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Crop water requirement and irrigation schedule of paddy in South Gujarat Region using the CROPWAT 8.0 model

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Abstract

Water is an essential natural resource for human survival and sustainable agricultural production. This study estimated the crop water requirement and irrigation schedule of paddy in the South Gujarat region using the CROPWAT 8.0 model. The study was conducted in two districts of South Gujarat, namely Valsad and Navsari, using data from 2012–13, 2013–14, 2022–23 and 2023–24 was analysed using climatic, crop and soil information. Reference Evapotranspiration (ET_0) was estimated using the FAO Penman–Monteith equation. The results revealed that the total crop water requirement of paddy ranged from 442.9 to 471.2 mm in Valsad and from 467.6 to 505.4 mm in Navsari. The mid-season growth stage recorded the highest Crop Evapotranspiration (ET_c) in both districts, whereas the nursery and initial growth stages exhibited the lowest ET_c values. Effective Rainfall (P_{eff}) ranged from 576.9 to 729.3 mm in Valsad and from 561.3 to 715.0 mm in Navsari, indicating that rainfall was sufficient to meet the crop water requirement. Furthermore, the actual irrigation requirement was negative in both districts, suggesting that supplemental irrigation was generally unnecessary for paddy cultivation under the prevailing climatic conditions of the South Gujarat region. These findings highlight the significant contribution of effective rainfall in meeting the water demand of paddy and provide useful information for efficient irrigation planning and water resource management in the region.

Keywords: Crop water requirement, irrigation schedule, evapotranspiration, effective rainfall, irrigation requirement, CROPWAT 8.0 model

1. Introduction

Water is an essential resource for human survival and agricultural production, with agriculture accounting for nearly 70 per cent of global freshwater withdrawals. Growing population, climate variability and increasing competition for water among different sectors have intensified the need for efficient irrigation and water management. In this context, estimation of Crop Water Requirement (CWR) is crucial for determining the amount of water needed to meet crop evapotranspiration demands under optimum growth conditions (Allen *et al.*, 1998; Kampman, 2007) [3, 8]. Accurate assessment of CWR helps in planning irrigation schedules, improving water-use efficiency and ensuring sustainable crop production. Proper irrigation scheduling enables water to be applied in the right quantity and at the appropriate time, thereby avoiding both water deficit and excess water application. Consequently, it contributes to higher crop productivity, conservation of freshwater resources and maintenance of soil health. Effective Rainfall (P_{eff}) represents the portion of total rainfall that is effectively utilised by the crop. Irrigation Requirement (IR) is the amount of water that must be supplied through irrigation to meet the crop water demand after accounting for P_{eff} .

Food and Agriculture Organisation (FAO) has developed CROPWAT model for determining the CWR and irrigation scheduling of different crops which has been widely used across the globe for various applications (Boualem, 2023;

Lee and Dang, 2019; Thimmareddy *et al.*, 2023) [7, 10, 14].

Paddy was selected for the present study because it is one of the most important staple food crops and among the most water-intensive crops cultivated in India. In South Gujarat, paddy occupies a major share of the kharif cropped area and plays a significant role in agricultural production and food security. As the crop requires large quantities of water throughout its growing period, accurate estimation of CWR is essential for efficient irrigation scheduling, improving water use efficiency and ensuring sustainable management of increasingly scarce water resources.

2. Materials and Methodology

Gujarat was chosen for the study because of its limited water availability relative to agricultural demand and its diverse climatic conditions. Estimation of CWR can support efficient irrigation planning and sustainable water resource management in the state, which was categorised into four regions, North Gujarat, Middle Gujarat, Saurashtra and South Gujarat. The study focused on the South Gujarat regions, which have the 2nd highest area (2942.59 00'ha) under paddy cultivation (Anon, 2023), favourable climate condition and dominant kharif crop in this region. Representative weather stations Valsad and Navsari from selected region were chosen for the analysis based on highest cultivated area. (Table 1). The crop growth season of paddy considered for the estimation of CWR is presented in Table 2. The paddy

crop growth period was divided into five stages: nursery, initial, crop development, mid-season and late-season. (Allen *et al.*, 1998) [3].

Table 1: Selection of Weather Stations/ Districts for Paddy Cultivation in South Gujarat (2021–23)

Crop	Gujarat Region	District/Weather Station
Paddy	South Gujrat	Valsad
		Navsari

Source: (Anon, 2023)

Table 2: Crop Growth Stages and Corresponding Crop Coefficients for Paddy

Month	Stages of paddy	Duration (days)	Crop coefficient (K _c)
June	Nursery	25	1.05-1.10
July	Initial	15	1.10-1.20
July-Aug	Crop Development	30	1.10-1.40
Aug-Sep	Mid-season	45	1.10-1.30
Sep-Nov	Late Season	30	0.90-1.00

Source: (Reddy and Reddy, 2023) [13]

Data for the years 2012–13, 2013–14, 2022–23 and 2023–24 were collected from various sources based on their availability. The climatic parameters considered for the study included mean maximum temperature (°C), mean minimum temperature (°C), mean relative humidity (%), mean wind speed (km day⁻¹), mean sunshine duration (hours day⁻¹), mean solar radiation (MJ m⁻² day⁻¹) and rainfall (mm month⁻¹). Weather data for the selected regions were obtained from the respective agricultural university of Gujarat. For the South Gujarat region, monthly weather data were collected from the Argo-Meteorological Cell, Department of Agricultural Engineering, N. M. College of Agriculture, Navsari Agricultural University, Navsari. (Anon, 2023b).

The collected climatic data were used to estimate the ET₀. CWR varies across different crop growth stages; therefore, K_c values for paddy were adopted according to the FAO-recommended guidelines (Table 3). Soil parameters, including total available soil moisture (mm m⁻¹), maximum rainfall infiltration rate (mm day⁻¹), maximum rooting depth (cm), initial soil moisture depletion (% of total available moisture) and initial available soil moisture (mm m⁻¹), were also considered following FAO guidelines. (Allen *et al.*, 1998) [3] The CWR was estimated using CROPWAT 8.0 models.

a. Reference Evapotranspiration (ET₀)

The concept of ET₀ was introduced by FAO. ET₀ was calculated on the basis of the FAO Penman - Monteith equation (Allen *et al.*, 1994a; Allen *et al.*, 1994b; Allen *et al.*, 1998; Jayaram, 2016; Memon and Jamsa, 2018; Reddy, 2007; Reddy and Reddy, 2023) [1, 2, 3, 9, 11, 12, 13].

$$ET_0 = \frac{0.408 \Delta(R_n - G) + \gamma 900 / (T + 273) U_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 U_2)}$$

Where,

ET₀ = Reference Crop Evapotranspiration (mm day⁻¹)

R_n = Net Radiation at the Crop Surface (MJ m⁻² day⁻¹)

G = Soil Heat Flux (MJ m⁻² day⁻¹)

T = Average Air Temperature (°C)

U₂ = Wind Speed measured at 2 m height (m s⁻¹)

E_s = Saturation Vapour Pressure (kpa)

E_a = Actual Vapour Pressure (kpa)

(E_s – E_a) = Vapour Pressure Deficit (kpa)

Δ = Slope of the Vapour Pressure Curve (kpa °C⁻¹)

Γ = Psychrometric Constant (kpa °C⁻¹)

b. Crop Water Requirement (CWR)

The CWR was calculated by accumulating the data on the ET_c (mm/day) over the complete growing period.

$$CWR = 10 * ET_c$$

Here, the factor 10 was included to convert mm into m³/ha.

The ET_c was calculated as follows:

$$ET_c = K_c * ET_0$$

Where,

K_c is the Crop Coefficient

ET₀ is the Reference Evapotranspiration in a state (mm/day).

c. Effective Rainfall (P_{eff})

The P_{eff} (Effective Rainfall) was generated from P_{tot} (Total Rainfall) by CROPWAT (FAO, 2023g). CROPWAT calculates with a simplified version of the USDA method. (Dastane, 1978; Kampman, 2007) [15, 8].

$$P_{tot} \leq \frac{250}{30} \rightarrow P_{eff} = P_{tot} * \frac{30}{125} * \left(\frac{125}{30} - 0.2 * P_{tot} \right)$$

$$P_{tot} > \frac{250}{30} \rightarrow P_{eff} = \left(\frac{125}{30} + 0.1 * P_{tot} \right)$$

d. Irrigation Requirement (IR)

Irrigation Requirement = Crop Water Requirement – Effective Rainfall

3. Results and Discussion

a. Crop Water Requirement of Paddy

The stage-wise CWR of paddy in Valsad and Navsari districts of South Gujarat for the years 2012-13, 2013-14, 2022-23 and 2023-24 is presented in Tables 3 and 4, respectively.

The results show that the total CWR of paddy ranged from 442.9 to 471.2 mm in Valsad and 467.6 to 505.4 mm in Navsari, with the highest values, 487.9 mm and 506.5 mm, in Valsad and Navsari, respectively, recorded during 2012–13. The higher CWR can be attributed to increased evapotranspiration during the mid-growth stage and less effective rainfall during the late-season stage, which requires more irrigation. Furthermore, paddy exhibited a declining trend over the decade in both districts. Navsari district shows high CWR in paddy because of less rainfall contribution as compared to Valsad, which needs more additional water requirement.

Among the different crop growth stages, the mid-season stage recorded the highest ET_c values, ranging from 147.3 to 153.8 mm in Valsad and 154.4 to 167.5 mm in Navsari. This was mainly due to full canopy development and peak physiological activity, resulting in maximum transpiration and water demand, along with additional evaporation from standing water in paddy fields. In contrast, lower ET_c values were observed during the nursery and initial stages (20.0 to 41.1 mm and 57.5 to 62.4 mm in Valsad; 18.3 to 21.0 mm and 63.6 to 101.7 mm in Navsari), attributed to limited canopy cover, lower leaf area and reduced crop transpiration during early growth stages.

Table 3: Stage-wise Crop Water Requirement of Paddy in Valsad District of South Gujarat

Transplanting date: 8 th Jul 2012-13				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
11 th Jun - 30 th Jun	Nursery/ LP	20.0	60.1	26.4
8 th July - 30 th Jul	Initial	107.9	154.9	65.4
1 st Aug - 30 th Aug	Development	105.2	140.9	0.0
1 st Sep - 10 th Oct	Mid	154.8	215.2	19.8
11 th Oct - 10 th Nov	Late	100.0	5.8	94.0
	Total	487.9	576.9	205.7
Transplanting date: 5 th Jul 2013-14				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
11 th Jun - 30 th Jun	Nursery/ LP	23.9	121.1	81.4
5 th July - 20 th Jul	Initial	57.5	154.0	0.0
21 st Jul - 20 th Aug	Development	94.0	179.1	0.0
21 st Aug - 30 th Sep	Mid	147.3	255.3	0.0
1 st Oct - 10 th Nov	Late	120.2	3.1	117.1
	Total	442.9	712.6	198.5
Transplanting date: 3 rd Jul 2022-23				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
11 th Jun - 30 th Jun	Nursery/ LP	41.1	89.2	54.9
3 rd July - 20 th Jul	Initial	62.4	151.1	56.0
21 st Jul - 20 th Aug	Development	105.8	188.2	0.0
21 st Aug - 30 th Sep	Mid	148.8	237.9	0.0
1 st Oct - 30 th Oct	Late	113.1	62.7	49.4
	Total	471.2	729.3	160.2
Transplanting date: 9 th Jul 2023-24				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
10 th Jun - 30 th Jun	Nursery/ LP	37.5	90.0	39.8
9 th Jul - 20 th Jul	Initial	57.5	158.6	68.0
21 st Jul - 20 th Aug	Development	102.2	121.8	18.9
21 st Aug - 30 th Sep	Mid	153.8	134.7	23.2
1 st Oct - 30 th Oct	Late	97.0	41.4	56.3
	Total	448.1	546.4	206.1

Note: The sum of stage-wise Crop Evapotranspiration (ET_c) values represents the total CWR for the crop during the entire growing period and LP = Land Preparation.

Table 4: Stage-wise Crop Water Requirement of Paddy in Navsari District of South Gujarat

Transplanting date: 8 th Jul 2012-13				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
11 th Jun - 30 th Jun	Nursery/ LP	39.8	74.9	31.1
8 th Jul - 30 th Jul	Initial	79.6	101.5	70.0
1 st Aug - 30 th Aug	Development	113.0	137.7	0.0
1 st Sep - 10 th Oct	Mid	155.3	235.7	0.0
11 th Oct - 10 th Nov	Late	118.7	11.9	106.9
	Total	506.5	561.5	207.9
Transplanting date: 6 th Jul 2013-14				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
11 th Jun - 30 th Jun	Nursery/ LP	18.3	102.3	28
6 th Jul - 20 th Jul	Initial	63.6	140.8	0.0
21 st Jul - 20 th Aug	Development	104.7	172.9	0.0
21 st Aug - 30 th Sep	Mid	154.4	243.9	0.0
1 st Oct - 10 th Nov	Late	126.6	41.8	84.7
	Total	467.6	701.8	112.7
Transplanting date: 3 rd Jul 2022-23				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
11 th Jun - 30 th Jun	Nursery/ LP	6.8	56.5	26.7
10 th Jul - 30 th Jul	Initial	101.7	224.4	0.0
1 st Aug - 30 th Aug	Development	122.5	177.8	0.0
1 st Sep - 10 th Oct	Mid	163.0	224.8	10.7
11 th Oct - 10 th Nov	Late	111.3	31.6	79.7
	Total	505.4	715.0	117.1
Transplanting date: 7 th Jul 2023-24				
Period	Stage	ET _c (mm)	P _{eff} (mm)	IR (mm)
11 th Jun - 30 th Jun	Nursery/ LP	21.0	84.7	0.0
7 th Jul - 30 th Jul	Initial	94.7	224.9	20.0
1 st Aug - 20 th Aug	Development	77.7	22.3	55.3
21 st Aug - 30 th Sep	Mid	167.5	169.1	29.3
1 st Oct - 10 th Nov	Late	138.4	3.5	132.7
	Total	499.3	504.3	237.4

Note: The sum of stage-wise Crop Evapotranspiration (ET_c) values represents the total CWR for the crop during the entire growing period and LP = Land Preparation.

The P_{eff} varied considerably across the study years, thereby influencing the IR of the crop. The total P_{eff} ranged from 576.9 to 729.3 mm, while IR ranged from 198.5 to 206.1 mm in Valsad. In Navsari, P_{eff} ranged from 561.3 to 715.0 mm, whereas IR varied from 112.7 to 237.4 mm. In both districts, supplemental irrigation was particularly required during the late growth stage to maintain adequate water levels in the paddy fields.

Overall, in both districts, P_{eff} is greater than IR, indicating paddy cultivation in south Gujarat depends on rainfall, there is no need for supplementary irrigation.

The crop water requirement (CWR) of paddy estimated in the present study was generally comparable with the findings of previous studies. Similar CWR ranges were reported by Kumar *et al.* (2024) ^[16] in different agro-climatic zones of Jharkhand (482.5–592.5 mm) and by Nath *et al.* (2022) ^[17] in Shivamogga district (542.4–606.1 mm). The CWR values observed in the selected districts of Valsad and Navsari were broadly consistent with these reported ranges, indicating the reliability of the estimated CWR under varying agro-climatic conditions.

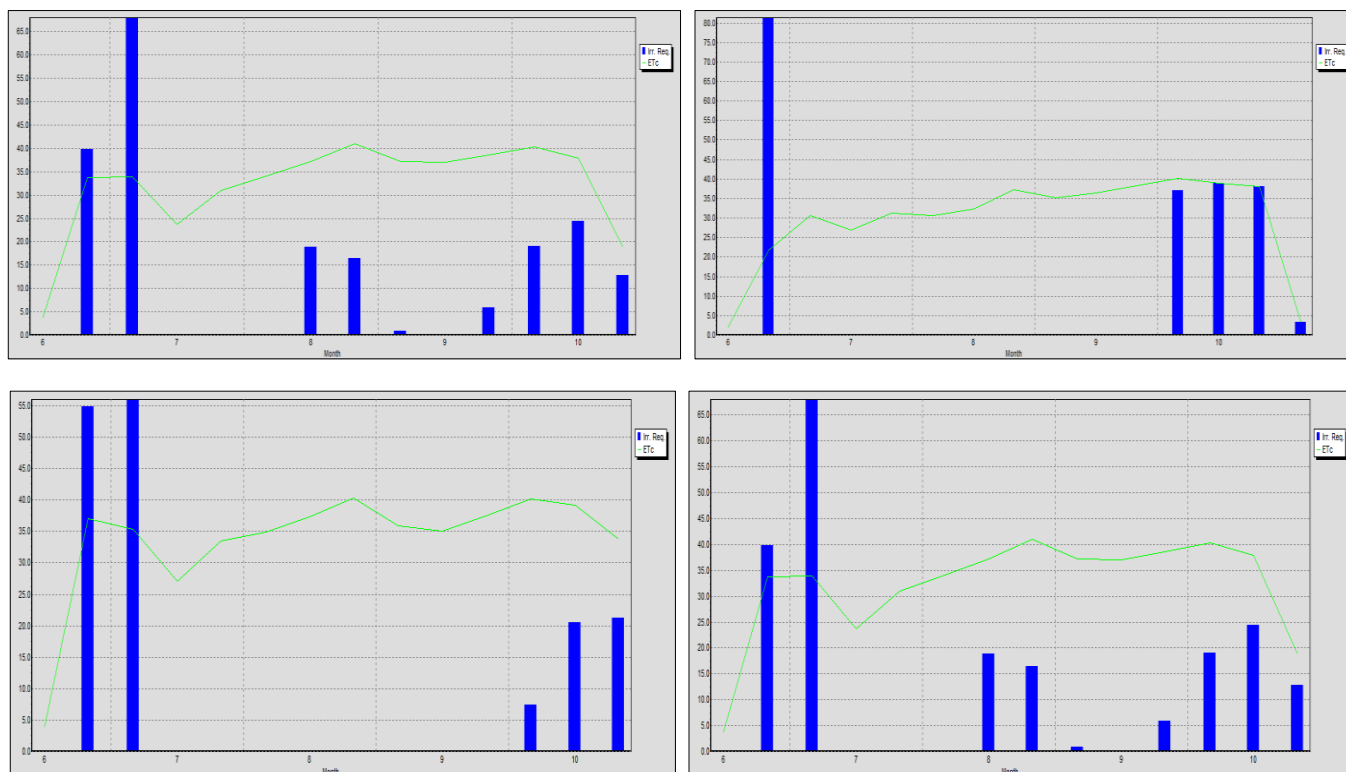
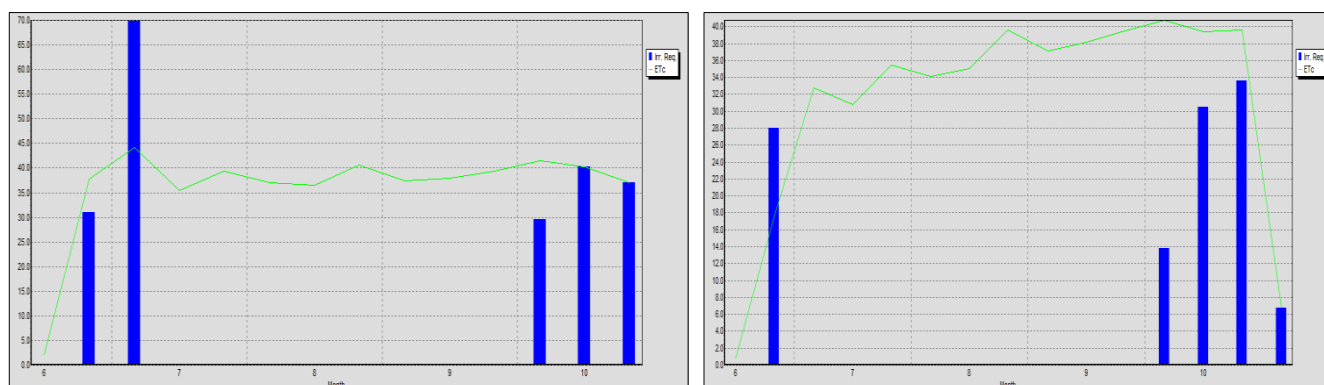


Fig 1: Crop Evapotranspiration and Irrigation Requirement of Valsad District (2012-13 to 2023-24)

Figures 1 and 2 show that for the paddy crop in Navsari and Valsad districts, irrigation is required only during the months when rainfall is insufficient (*i.e.*, outside the monsoon

season). During the monsoon season, rainfall is adequate to meet the crop water requirement (CWR) of paddy in both districts.



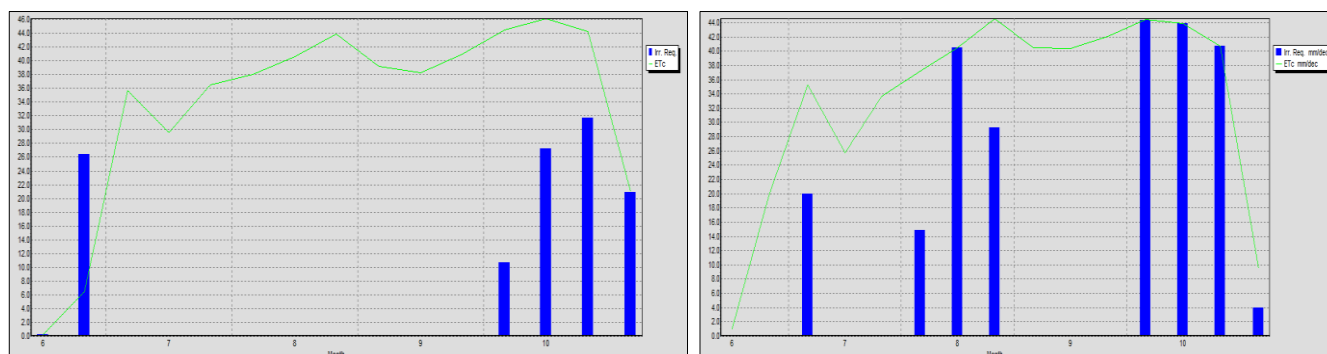


Fig 2: Crop Evapotranspiration and Irrigation Requirement of Navsari District (2012-13 to 2023-24)

b. Irrigation Dynamics of Crop Water Use, Efficiency and Losses of Paddy

Table 5: Irrigation Dynamics of Crop Water Use, Efficiency and Losses of Paddy in Valsad

Particulars	Year			
	2012-13	2013-14	2022-23	2023-24
Total gross irrigation (mm)	566.3	543.7	370.0	869.2
Total net Irrigation (mm)	396.4	380.6	259.0	608.4
Total irrigation losses (mm)	90.0	90.0	60.0	150.0
Total percolation losses (mm)	448.3	513.4	500.8	518.7
Actual water use by crop (mm)	436.5	403.5	419.6	380.3
Potential water use by crop (mm)	436.5	403.5	419.6	380.3
Efficiency irrigation schedule (%)	77.3	76.4	76.8	75.3
Deficiency irrigation schedule (%)	0.0	0.0	0.0	0.0
Total rainfall (mm)	1211.0	2288.5	2227.1	1349.1
Effective rainfall (mm)	666.1	703.6	822.9	539.1
Total rain loss (mm)	544.9	1584.9	1404.2	810.0
Moist deficit at harvest (mm)	0.0	0.0	0.0	0.0
Actual irrigation requirement (mm)	-229.6	-300.1	-403.3	-158.8
Efficiency rain (%)	55.0	30.7	37.0	40.0

The irrigation dynamics of crop water use, efficiency and losses of paddy in Valsad and Navsari districts are presented in Tables 5 and 6, respectively. The predominantly negative actual irrigation requirement across both districts indicates that P_{eff} was generally sufficient to meet the water demand of paddy. Therefore, paddy cultivation in the study area was

primarily rainfall-dependent, with irrigation serving a supplementary role. An irrigation efficiency of 100 per cent was assumed for both districts. High percolation losses were observed in both areas. However, substantial rainfall losses highlight the need for improved rainwater management practices.

Table 6: Irrigation Dynamics of Crop Water Use, Efficiency and Losses of Paddy in Navsari District

Particulars	Year			
	2012-13	2013-14	2022-23	2023-24
Total gross irrigation (mm)	455.0	327.9	322.6	567.7
Total net Irrigation (mm)	318.5	229.5	225.8	397.4
Total irrigation losses (mm)	0.0	0.0	0.0	0.0
Total percolation losses (mm)	402.9	493.2	497.0	474.5
Actual water use by crop (mm)	450.2	429.5	463.0	454.1
Potential water use by crop (mm)	450.2	429.5	463.0	454.1
Efficiency irrigation schedule (%)	100	100	100	100
Deficiency irrigation schedule (%)	0.0	0.0	0.0	0.0
Total rainfall (mm)	1133.7	1985.6	2256.0	1417.5
Effective rainfall (mm)	689.5	850.0	875.2	642.0
Total rain loss (mm)	444.2	1135.7	1380.7	775.5
Moist deficit at harvest (mm)	0.0	0.0	0.0	0.0
Actual irrigation requirement (mm)	-239.3	-420.5	-412.2	-187.9
Efficiency rain (%)	60.8	42.8	38.8	45.3

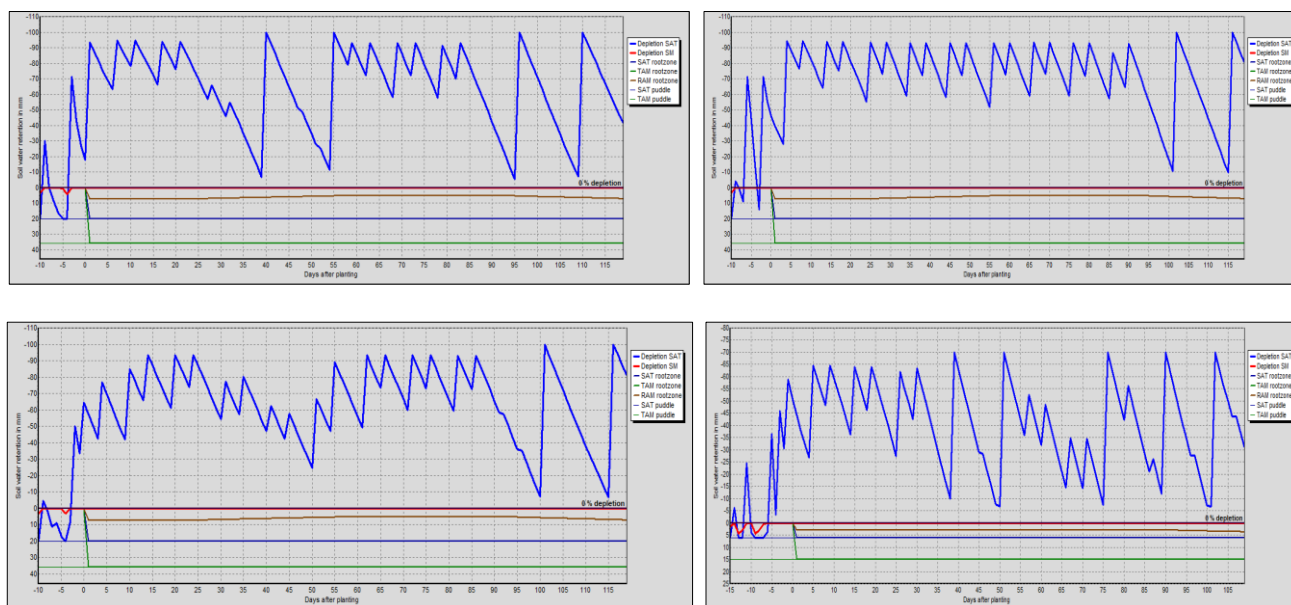


Fig 3: Irrigation Schedule of Valsad District (2012-13 to 2023-24)

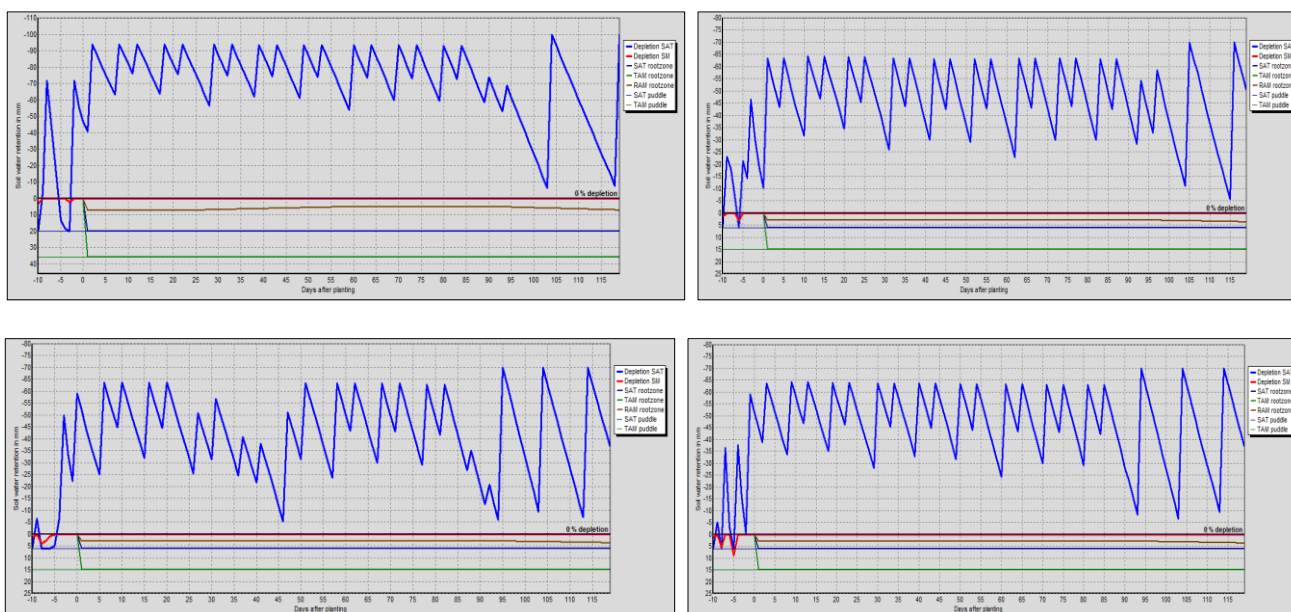


Fig 4: Irrigation Schedule of Navsari District (2012-13 to 2023-24)

4. Conclusion

The Crop water requirement and irrigation schedule of paddy were computed for Valsad and Navsari districts of South Gujarat using CROPWAT 8.0 model. The result revealed that in both district CWR of paddy varies among the different stages. In both district major depends on rainfall it means rainfall is sufficient to meet crop water needs, therefore supplement irrigation is less/not required to in both districts. Navsari District show higher CWR as compare to Valsad district. Higher gross and net irrigation requirement in Valsad district as compare to Navsari district. And both districts show negative actual irrigation requirement and high percolation losses and rainfall losses.

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