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Research Article

Water Requirement and Irrigation Scheduling of Potato (*Solanum tuberosum* L.) by Using CROPWAT 8.0 at Welmera District, Central Highland of Ethiopia

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Abstract

In Welmera district, due to poor management of irrigation water, determination of crop water requirements and appropriate irrigation scheduling is important to prevent over or under-irrigation. The 30-year climatic data (1993- 2023) collected from Holeta Agricultural Research Center were used to estimate potato water requirements and irrigation scheduling using CROPWAT 8.0 model. The results shows that, the CWR, NIR and GIR for potato crop was 444.9 mm, 371.7 mm and 619.5 mm respectively. For the early January planted potato, irrigation should be given fourteen times (1-Jan, 9-Jan, 19-Jan, 29-Jan, 5-Feb, 12-Feb, 19-Feb, 26-Feb, 5-Mar, 11-Mar, 19- Mar, 26-Mar, 31-Mar and last irrigation on 10-Apr) with a gross irrigation water amount of 24.2 mm, 19.9 mm, 23.3 mm, 24.2 mm, 26.9 mm, 35.5mm, 38 mm, 43.5 mm, 43.4 mm, 40.8 mm, 41.9 mm, 39.5 mm, 40.2 mm and 42.9 mm depth respectively. The results obtained from this study can be useful in preventing over or under-irrigation and for future planning of water resource, thereby helping to save water in meeting the CWRs, and can be used as a guide for farmers to select the amount and frequency of irrigation for the crop being studied.

Keywords

Climate Data, Cropwat 8.0, ETo, Crop Water Requirement, Irrigation Scheduling, Potato

1. Introduction

Population growth, high water competition, and the effect of climate change have caused water shortage problems in Ethiopia. Proper water management improves water use efficiency; determining the water requirement of field crops is an option for improving water productivity [22]. Not watering at the right time and correct amount can result in plant water stress and reduce the quality and yields of crops. On the other hand, over-watering can increase the risk of nutrients leaching below the root zone, waste resources (water, energy, and nutrients), and environmental impacts [5]. The irrigation scheduling is the process of determining when to irrigate and how much water to apply per irrigation. Proper irrigation scheduling is essential for the efficient use of water, energy and other production inputs [4, 8]. CROPWAT 8.0 is a widely used method by various scientists to estimate crop evapotranspiration, CWR, and irrigation scheduling [7, 14, 17, 19]. Potato (*Solanum tubersum* L.) is a root crop and ranks first in its volume of production and consumption followed by cassava, sweet potato and yam in Ethiopia [24].

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During the dry season, there was water conflict among the water users in the district due to the scarcity of irrigation water and large competition among the water user. Currently, irrigated potato 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. By considering the lacking of adequate information and knowledge gap on crop water and irrigation requirements among the farmers practicing irrigation for most of the crops grown in the area, the current studies aims to estimate the Crop Water Requirement and irrigation schedules for potato crop in the Welmera district using CROPWAT 8.0 model.

2. Materials and Methods

2.1. Description of the 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 2400 m above sea level. Total geographical area of the district is 1046 km^2 and the average annual rainfall is 1034 mm. The average minimum and maximum temperature of Welmera district is 6.4 ℃ and 22.7 ℃ respectively. 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.

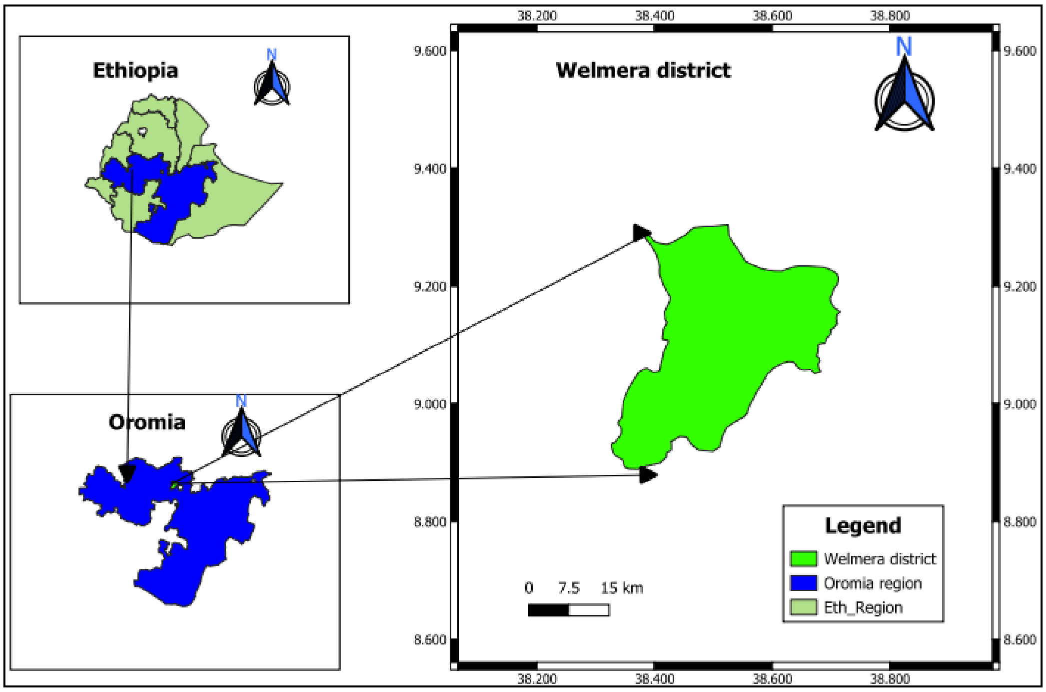

Figure 1. Geographical location of the study area.

In the study area, June to September is the main rainy season, which accounts for 70% of the total rainfall. Based on 30 years (1993-2023). The average annual rainfall for the study area was 1034.3 mm. The mean annual minimum and maximum temperatures of the study area were 6.4 ℃ and 22.7 ℃ respectively (Table 1).

Table 1. Climate characteristics.

Month	Min Temp ℃	Max Temp ℃	Humidity %	Wind km/day	Sun Hours	Rad MJ/m?/day
January	4.1	23.5	51	104	10.4	22.7
February	5.2	24.3	54	112	9.6	22.9
March	6.8	24.5	55	112	7.9	21.5

Month	Min Temp ℃	Max Temp ℃	Humidity %	Wind km/day	Sun Hours	Rad MJ/m?/day
April	8.4	24.1	61	104	7.2	20.6
May	8.3	24.4	59	112	7.4	20.4
June	8.1	22.7	69	69	5.7	17.5
July	9.3	20.3	78	69	3	13.6
August	9.2	20	81	69	3.1	14
September	7.8	20.6	72	86	5	16.9
October	4.8	22.4	59	138	8.3	21.2
November	2.8	22.8	54	130	9.8	22.1
December	2.2	23.1	58	130	9.7	21.2
Average	6.4	22.7	63	103	7.3	19.6

The monthly evapotranspiration was greater than monthly rainfall starting from the month of June to September (Figure 2). The remaining month of the year evapotranspiration exceeds rainfall this implies that for production of potato during the rainfall season (June to September), the seasonal available effective rain fall is enough to compensate the Crop water requirement. So, there is no any extra irrigation requirement is needed and in the remaining season, available effective rain fall is less to compensate the Crop water requirement. Therefore, the amount of water needed by crops to meet the water loss through evapotranspiration, should be applied by using irrigation to grow crops optimally.

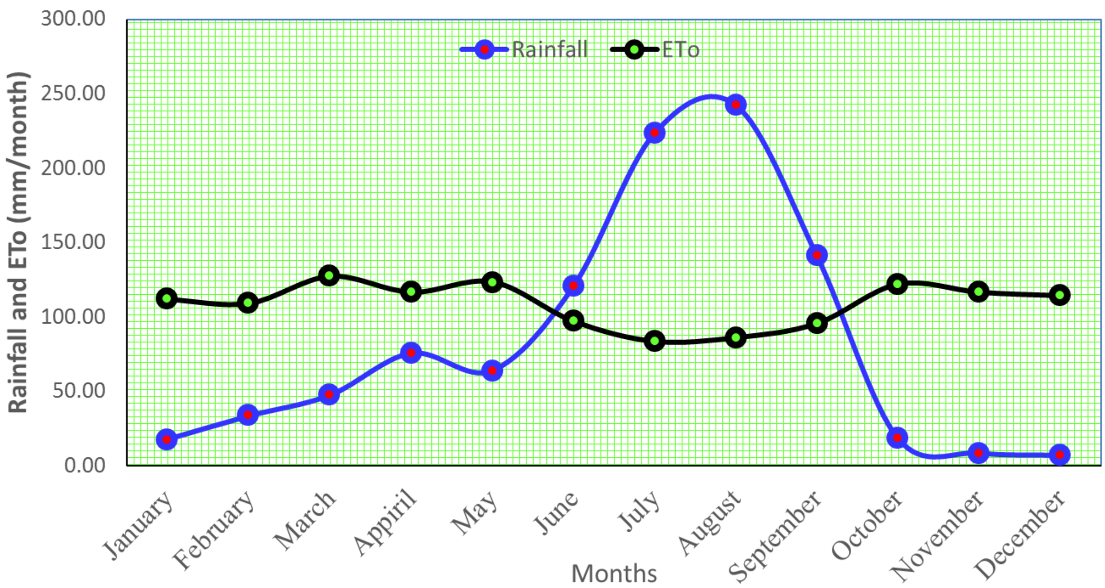

Figure 2. *Monthly rainfall as compared with reference evapotranspiration.*

3. CROPWAT 8.0 Model Description

CROPWAT model is a decision-making tool developed by water development division of FAO in computer programing language for the determination of reference crop evapotranspiration, crop water requirement, crop irrigation requirement, and irrigation scheduling based on soil, climate and crop data [18]. In addition, the program allows the development of irrigation schedules for different management conditions and the calculation of scheme water supply for varying crop patterns.

4. Input Data Required for Calculation of CWR, IWR, and Irrigation Scheduling

Cropwat for windows uses climate data, soil data, and crop data for the calculation of crop water requirements and irrigation requirements [12]. Once all the data is entered, CROPWAT 8.0 for Windows automatically calculates the reference evapotranspiration, effective rainfall, net irrigation requirement, gross irrigation requirement and irrigation scheduling. The model required the following data for estimating crop water requirements (CWR).

4.1. Climate Data

ETo is considered an essential factor in determining the crop water requirement and effective irrigation scheduling [13]. In calculating the reference evapotranspiration (ETo), the study utilized 30 years of monthly maximum and minimum temperature, relative humidity, sunshine hour and wind speed data collected from the Holeta Agricultural Research Center Meteorological station. In this study, the FAO56-Penman Montieth method Eq. (1) has been used for ETo determination because, Penman– Monteith equation is most widely used method around the globe [10, 20]. The 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 (℃)

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})

4.2. Crop Data

Potato is one of the major crops grown in this district. CROPWAT requires the crop data like, planting date, harvesting date, yield response factor, Crop coefficient (KC) and the crop growth stages. The crop growing season has been divided into four [6]. The initial stage refers to crop germination/transplanting. It also refers when the soil surface is not covered by the crop (canopy cover < 10%). The crop development stage denotes the vegetative period of the crop that includes from the end of initial stage to full canopy cover (canopy cover 70 – 80%). The mid-season stage represents the period between full ground cover to the time of start of maturity (leaf yellowing). Late season stage stands for the crop period from end of mid-season stage to full maturity [3]. The information was obtained from FAO manual 56 and adapted to the local climate conditions. In Table 2, the details of crop information, including sowing date, crop coefficient, and duration of growth stages, were described.

Table 2. Details of the crop required as per the CROPWAT model.

Crop Name: Potato	**Planting date: 01/01**			**Harvesting date: 30/04**	
Stage	Initial	Development	Mid	Late	Total
Length (days)	25	30	40	25	120
Kc Values	0.50	- ->	1.15	0.75	
Rooting depth (m)	0.30	- ->	0.6	0.60	
Critical depletion	0.25	- ->	0.3	0.50	
Yield response f.	0.45	0.8	0.8	0.30	110
Crop height (m)			0.6		

4.3. Soil Data

In order to determine the CWR and irrigation scheduling, the model requires information on, Soil type, total available soil moisture, maximum rooting depth and initial soil moisture depletion (% of total available moisture). This information was obtained from FAO Manual 56 and Information on soil properties i.e., Field Capacity (FC), Permanent Wilting Point (PWP), infiltration rate, initial soil moisture depletion were done at Holeta Agricultural Research Center soil laboratory using the gravimetric method.

4.4. Rain Data

The average monthly rainfall data recorded from Holeta meteorological station for a period of 30 years (1993 - 2023) was used and applied in CROPWAT model for the estimation of effective rainfall. The fraction of rainfall that is stored in the soil profile and helps in the growth of crops is effective rainfall. 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).

5. Crop Water Requirement Estimation

The term crop water requirement is defined as the "amount of water required to compensate the evapotranspiration loss from the cropped field". "Although the values for crop evapotranspiration and crop water requirement are identical, crop water requirement refers to the amount of water that needs to be supplied, while crop evapotranspiration refers to the amount of water that is lost through evapotranspiration [2]. The Crop evapotranspiration (ETc) is obtained by multiplying reference crop evapotranspiration (ETo) values with the Crop coefficients (Kc). The Kc values for potato 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 day.

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.

6. Irrigation Scheduling

The primary objective of irrigation scheduling is to apply water at the right period and in the right amount. Potato crop has several stages, namely the initial stage, the developmental stage, the middle stage, and the late stage. At each stage, the irrigation requirement is different, so irrigation must be properly planned for the optimal use of water [19]. The irrigation scheduling option in CROPWAT provides a number of options depending on user’s objectives, available water sources, the conditions of the irrigation system. In this study case for potato crop, the irrigation scheduling can be done at 35% depletion level as irrigation application time as indicated in FAO 56, and the irrigation application option of refill soil to field capacity at 100% was selected. The gross irrigation requirement was estimated by considering 60% application efficiency for the furrow irrigation system. It basically varied between 60 and 80% for surface irrigation systems [23].

7. 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.

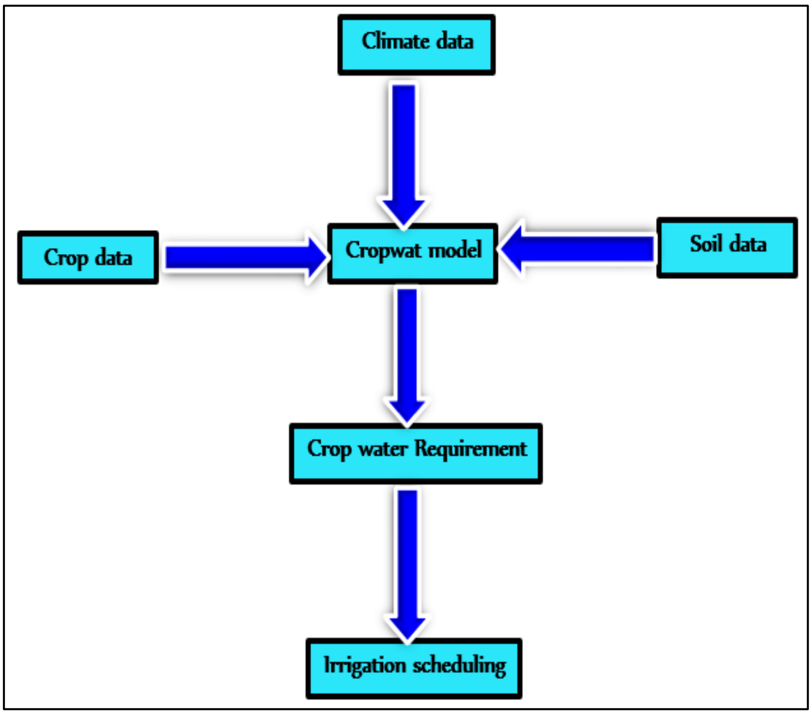

Figure 3. *Flow chart for the estimation of crop water requirement and scheduling using CROPWAT model.*

8. Results and Discussion

8.1. 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 particle size of the sample was determined using the hydrometer method [22]. The result 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 (30-60 cm) and the 3rd layer (60-90 cm) 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 3 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 3. *Physico-chemical properties of soils in the study area.*

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

8.2. Reference Evapotranspiration (ETo)

The reference evapotranspiration (ETo) for the district was calculated from the Penman-Montieth equation using agro-climatic data. The ETo was found maximum (4.2 mm/ day) in the month of February and March and minimum (2.6 mm/ day) in the month of July (Figure 4). According to this study, ETo was high during the dry season due to the high temperature, and it decreased during the rainy season due to the low temperature. Further, it was seen that an increase in radiation value brings an increase in the ETo value, thus, depicting direct relation.

A significant variation in ETo between seasons can be caused by variations in climatic factors such as temperatures, solar radiation, and rainfall as well as wind, and relative humidity. The results obtained in this study are similar to [1, 15], which showed that ETo was lowest during the peak of the rainy season to highest during the peak of the dry season.

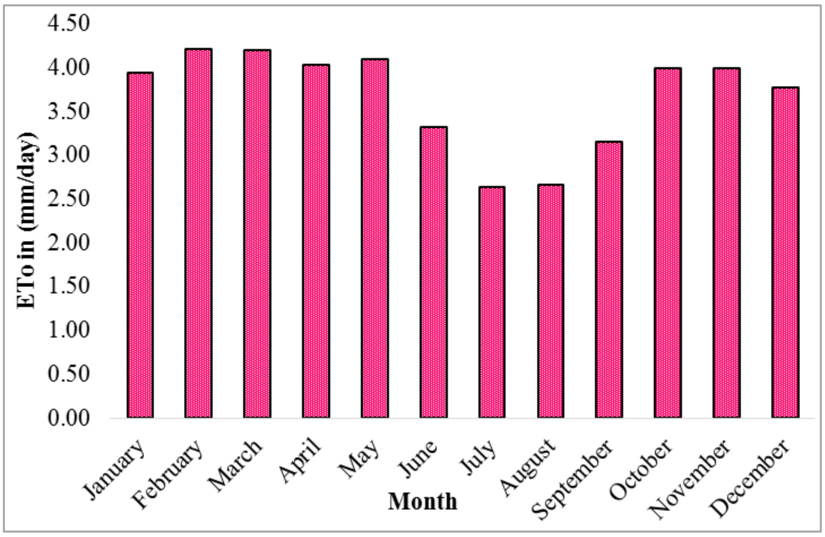

Figure 4. *Monthly reference evapotranspiration (ETo) at Welmera district.*

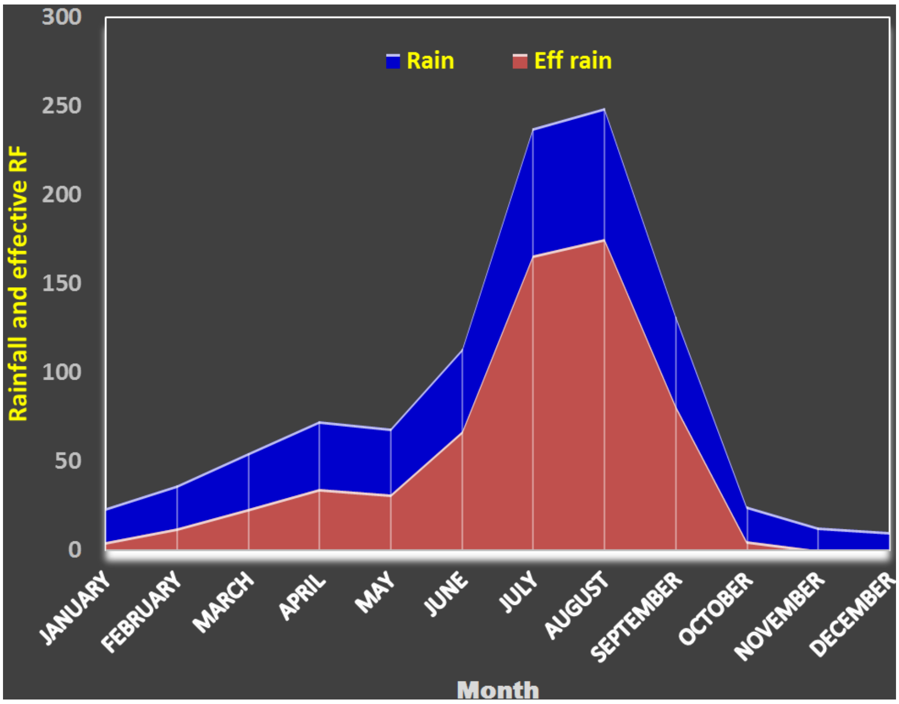

Figure 5. *Rainfall and effective rainfall of the district.*

8.3. Rainfall and Effective Rainfall

Effective rainfall is that fraction of the overall rainfall that substitutes or possibly reduces the respective net amount of irrigation water needed. The effective rainfall (Peff) for the district was calculated using the USDA-SCS method. Figure 5 represents the month-wise total and effective rainfall of the study area. 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.

8.4. 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 potato crop. The crop water requirement and gross irrigation water requirement of potato, was 444.9 mm, and 619.5 mm respectively (Table 4). The demand of water is more for the mid-season stage during which the development of tuber was initiated, hence more water requirement in mid-season stage. The variation in crop water requirement is due to differences in crop growth phases, crop coefficients, and cropping area [9]. These result are in agreement with [11]. The determined above crop water requirement for potato crop are within the range indicated in the FAO 66 [22] which are 350 to 650 mm for potato.

Table 4. *Crop water Requirement, net and gross irrigation requirement for potato.*

Month	Decade	Stage	Kc Coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	NIR Req. mm/dec	GIR mm/dec
Jan	1	Init	0.5	1.95	19.5	0.8	18.6	31.0
Jan	2	Init	0.5	1.97	19.7	1.2	18.5	30.8
Jan	3	Deve	0.54	2.19	24.1	2.2	21.9	36.5
Feb	1	Deve	0.75	3.11	31.1	3.1	28.1	46.8
Feb	2	Deve	0.98	4.12	41.2	3.9	37.3	62.2
Feb	3	Mid	1.15	4.83	38.7	5.1	33.5	55.8
Mar	1	Mid	1.16	4.89	48.9	6.4	42.6	71.0
Mar	2	Mid	1.16	4.89	48.9	7.6	41.3	68.8
Mar	3	Mid	1.16	4.82	53	8.9	44.2	73.7
Apr	1	Late	1.14	4.65	46.5	10.6	36	60.0
Apr	2	Late	0.99	3.99	39.9	12.1	27.8	46.3
Apr	3	Late	0.82	3.34	33.4	11.5	21.9	36.5
Total					444.9	73.2	371.7	619.5

Where, Dev = Development stage, Mid = Middle stage, Init = Initial stage, NIR= Net irrigation requirement, GIR= Gross irrigation requirement

8.5. 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 planting to harvesting) for potato planted on January 1st took 120 days. irrigation should be given fourteen times (1-Jan, 9-Jan, 19-Jan, 29-Jan, 5-Feb, 12-Feb, 19-Feb, 26-Feb, 5-Mar, 11-Mar, 19- Mar, 26-Mar, 31-Mar and last irrigation on 10-Apr) with a gross irrigation water amount of 24.2 mm, 19.9 mm, 23.3 mm, 24.2 mm, 26.9 mm, 35.5mm, 38 mm, 43.5 mm, 43.4 mm, 40.8 mm, 41.9 mm, 39.5 mm, 40.2 mm and 42.9 mm depth respectively (Table 5). The difference between GIR and NIR represents field irrigation losses [16].

***Table 5**. Irrigation requirement and irrigation scheduling of early January planted potato.*

Date	Day	Stage	Net Irr mm	Gr. Irr mm	Flow l/s/ha
1-Jan	1	Init	14.5	24.2	2.80
9-Jan	9	Init	11.9	19.9	0.29
19-Jan	19	Init	14.0	23.3	0.27
29-Jan	29	Dev	14.5	24.2	0.28
5-Feb	36	Dev	16.1	26.9	0.44
12-Feb	43	Dev	21.3	35.5	0.59
19-Feb	50	Dev	22.8	38.0	0.63
26-Feb	57	Mid	26.1	43.5	0.72
5-Mar	64	Mid	26.0	43.4	0.72
11-Mar	70	Mid	24.5	40.8	0.79
19-Mar	78	Mid	25.1	41.9	0.61
26-Mar	85	Mid	23.7	39.5	0.65
31-Mar	90	Mid	24.1	40.2	0.93
10-Apr	100	End	25.8	42.9	0.50
30-Apr	End	End			

9. Conclusion

The present study was carried out to determine the crop water requirement (CWR), irrigation water requirement (IWR), and irrigation scheduling for potato crop grown in the Welmera district using the CROPWAT model based on climatic, soil, and crop data. The analysis revealed that the total CWR, NIR and GIR for the entire growing season for potato, was found to be 444.9; 371.7; and 619.5 mm respectively.

For early January planted potato, irrigation should be given fourteen times (1-Jan, 9-Jan, 19-Jan, 29-Jan, 5-Feb, 12-Feb, 19-Feb, 26-Feb, 5-Mar, 11-Mar, 19- Mar, 26-Mar, 31-Mar and last irrigation on 10-Apr) with a gross irrigation water amount of 24.2 mm, 19.9 mm, 23.3 mm, 24.2 mm, 26.9 mm, 35.5mm, 38 mm, 43.5 mm, 43.4 mm, 40.8 mm, 41.9 mm, 39.5 mm, 40.2 mm and 42.9 mm depth respectively. The findings obtained from this study can be used by agronomist and irrigation engineer for calculating irrigation scheduling and crop water requirement assessment, thereby helping to save water in meeting the CWRs, and can be used as a guide for farmers to select the amount and frequency of irrigation 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, Visualization, Writing – original draft, Writing – review & editing

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

Conflicts of Interest

The authors declare no conflicts of interest.

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