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Optimizing Irrigation Scheduling for Tomato Cultivation CROPWAT 8 Case Study from lower Wadi Bana, Abyan Delta, Yemen

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Abstract

Agricultural hydrology represents a pivotal domain for comprehending and administering water resources to facilitate sustainable agricultural methodologies. The scheduling of irrigation constitutes a fundamental aspect of efficient water management, aiding in the evaluation of the water needs of diverse crops during their growth phases leading up to harvest. This data is essential for crafting comprehensive water management strategies, especially in regions experiencing water deficiency, such as Delta Abyan. In the present investigation, the CROPWAT 8.0 model was employed to enhance irrigation methodologies for tomato cultivation, with the objective of precisely estimating water requirements and establishing optimal irrigation intervals. Hydrological information, encompassing precipitation, soil attributes, and climatic variables (including maximum and minimum temperatures, relative humidity, sunshine duration, and solar radiation), was systematically gathered and examined through the model. The findings indicated that October exhibited the peak reference evapotranspiration (ET) rate and water demand, with measurements of 5.43 mm/day and 59.1 mm, correspondingly. This phenomenon is linked to the crop being in its active growth and flowering phases. Conversely, December displayed the lowest reference evapotranspiration (ET_0) rate and water demand, with figures of 4.51 mm/day and 10.2 mm, respectively, signifying that the crop was progressing towards the harvest phase. The cumulative water requirement for the tomato crop was determined to be 625.9 mm. Tomatoes display a pronounced water consumption rate relative to other crops in Delta Abyan, particularly during their intense growth and flowering stages. They rank among the highest in terms of water consumption, akin to other crops with elevated water demands, such as cotton.

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1. INTRODUCTION

Delta Abyan is recognized as one of the paramount agricultural zones in Yemen, significantly influencing the nation's agricultural output. Nevertheless, the region faces substantial obstacles owing to water scarcity, which is exacerbated by the repercussions of climate change, adversely impacting agricultural efficiency and jeopardizing its long-term viability. Furthermore, persistent conflict in the region, inadequate water management practices, and excessive extraction of groundwater further intensify the crisis, rendering the situation increasingly dire. This study aimed to evaluate the water demands of tomato cultivation from a hydrological standpoint, with emphasis on identifying the necessary water volumes for each developmental phase of the crop. The implementation of effective water management practices in tomato agriculture is imperative to ensure the sustainable utilization of groundwater and mitigate overextraction, which could precipitate the depletion of this essential resource. The excessive withdrawal of groundwater has dire implications for the area, including the intrusion of seawater into groundwater supplies and salinization of soils, which threatens agricultural sustainability and compromises the long-term viability of life in Delta Abyan. The Food and Agriculture Organization has developed a sophisticated modeling tool, CROPWAT 8.0, to analyze the responsiveness of various crops to the quantitative and qualitative aspects of irrigation management, as referenced by [1, 2]. This tool was used to compute the water requirements of the tomato crops throughout their growth stages. The program utilizes extensive hydrological data encompassing climatic conditions and geological characteristics, such as soil type and attributes. By assimilating these crucial parameters, the program facilitates precise estimation of water requirements, thereby promoting more effective irrigation management.

2. MATERIALS AND METHODS

2.1. Study area and literature review

This study was conducted in the Delta Abyan region, located in the lower Wadi Bana, Yemen. Delta Abyan is a flatland area with the highest elevation at Bateis, approximately 170 m above sea level, and covers an area of 469.9 km^2. As shown in Fig. (1), land use in the region is classified into several categories: agricultural land accounted for 390 km^2 in 2013, while non-agricultural land covered 57.17 km^2. The drainage density of the region is 6.5 km^2, with urban areas occupying 15.21 km^2, and mining roads occupying 1 km^2. By 2018, the extent of agricultural land had changed substantially because of the ongoing conflict in Yemen Fig. (2). Three major wadis intersect the delta: Wadi Bana, Wadi Hassan, and Wadi Suhaybiyah. Wadi Bana flows along the northern perimeter of the delta towards the Gulf of Aden. The delta slopes southward from the Bateis to Ja'ar, where the gradient flattens and shifts southeastward. Wadi Hassan enters the delta to the east of Bateis, following a path along the eastern edge, and ultimately flows toward the Gulf of Aden. Wadi Suhaybiyah entered from the west and flowed along the western edge of the delta before merging with Wadi Bana. The coastal plain of Delta Abyan is characterized by a hot and arid climate for most of the year. During the summer, temperatures range from 30C^0 to 40C^0, whereas in the winter, temperatures range between 20C^0 and 30C^0, with an average annual temperature of approximately 28C^0. The region experiences high solar radiation, elevated humidity levels, and frequent dusty winds, particularly in July and August.

Delta Abyan, located in the southwestern drainage basin of Yemen, encompasses wadi catchments that originate in the high-rainfall areas of the southern highlands and midlands, draining toward the Gulf of Aden coastal plain [4]. Known as the Abyan Delta, this flat plain lies in an arid to subtropical zone, approximately

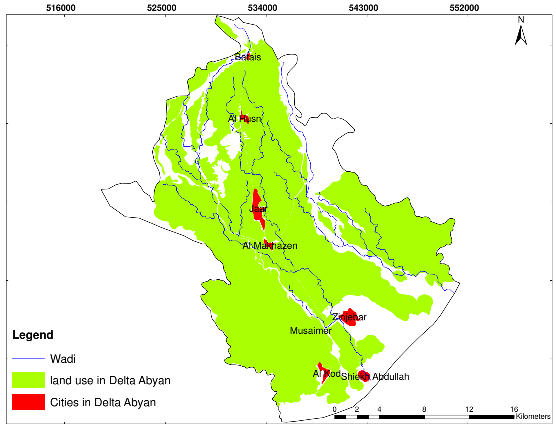

Figure 1. Illustrates the irrigated command areas and population centers of Wadi Bana in the Abyan Delta for the year 2013

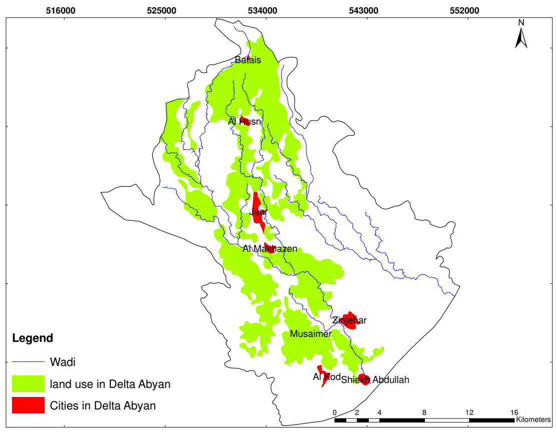

Figure 2. Shows the irrigated command areas and population centers of Wadi Bana in the Abyan Delta. This figure is modified after [3].

55 km east of Aden city [5]. The delta is a vital source of water for irrigation and water supply and represents one of Yemen's most promising regions for agricultural development [6, 7].

Three major wadis, Wadi Suhaybiyah, Wadi Bana, and Wadi Hassan, cross Delta Abyan from west to east. These wadis have large catchment areas of 1,593.4 km^2, 7,400 km^2, and 3,177.3 km^2, respectively. The Abyan Delta catchment is predominantly composed of barren or sparsely vegetated land, accounting for about 24.7% of the total catchment area (469.9 km^2), with urban areas covering 3.24% (cities) and 0.21% (mining roads). The stream network is mainly located in the upper part of the catchment, covering 1.4% of the total area. Irrigated croplands occupies approximately 331.9 km^2, representing over 70.5% of the total catchment area. Delta Abyan is considered one of the most prime farmland areas in the southern coastal plains of Yemen [6] and has experienced significant agricultural activity, especially in Wadi Bana near the delta mouth. A remote sensing study revealed that Wadi Bana accounts for 84% of the total cultivated area in the Abyan Delta catchment, with nearly

Table 1. Cropped area in hectare in Delta Abyan

Year	Cotton	Groundnuts	Sorghum	Maize	Millet	Tomatoes	Sweet Melon
2007	4,730	2,078	9,808	977	6,149	759	217
2008	4,881	2,119	7,356	821	5,227	774	221
2009	5,125	2,183	14,230	755	4,704	797	232
2010	5,226	2,205	20,033	971	6,621	825	242
2011	4,519	2,114	15,339	836	5,113	713	208
2012	3,351	1,934	14,175	613	2,193	701	116
2013	2,611	1,946	13,922	677	3,116	589	156
2014	2,525	1,950	11,321	613	5,012	576	173
2015	2,273	1,872	9,623	490	3,910	403	161
2016	1,860	1,870	8,196	490	5,319	340	189
2017	1,851	1,851	8,185	475	5,213	337	191
2018	1,703	1,856	8,594	494	5,422	347	190
2019	2,352	1,879	8,860	488	3,859	400	161
2020	2,352	1,879	8,860	488	3,859	400	161
2021	2,352	1,898	8,860	493	3,859	408	169
Average	3,181	1,976	11,157	645	4,638	558	186

44,000 hectares of cropland, of which 40,000 hectares are irrigated, compared to 9,400 hectares in 1980 [8]. In the lower part of the Abyan Delta, the total maximum irrigated area reported thus far is approximately 23,000 hectares, of which 11,000 to 19,000 hectares are irrigated by spate irrigation, depending on the availability of floods [9]. Wadi Hassan and Wadi Suhaybiyah contributed less than 10% of the total cultivated area, with estimated cropland areas of 5,500 ha and 3,000 ha, respectively. Agriculture is the primary economic activity of the Abyan Delta. The cultivated area and cropping patterns vary from year to year depending on the quantity and frequency of spates. Agricultural crops grown in the Abyan Delta include sorghum, sesame, cotton, groundnuts, tomatoes, sweet melons, maize, millet, and other vegetables. The southern coastal plains of Yemen [6] have experienced significant agricultural activity, especially in Wadi Bana near the delta mouth. The water sources for irrigation in the Abyan Delta originate from the surface runoff of Wadi Bana, with the two irrigation seasons accounting for approximately 90% of the total surface runoff. The Khareef season (July 1 to October 15) receives 66% of the annual runoff, whereas the Seif season (March 16 to May 31) receives approximately 24%. However, these sources are insufficient for meeting the full economic irrigation potential of the region. Additionally, the distribution of water shortages is uneven, exacerbating local conflicts [10].

Cropping patterns are in transition owing to the process of agricultural privatization. More than half of the cropped area in the spate irrigation zones is occupied by sorghum (mainly grain), with sorghum covering 49% of the area according to the Agricultural Statistics Books from 2007 to 2021. Other important crops included millet (21%), cotton (14% in the upstream zone), and tomato (3%) (Table 1 and Fig. 3).

Delta Abyan, Yemen faces significant challenges in water resource management because of its arid climate and dependence on groundwater for irrigation. Several studies have addressed water use efficiency and irrigation practices in this region. Emphasized the over-extraction of groundwater and called for more efficient water management strategies such as improved irrigation systems. Al-Saadi et al. found that drip irrigation was more water efficient than surface irrigation, suggesting its potential for conserving water in the region [11]. Climate related studies by Al-Maktari et al. showed that temperature fluctuations and inconsistent rainfall significantly impact crop water demands, further highlighting the need for localized climate data in irrigation planning [12]. Collectively, these studies suggest that adopting modern irrigation techniques, leveraging advanced models, and using remote sensing technologies could greatly improve water-use efficiency in Delta Abyan, although further research is needed to customize these solutions to the specific conditions of the region.

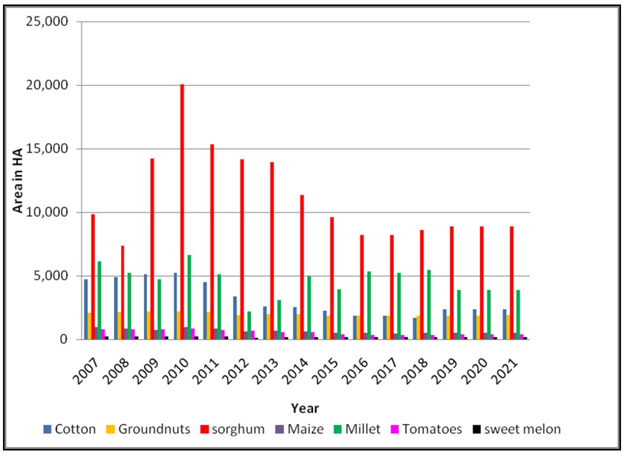

Figure 3. Crop type in Delta Abyan area

2.2. CROPWAT 8.0 model and Data Requirement

CROPWAT 8.0, a software developed by the FAO, was designed to calculate reference evapotranspiration (ET_0), crop water requirements (CWR), irrigation scheduling, and irrigation water requirements (IR). It uses data on

Table 2. climate Date for Delta Abyan

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	C^0	C^0	(%)	km/day	hours	$MJ/m^2/day$	mm/day
January	24.0	25.5	76	470	7.8	18.1	4.33
February	23.8	26.1	78	469	7.5	19.1	4.34
March	26.7	28.0	78	440	7.8	20.9	4.93
April	28.1	29.0	76	379	8.4	22.5	5.43
May	30.2	31.1	76	312	9.3	23.6	5.82
June	29.9	31.8	77	251	7.2	20.1	5.13
July	29.9	32.2	80	362	6.7	19.5	5.1
August	29.7	31.5	81	317	7.8	21.3	5.16
September	30.8	32.0	78	246	7.9	21.2	5.3
October	29.2	30.5	72	305	9.1	21.7	5.62
November	27.5	29.4	72	454	8.5	19.3	5.42
December	25.6	26.6	73	485	7.5	17.2	4.73
Average	27.9	29.5	76	374	8.0	20.4	5.11

rainfall, soil, crops, and the climate. The software includes general information on various crop characteristics, local climate, and soil properties, helping to optimize irrigation schedules and compute water supply requirements for different crop patterns under both irrigated and rainfed conditions. Climatic data, including monthly maximum and minimum temperatures (C^0), wind speed (km/h), mean relative humidity (%), and sunshine hours (h) (Table 2) and Fig. 4, covering a period of 15 years (1991-2005) were collected from stations in Delta Abyan. Rainfall data covering 38 years from 1970-2008, to data were processed, and missing values were filled using regression equations for rainfall. Crop data for tomato were obtained from the FAO Manual 56 and incorporated into CROPWAT 8.0. These data included rooting depth, crop coefficient, critical depletion, yield response factor, and duration of plant growth stages. Planting dates were based on a guide for agricultural operations in the Abyan Delta. The soil parameters obtained from the FAO CROPWAT 8.0 model provide detailed information on the soil near the climatic station, such as the total available moisture content, initial moisture depletion, maximum rain infiltration rate, and maximum rooting depth. The United States Department of Agriculture (USDA) soil conservation (S.C.) method was applied [13].According to the FAO standards, the soil in the Delta Abyan area is classified as medium type (Table 3).

Table 3. General soil data for Delta Abyan

Parameter	Value
Soil Name	Medium (loam)
Total Available Soil Moisture (FC-WP)	290 mm/meter
Maximum Rain Infiltration Rate	40 mm/day
Maximum Rooting Depth	0.9 cm
Initial Soil Moisture Depletion (as % TAM)	0 mm/meter

3. RESULTS AND DISCUSSION

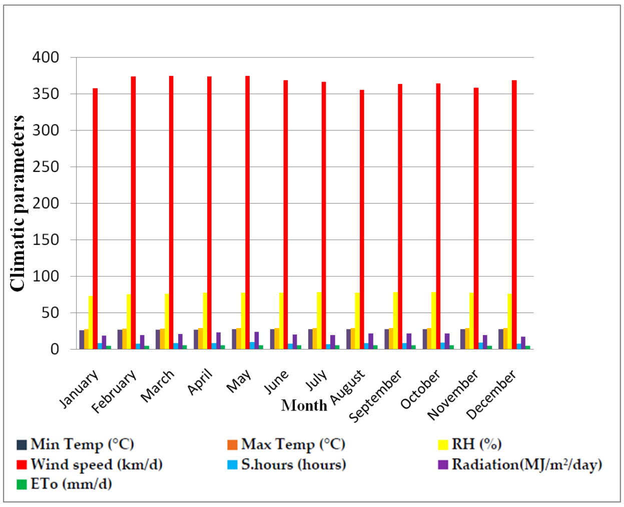

Figure 4. Average monthly variation in weather station parameters

3.1. Reference Evapotranspiration

There was variation in ET_0 in Delta Abyan. It started to increase in January and peaked in May. Then, from July to the peak in August, and subsequently declined, reaching its lowest point in December. Fig.(5, illustrates the monthly variation in ET_0 in Delta Abyan.

3.2. Crop evapotranspiration in Delta Abyan

Evapotranspiration (ET) was calculated using the CROPWAT 8.0 model, which serves as a measure of the atmospheric evaporative demand. Reference evapotranspiration (ET_0) was determined using the FAO Penman-Monteith equation [14] implemented through the ET_0 calculator embedded within the CROPWAT 8.0 software [15]. Monthly meteorological data, including geographical coordinates of the study area, were collected for this purpose. The long-term monthly ET_0 data generated by the CROPWAT 8.0 model were analyzed by fitting them to various standard frequency distribution models using a

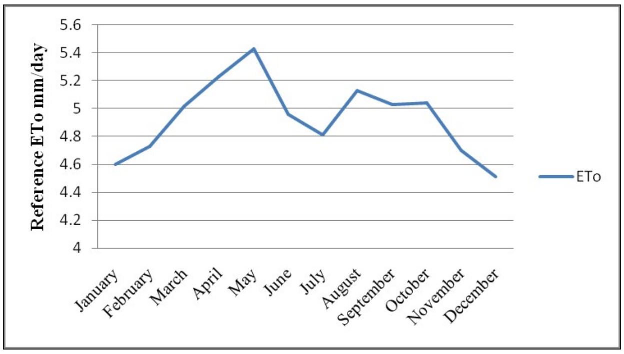

Figure 5. Reference Evaporation in Delta Abyan

computer-based statistical package. The distribution that most closely matched the observed data was selected based on the chi-squared test for goodness of fit. This distribution was subsequently used to estimate the occurrence of ET_0 values at the 80% probability level. The ET_0 values for each month were computed using the formula provided in CROPWAT 8.0. This approach ensures accurate estimation of ET_0, which is crucial for determining crop water requirements and optimizing irrigation scheduling.

$$ET_0 = \frac{0.408 * \Delta * (Rn - G) + \gamma * \frac{900 * u_2 * (es - ea)}{T + 273}}{\Delta + \gamma * (1 + .034 * u_2)} \quad (1)$$

where ET_0 is the reference evapotranspiration (mm/day), Rn is the net radiation at the crop surface $(MJ/m^2/day)$,G is the soil heat flux density $(MJ/m^2/day)$,T is the mean daily air temperature (C^0) at 2 m above the ground, u_2 is the wind speed at 2 m height (m/s), ea is the actual vapor pressure (kPa), es is the saturation vapor pressure (kPa), $(es - ea)$ is the saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa/C^0), and γ is the psychrometric constant (kPa/C^0).

In Delta Abyan crop evapotranspiration of Tomato results of decadal ETc, ER and irrigation requirement (IR) for the major Kharif and Rabi crops cultivated in the Delta Abyan have been shown in Fig.6. The seasonal crop water requirement of Delta Abyan was determined to be 625.9 mm, while the total effective rainfall received throughout the growing Delta Abyan season was 18.1 mm. Irrigation constitutes a significant proportion of the crop water demand. Conversely, effective rainfall accounts for only a small portion of overall crop evapotranspiration. Daily crop evapotranspiration rose from 3.1 mm/day (during the starting stage) to a maximum ET of 5.49 mm/day (during the mid-season stage). The seasonal average crop evapotranspiration rate was 4.3 mm/day.

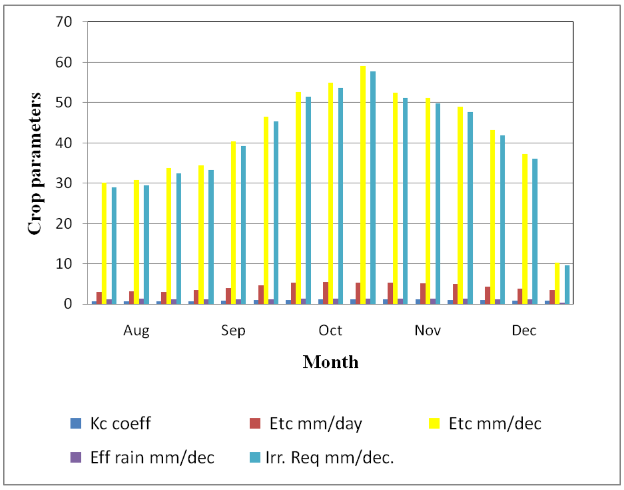

Figure 6. The seasonal crop water requirement of Delta Abyan

3.3. Effective Rainfall Estimation

In arid and semiarid climates, agricultural production is heavily reliant on rainfall. However, not all rainfall is available for crop use, as some is lost through deep infiltration and surface runoff. According to Moseki et al. [16], the amount of water that remains available for plants after accounting for all these losses is known as the effective rainfall. The estimation of effective rainfall values depends on the location of the study area and the amount of rainfall that the region receives. The equations below, as recommended by the US Soil Conservation Service for CROPWAT 8.0, were used to calculate the monthly effective rainfall values [17].

$$P_{eff} = \frac{P * (125 - .3P)}{125} \ (for P \leq 250mm) \quad (2)$$

$$P_{eff} = 125 + 0.1 * P \ (for P > 250mm), \quad (3)$$

Where, P_{eff} represents the effective rainfall (mm) and P is the total rainfall (mm). The effective rainfall values were calculated using Eq.

In Delta Abyan terms of effective rainfall, the maximum value recorded was 5.2 mm, which occurred in January, while the minimum was 2.9 mm, observed in June Table (4). Irrigation is not required based on the total rainfall periods in which the effective rainfall exceeds the crop evapotranspiration (ETc) values. Therefore, crop water requirement (CWR) values were calculated for cases in which ETc values surpassed the effective rainfall.

3.4. Crop coefficient (K_c)

The crop coefficient K_c is a dimensionless factor that represents the ratio of the actual evapotranspiration (ETc) for a specific crop grown under optimal conditions to the reference evapotranspiration (ET_0) of a standardized reference crop, typically a well-watered grass surface. K_c is used to scale the reference evapotranspiration to the specific water demands of a given crop, incorporating

Table 4. Effective Rainfall Data

Month	Rain (mm)	Eff. Rain (mm)
January	5.2	5.2
February	4.2	4.2
March	4.4	4.4
April	3.3	3.3
May	3.7	3.7
June	2.9	2.9
July	3.4	3.4
August	3.8	3.8
September	3.5	3.5
October	4.1	4.1
November	4.1	4.1
December	3.7	3.7
Total	46.3	46.3

variations in growth stage, climatic conditions, and other agronomic factors. By adjusting the ET_0 with the appropriate K_c value, the model provides a more accurate estimation of the crop's water requirements throughout its growing cycle, ensuring better irrigation management and water use efficiency. The crop coefficient is typically expressed as

$$K_c = \frac{ET_c}{ET_0}, \quad (4)$$

where ETc is the actual evapotranspiration of the crop (mm/day) and ET_0 is the reference evapotranspiration (mm/day).

The crop coefficient K_c is dynamic and varies depending on the crop type, growth stage (initial, mid, and late stages), and prevailing environmental conditions. Throughout the different growth phases, K_c is adjusted to reflect the changing evapotranspiration demands of the crop. As the crop transitions through its developmental stages, the K_c value typically increases during the vegetative phase, peaks during the reproductive phase, and decreases as the crop matures, thereby accurately capturing fluctuating water requirements over time. This adjustment allows for a more precise estimation of the crop's water needs, ensuring optimal irrigation management based on the physiological growth and environmental context of the crop.

$$ET_c = K_c * ET_0 \quad (5)$$

where ET_c is the water requirement of the crop. The actual water requirements of the crop can be calculated during each growth stage by multiplying the reference evapotranspiration (ET_0) by the crop coefficient K_c. These values are crucial for the accurate scheduling of irrigation and optimization of water-use efficiency in crop production. The factors influencing the crop coefficient K_c, including crop type, growth stage, and environmental conditions, collectively determine the water demand of the crop and contribute to the temporal variation of K_c across its growth stages. K_c is typically defined for distinct growth phases (initial, mid, and late stages), and other cultivation data, including planting date, harvest date, rooting depth(m), critical depletion, yield response f, and crop height (m), to better align with the crop's evolving water requirements as it progresses through its developmental cycle. These stage-specific adjustments ensure that irrigation scheduling and water management are precisely tailored to the crop's actual evapotranspiration needs, enhancing the overall water use efficiency [18]. In Delta Abyan, the K_c values in the initial, middle, and late phases were 0.6, 1.15, and 0.8, respectively. Table (5) Rooting depths in the initial, mid, and late stages were 0.25 m,1 m, and 1 m, respectively. The critical depletion values in the initial, mid, and late stages were 0.3 m, 0.4 m, and 0.5 m, respectively. Yield responses in the initial, develop, mid, and late stages were 0.5, 0.6, 1.1, and 0.8, respectively. The crop height 0.6 m.

Table 5. Tomato K_c values and cultivation data

Crop Name	Tomato			
Planting date	1-Aug			
Harvest date	23-Dec			
Stage	Initial	Develop	Mid	Late
Length (days)	30	40	45	30
Kc values	0.6	...	1.15	0.8
Rooting depth (m)	0.25	...	1	1
Critical depletion	0.3	...	0.4	0.5
Yield response f.	0.5	0.6	1.1	0.8
Crop height (m)	...	...	0.6	...

3.5. Irrigation Scheduling

The irrigation interval was adjusted based on the growth stage of the tomato crop. As the crop progressed through different growth phases, its water requirements varied, which influenced both the frequency and volume of irrigation. The total net irrigation requirement was 537.1 mm, while the total gross irrigation requirement amounted to 767.2 mm Table (6). The net irrigation requirement refers to the amount of water needed to meet the crop evapotranspiration demand, whereas the gross irrigation requirement includes additional water losses due to factors such as evaporation, runoff, and inefficiencies within the irrigation system. These values are essential for the design of an effective irrigation schedule, as shown in Fig. (7), which fulfills the crop's water requirements while minimizing water loss and enhancing water-use efficiency. Based on Table (6) the first irrigation for the germination stage occurred 12 days after planting with a water amount of 30.1 mm, while the second irrigation took place on day 29 with a water amount of 50.3 mm. Irrigation for the vegetative growth stage started on day 52 with a water amount of 83.2 mm. In the flowering stage, the first irrigation occurred on day 76 with a water amount of 118.8 mm, and the second irrigation took place on day 99 with a water amount of 119.8 mm. Finally, in the maturation stage, irrigation occurred on day 126 with a water amount of 129.9 mm, which is the last irrigation stage for the crop (Fig.7).

Table 6. Irrigation of Tomato scheduling

Data	12-Aug	29-Aug	21-Sep	15-Oct	7-Nov	4-Dec	23-Dec
Day	12	29	52	76	99	126	End
Stage	init	init	Dev	mid	mid	End	End
Rain (mm)	0	0	0	0	0.7	0	0.6
Ks Fract	1	1	1	1	1	1	1
Eta %	100	100	100	100	100	100	100
Depl %	32	31	36	41	41	45	23
Net (mm)	35.1	50.3	83.2	118.8	119.8	129.9	
Irr. Deficit (mm)	0	0	0	0	0	0	
Loss (mm)	0	0	0	0	0	0	
Gr	50.1	71.9	118.8	169.7	171.2	185.5	
Irr. Deficit (mm)	0.48	0.49	0.6	0.82	0.86	0.8	

Total gross irrigation	767.2	mm	Total rainfall	18.5	mm
Total net irrigation	537.1	mm	Effective rainfall	17.9	mm
Total irrigation losses	0	mm	Total rain loss	0.6	mm
Actual water use by crop	622.5	mm	Moist deficit at harvest	67.5	mm
Potential water use by crop	622.5	mm	Actual Irrigation Requirement	604.6	mm

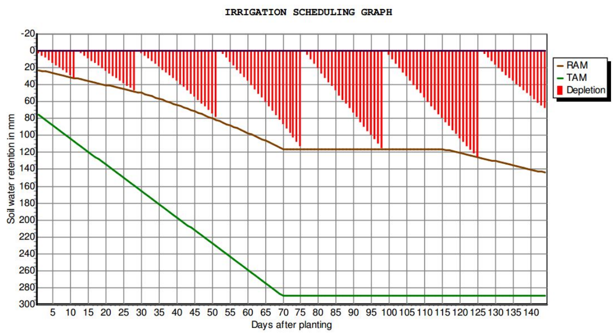

Figure 7. Irrigation Tomato scheduling graph

This study provides accurate estimates of the water requirements for tomato crops using the CROPWAT model, which represents an important step towards improving irrigation management. The water requirements identified for each growth stage of the crop should be considered, as each stage requires varying amounts of water. For example, during the early growth stage, water needs are lower than during the flowering and maturation stages, where water requirements increase significantly. Farmers in Delta Abyan should determine appropriate irrigation schedules and required water amounts based on these needs. These data should be applied using modern irrigation techniques, such as drip irrigation or sprinkler systems, which allow for precise and efficient delivery of water to the roots. Local conditions, such as temperature, humidity, and soil type, should also be monitored, as these factors influence crop water requirements.

4. CONCLUSION

In conclusion, this study aimed to assess the water requirements and irrigation needs of tomato farming in Delta Abyan using the CROPWAT model, which is essential for calculating crop evapotranspiration and developing irrigation plans. The findings indicated that tomatoes rank as the second most water-demanding crop after cotton in the area, despite being grown over an average area of 558 hectares. This underscores the need for efficient irrigation methodologies and sustainable water governance, particularly in regions facing water scarcity, to guarantee the enduring sustainability of crops without exhausting local water supply. To address this issue, an irrigation timetable was established for each developmental phase of the crop. In the germination phase, the initial irrigation should be conducted 12 days post-planting, utilizing 30.1 mm of water, followed by subsequent irrigation on day 29 (50.3 mm. In the vegetative growth phase, the first irrigation should be transpired on day 52, using 83.2 mm of water. During the flowering phase, the first irrigation was executed on day 76 (118.8 mm, and the second irrigation on day 99 (119.8 mm. Finally, in the maturation phase, irrigation should occur on day 126 (129.9 mm, marking the final irrigation for the crop. Moreover, it is crucial to continuously monitor climatic conditions and soil moisture levels to modify the irrigation schedule as needed, thereby augmenting water-use efficiency and ensuring optimal agricultural productivity.

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