jan, 5-Jan, 10-Jan, 16-Jan, 21-Jan, 29-Jan, 6-Feb, 15-Feb, 26-Feb, 12-Mar, 26-Mar, and the last irrigation on 10-Apr) with a gross irrigation water amount of 53.9mm, 19.3mm, 25.5mm, 30.7mm, 30.6mm, 36.4mm, 47.8mm, 58.5mm, 73.4mm, 83.5mm, 80.9mm, 80.7mm irrigation depth respectively. The findings obtained from this study can be useful for optimal irrigation management and agricultural planning for growing cabbage, and tomato in the study area.

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