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Multiple approaches for estimation of reference evapotranspiration in Halayapura micro-watershed

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Abstract

Reference evapotranspiration (ET_0) is an important hydrological parameter used for estimating crop water requirement, irrigation scheduling, and sustainable water resource management, particularly in semi-arid regions where water scarcity is a major challenge. The present study was carried out in the Halayapura-1 micro-watershed of Tumkur district, Karnataka, India, to estimate and compare ET_0 using four different methods namely CROPWAT model, FAO-56 Penman-Monteith, Hargreaves, and Priestley-Taylor methods for the period 2016-2024. Daily meteorological data including temperature, relative humidity, solar radiation, and wind speed obtained from an Automatic Weather Station (AWS) were used for the analysis. The results showed clear seasonal and annual variations in ET_0 across all methods. Higher ET_0 values were consistently observed during the summer months (March-May) due to increased temperature and solar radiation, whereas lower values occurred during the monsoon and post-monsoon periods because of higher humidity and cloud cover. The annual ET_0 estimated by the CROPWAT model ranged from 1199.03 to 1567.15 mm, while Penman-Monteith values ranged from 1208.21 to 1650.29 mm. The Hargreaves method produced comparatively higher annual ET_0 values ranging from 1302.28 to 1760.72 mm, whereas the Priestley-Taylor method estimated relatively lower values ranging from 1065.36 to 1460.91 mm. Regression analysis revealed strong agreement between the methods and the Penman-Monteith method, with coefficient of determination (R^2) values of 0.9245 for CROPWAT, 0.922 for Hargreaves, and 0.8928 for Priestley-Taylor. Among the evaluated methods, the Hargreaves method showed the closest agreement with the Penman-Monteith method under semi-arid conditions. The study highlights the applicability of simplified ET_0 estimation methods in data-scarce regions and provides useful information for irrigation planning, crop water management, and sustainable utilization of limited water resources in semi-arid micro-watersheds.

Keywords: Reference evapotranspiration, Penman-Monteith, Hargreaves, Priestley-Taylor, CROPWAT, semi-arid region, irrigation scheduling, micro-watershed

1. Introduction

Water is one of the most vital natural resources for life and agriculture. Its demand is rising sharply across the world. Climate variability and population growth are the main drivers. Rapid urbanization has added further pressure on limited supplies. Irrigated agriculture alone consumes more than 80 per cent of available water in arid regions. Efficient water management has therefore become a global priority (Al-Ghobari, 2000) [2]. Semi-arid regions face the greatest water stress. Rainfall is scarce and unevenly distributed here. Evaporative demand remains consistently high through the year. Agricultural production in these areas depends heavily on irrigation. Accurate estimation of crop water requirement is essential under such conditions. This requirement is best derived from reference evapotranspiration (ET_0). Evapotranspiration (ET) is a key process in the hydrological cycle. It links the surface water balance with the surface energy balance (Zhao *et al.*, 2013) [25]. ET represents combined water loss from soil and vegetation. Evaporation dominates from bare soil during early crop stages. Transpiration becomes dominant once the canopy fully develops (Rosenberg *et al.*, 1983; Mavi and Tupper, 2004) [19, 15]. ET is closely linked to crop growth, drought monitoring and irrigation scheduling (Allen *et al.*, 2007; Mousumi *et al.*, 2019) [3, 16].

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Direct measurement of crop evapotranspiration is difficult in practice. Lysimeters and micrometeorological systems are costly to install. Their operation also demands continuous skilled maintenance (Rosenberg *et al.*, 1983) ^[19]. Reference evapotranspiration was therefore introduced as a practical alternative. It quantifies the evaporative demand of a hypothetical reference surface. This surface is independent of crop type, growth stage, and management (Allen *et al.*, 1998) ^[1]. Numerous methods exist for estimating ET_o . Development of these methods began in the nineteenth century (Brutsaert, 1982) ^[7]. Xu and Singh (2002) ^[24] grouped them into six broad categories. These are water budget, mass transfer, combination, radiation based, temperature based, and pan evaporation methods. Harbeck (1962) ^[10] contributed early work on mass-transfer based evaporation estimation. Thornthwaite (1948) ^[23] proposed one of the first temperature-based classifications for climate and water balance studies.

Penman (1948) first combined energy balance and aerodynamic principles for open-water evaporation. Monteith (1965) extended this approach by adding canopy and surface resistance terms. This combination became the basis of the Penman-Monteith method. The FAO-56 Penman-Monteith method is now the globally accepted standard (Allen *et al.*, 1998) ^[1]. Its strong physical basis gives reliable results across diverse climates (Pereira *et al.*, 2015; Feng *et al.*, 2016; Tabari *et al.*, 2013) ^[17, 9, 22].

The Penman-Monteith method, however, needs extensive meteorological inputs. Temperature, humidity, wind speed, and solar radiation must all be recorded accurately. Such complete datasets are often unavailable in developing regions. Simpler empirical methods have therefore gained wide acceptance as alternatives. The Hargreaves method estimates ET_o using only temperature data. The Priestley-Taylor method relies mainly on radiation and temperature.

These simplified methods reduce data requirements considerably. Their accuracy, however, varies with local climatic conditions. Advective energy from dry surroundings can inflate evapotranspiration estimates (Tanner, 1967). Local calibration is therefore recommended before wider application. Berti *et al.* (2014) ^[6] reported Hargreaves overestimation of ET_o in north-eastern Italy. Aschonitis *et al.* (2015) ^[5] reassessed Priestley-Taylor performance under Italian climatic conditions.

CROPWAT software offers a further practical option for ET_o estimation. It applies the FAO-56 Penman-Monteith equation internally (Reddy *et al.*, 2020) ^[18]. It further supports crop water requirement and irrigation scheduling calculations. Saha *et al.* (2018) ^[20] used CROPWAT for barley water requirement estimation in Punjab. Reddy *et al.* (2020) ^[18] applied it for irrigation planning in Raichur, Karnataka. Both studies confirmed its practical value for Indian field conditions. Comparative evaluation of ET_o methods is an active research area worldwide. Lang *et al.* (2017) ^[12] compared eight methods against Penman-Monteith in south-western China. Karimi *et al.* (2017) ^[11] tested method performance across humid stations in South Korea. Chattopadhyay and Hulme (1997) ^[8] examined evaporation trends

over India under climatic change. Shahid (2011) ^[21] linked climate change to rising irrigation demand in Bangladesh. These studies confirm that method performance is strongly climate dependent.

Semi-arid watersheds present particular estimation challenges. Temperature swings are large across seasons here. Wind-driven advection is also common in open agricultural land. Simplified methods may therefore show systematic bias under such conditions. Local performance evaluation is essential before any method is adopted for irrigation planning. Comparative studies of this kind remain limited for Karnataka's semi-arid micro-watersheds.

The Halayapura-1 micro-watershed reflects these regional challenges closely. It lies within the Eastern Dry Zone of Karnataka. Annual rainfall here is both scarce and erratic. Groundwater pumping through bore wells is therefore common practice. Accurate ET_o estimation is essential for sustainable groundwater use in this setting. An Automatic Weather Station was recently installed here under the REWARD project. This has created a valuable long-term dataset for local method comparison. No earlier study has compared multiple ET_o methods for this micro-watershed. This is a clear gap in the local knowledge base. Filling this gap can guide method selection for similar semi-arid watersheds elsewhere. It can also support day-to-day irrigation decisions taken by local farmers. The present study was designed to address this need directly. The present study was carried out with the following specific objectives:

1. To estimate the monthly and annual reference evapotranspiration (ET_o) of the Halayapura-1 micro-watershed using the CROPWAT, FAO-56 Penman-Monteith, Hargreaves, and Priestley-Taylor methods for the period 2016-2024, and to assess their seasonal and inter-annual variations.
2. To identify the most suitable reference evapotranspiration estimation method for irrigation scheduling and water resource planning under the semi-arid conditions of the study area.

2. Materials and Methods

The Halayapura-1 micro-watershed henceforth nomenclatured as study area is a part of Hosalaya sub-watershed, Tumkur Taluk and District covering an area of 503 ha is located at North latitudes 13°08'31" to 13°10'04" and East longitudes 77°05'45" to 77°07'19" spread across Thondagere, Niduvalalu, Chikkanahalli and Thavarekere, Thondagere Kavalu and Sugganahalli villages. The micro watershed code is 4B3C5n1 and is located at an elevation of 840 m above mean sea level (MSL) (Fig.1).

The study area is a part of the Eastern Dry-Zone of Karnataka. December is the coldest month with mean daily minimum temperature of 16.50 °C, while May is the hottest month with mean daily maximum temperature of 38.10° C. Relative humidity of over 87 per cent is common during monsoon period. Wind speed exceeding 25.8 km/h during the months of July and August.

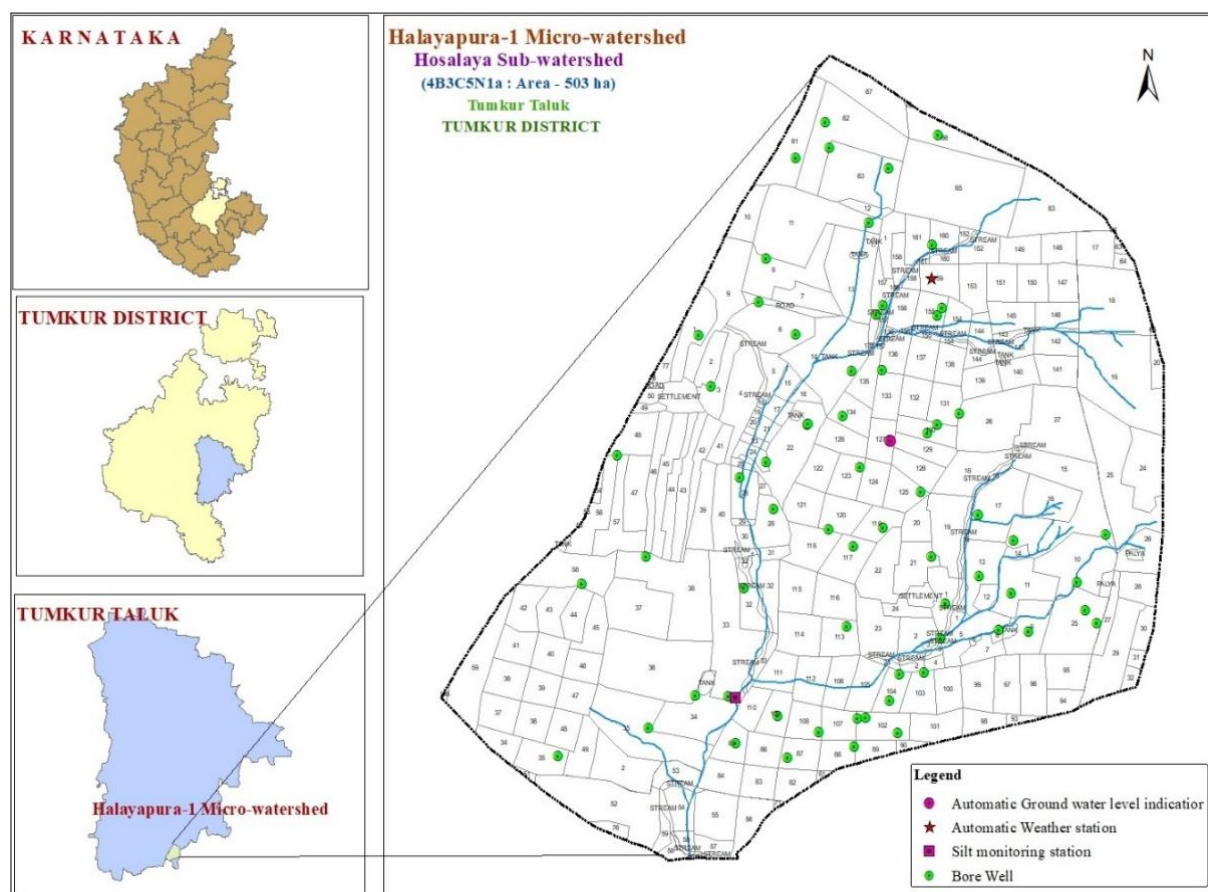


Fig 1: Location map depicting the study area of the Halayapura-1 micro-watershed

The study used observed daily weather data of maximum and minimum temperature ($^{\circ}\text{C}$), relative humidity (%), wind speed (ms^{-1}), solar radiation ($\text{MJ m}^{-2} \text{d}^{-1}$) were monitored from an Automatic Weather Station (AWS) integrated with net radiometer system installed in the study area under the world bank assisted project viz. Rejuvenating watersheds for agricultural resilience through innovative technique and development (REWARD), UAS GKVK Bangalore. In the present study, the weather data recorded at 15-minute intervals were first aggregated into hourly values using Microsoft Excel. The temperature data were organized by creating separate columns for maximum and minimum temperature.

The performances of the CROPWAT, Penman-Monteith, Hargreaves (HAG, temperature-based) and Priestley-Taylor (PT, radiation-based) methods were evaluated. Data requirements for a particular model and the available data at the station were the main factors in selecting the alternative methods for comparison. CROPWAT is decision support software developed by the FAO (Food and Agriculture Organization) to assist in the planning and management of irrigation. The required meteorological inputs, including maximum and minimum temperature, relative humidity, wind speed, and solar radiation, were imported into the software for the study period. It helps to estimate crop water requirements and irrigation scheduling based on climate, crop, and soil data. The software uses the FAO Penman-Monteith method for calculating reference evapotranspiration (ET_0) CROPWAT also evaluates the impact of water deficits on crop yield.

The FAO-56 Penman-Monteith equation (Allen *et al.*, 1998) [1] was used as the reference method for estimating ET_0 because it incorporates both energy balance and aerodynamic components. Daily meteorological observations from the AWS were used in

the calculations. For daily time-step calculations, the soil heat flux was assumed to be zero ($0 \text{ MJ m}^{-2} \text{ day}^{-1}$), as recommended in FAO-56. Wind speed measured by the AWS was standardized to the 2 m reference height. Penman-Monteith equation is mathematically expressed and given below:

$$\text{ET}_0 = \frac{0.408\Delta(R_n - G) + y \frac{900}{T + 273} U(e_s - e_a)}{\Delta + y(1 + 0.34U)}$$

where,

ET_0 = reference evapotranspiration, mm

R_n - net radiation at the crop surface, $\text{MJ/m}^2/\text{day}$

G - soil heat flux density, $\text{MJ/m}^2/\text{day}$

T - mean daily air temperature at 2 m height, $^{\circ}\text{C}$

U - wind speed at 2 m height, m/s

e_s - saturation vapour pressure, kPa

e_a - actual vapour pressure, kPa

$(e_s - e_a)$ - saturation vapour pressure deficit, kPa

Δ - slope vapour pressure curve, $\text{kPa}/^{\circ}\text{C}$

y - psychrometric constant, $\text{kPa}/^{\circ}\text{C}$

The Hargreaves method was applied using daily maximum and minimum air temperature together with extraterrestrial radiation to estimate reference evapotranspiration. Hargreaves *et al.* (1985) proposed a method for estimating ET_0 using data on temperature and latitude. The method can be expressed as

$$\text{ET}_0 = 0.0023 \times Ra \times (T + 17.8) \times \text{TD}^{0.50}$$

Where,

T = mean daily air temperature at 2 m height, $^{\circ}\text{C}$

Ra = extra-terrestrial radiation, ($\text{MJ/m}^2/\text{day}$)

TD = min and max temperature difference, °C

The Priestley–Taylor method was applied using net radiation and temperature data obtained from the AWS. A Priestley-Taylor coefficient a_{pt} of 1.26 was adopted, which the standard value is recommended for reference evapotranspiration estimation in the absence of local calibration (Allen *et al.*, 1998) ^[1].

$$ET_r = a_{pt} \times \frac{\Delta}{\Delta + \gamma} (R_n - G)$$

Where,

ET_r = Reference evapotranspiration

Δ = slope of the vapour pressure curve in [kPa/°C]

γ - Psychrometric constant [kPa/°C]

R_n - net radiation at the crop surface [MJ/m²/day]

G - Soil heat flux density [MJ/m²/day]

a_{pt} = is a parameter equal to 1.26 for humid climates, equal to 1.74 for arid and equal 1.50 climates.

Coefficient of determination is widely used to evaluate the goodness of fit. It ranges from 0.0 to 1.0, with higher values indicating better agreement and was calculated by using the following equation;

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

where,

y_i = Observed (actual/reference) value

$\hat{y}_i$ = Predicted (estimated) value

$\bar{y}$ = Mean of the observed values

n = Number of observations

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2}$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |P_i - O_i|$$

Where:

P_i = predicted ET_o value

O_i = observed/reference ET_o value (Penman-Monteith)

n = number of observations

3. Results and Discussion

The reference evapotranspiration (ET_o) was estimated using CROPWAT model from the year 2016 to 2024 for the Halayapura-1 micro-watershed (Table1). The results indicate considerable monthly, seasonal, and inter-annual variation in ET_o , which is primarily influenced by prevailing climatic conditions such as temperature, solar radiation, humidity and wind speed in the area.

It is evident that the highest monthly ET_o values were consistently observed during the summer months, particularly in March, April, and May, with values exceeding 150 mm in some years and ranging from 140.19 to 170.74 mm during 2016-2024 (Table1). This is due to higher temperatures and increased evaporative demand during the period, it is evident that the evaporative demand was met by supplying water through irrigation using groundwater in addition to rainfall since, the micro-watershed has more number of bore wells (63 no.) and pumping water during scanty rainfall/dry spells situation is quite common. Conversely, the lowest ET_o values were recorded during July, September and November, with a lowest value of 93.37mm in September, 2016 coinciding with the monsoon and post-monsoon periods, where increased cloud cover has reduced radiation effect reduced the evaporative demand.

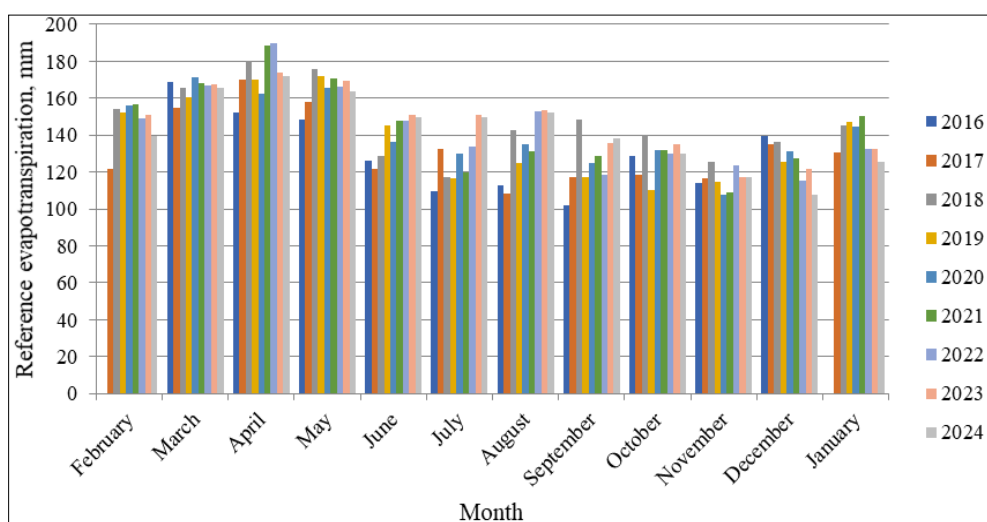
The annual total ET_o ranged from a minimum of 1199.03 mm in 2016 to a maximum of 1567.15 mm in 2018. This variation, highlights the inter-annual climatic fluctuations indicating varied crop water requirements in the watershed. On an average, the annual ET_o values for the study period was around 1450 mm indicating a moderately high evaporative demand in the region. The similar observation recorded by Reddy *et al.*, 2020 ^[18] with the result of Evapotranspiration ET_o and monthly effective rainfall calculated using CROPWAT model. The ET_o was low in December (63.34 mm/month), increased during the Jan-May, reached maximum value of 170.70 mm/months. Saha *et al.*, 2018 ^[20] reported that the monthly ET_o during the barley growing season was higher at Ludhiana (2.74 mm day⁻¹) than at Gurdaspur (2.17 mm day⁻¹), with maximum values observed in April and minimum in December. The higher ET_o at Ludhiana was attributed to higher temperature, wind speed, sunshine hours, and lower relative humidity.

Table 1: Estimated reference evapotranspiration using CROPWAT model during 2016 to 2024

Sl. No.	Month	ET _o (mm)								
		2016	2017	2018	2019	2020	2021	2022	2023	2024
1	February	-	117.37	133.93	134.86	140.42	144.47	129.74	137.18	123.56
2	March	158.28	141.74	150.37	147.78	159.05	154.84	153.74	155.16	148.6
3	April	154.12	159.49	158.94	156.42	150.6	168.58	170.74	159.91	152.43
4	May	140.24	140.19	160.3	158.73	149.5	159.26	146.08	140.36	153.19
5	June	106.54	127.03	110.92	120.13	122.47	122.41	125.32	135.8	138.47
6	July	95.01	112.35	115.24	101.85	117.65	109.29	111.87	133.45	140.45
7	August	112.93	122.37	128.25	109.85	120.18	123.35	113.16	124.54	139.5
8	September	93.37	112.75	131.84	100.87	108.83	112.23	102.19	121.25	126.21
9	October	123.33	114.4	128.44	111.17	114.48	109.33	125.46	119.45	121.3
10	November	107.08	102.96	110.7	99.3	95.87	92.5	116.25	112.22	99.67
11	December	108.13	111.06	117.07	108.76	108.61	108.31	93.95	103.56	92.87
12	January	-	109.77	121.15	122.08	133.96	125.69	109.67	118.74	110.12
	Total	1199.03	1471.48	1567.15	1471.80	1521.62	1530.26	1498.17	1561.62	1546.31

Table 2: Estimated reference evapotranspiration by Penman-Monteith method during 2016 to 2024

		ET _o (mm)								
Sl. No.	Month	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	February	-	110.94	142.87	142.45	147.87	148.97	137.63	145.56	128.98
2	March	158.29	146.25	159.87	153.67	163.87	162.87	157.89	159.89	156.14
3	April	144.06	157	172.67	160.22	153.89	178.07	180.34	162.62	163.86
4	May	139.56	148.87	164.87	163.32	156.98	162.76	158.11	156.88	154.98
5	June	116.65	111.93	120.76	135.67	124.59	138.46	138.16	142.39	140.4
6	July	98.64	121.87	108.65	106.88	121.87	110.51	122.44	141.89	139.73
7	August	103.65	98.22	133.6	115.87	125.98	116.7	121.22	143.91	142.35
8	September	92.54	108.34	138.87	107.67	113.57	119.45	108.16	126.11	128.34
9	October	119.45	120.45	130.9	101.05	120.68	120.48	121.23	124.24	119.35
10	November	104.74	105.81	114.42	106.15	98.57	99.71	112.95	107.58	108.35
11	December	130.63	124.98	127.19	115.72	121.9	118.87	104.34	110.91	98.35
12	January	-	121.90	135.62	137.67	135.87	139.87	121.45	123.56	116.87
	Total	1208.21	1476.54	1650.29	1546.31	1585.64	1616.72	1586.92	1645.54	1597.00

**Fig 2:** Monthly reference evapotranspiration estimated using Hargreaves method for the year 2016 to 2024**Table 3:** Estimated reference evapotranspiration using the Priestley-Taylor method during 2016 to 2024

		ET _o (mm)								
Sl.No	Month	2016	2017	2018	2019	2020	2021	2022	2023	2024
1	February	-	128.98	125.87	129.51	124.87	135.89	120.76	130.87	112.87
2	March	138.87	130.76	141.87	141.8	146.98	143.87	139.98	142.87	139.87
3	April	134.76	149.98	151.76	150.53	147.87	155.87	160.98	145.98	150.98
4	May	130.65	151.87	146.65	152.16	142.87	150.98	146.65	140.65	144.98
5	June	95.97	119.98	105.76	124.85	102.87	110.87	120.87	123.52	134.87
6	July	83.87	92.87	100.76	94.23	110.98	98.98	110.87	129.98	117.98
7	August	87.87	105.26	115.65	104.72	112.98	101.98	105.98	118.98	125.98
8	September	82.87	94.87	121.65	92.03	101.87	114.98	95.98	107.42	116.98
9	October	107.76	91.87	114.65	90.87	108.87	108.98	110.87	102.98	104.98
10	November	95.87	95.87	103.66	96.76	86.56	86.98	100.54	91.98	93.37
11	December	106.87	101.25	116.87	103.71	107.98	103.98	94.98	102.98	86.98
12	January	-	122.65	115.76	113.91	120.98	123.52	114.98	112.76	104.76
	Total	1065.36	1386.21	1460.91	1395.08	1410.68	1436.88	1423.44	1450.97	1434.60

The ET_o was calculated using different methods namely Penman-Monteith, Priestley-Taylor and Hargreaves are discussed in the following sections. The estimated monthly and annual reference evapotranspiration values obtained using the Penman-Monteith method for the period 2016-2024 are given in Table 2. The results showed that ET_o varied across the months, with relatively higher values recorded during the summer season (March to May), ranging from 163.87 to 164.87 mm reflecting the impact of high temperatures and solar radiation. The monsoon months such as July and August showed comparatively lower values ranging from 98.64 to 111.93 mm which can be attributed to increased cloud cover in turn low solar radiation that reduced the

evaporative demand. The total annual ET_o ranged between 1208.21 mm in 2016 and 1650.29 mm in 2018, indicating year-to-year variability in climatic conditions that directly influence water requirements for crops in the watershed Lang *et al.*, (2017) [12] studied in western China and got similar results with respect to their climatic regions.

The ET_o estimated using the Hargreaves method for the years 2016 to 2024 are shown in Fig.2. Similar to other methods, the highest monthly values were observed during the summer months, particularly in March, April, and May ranging from 148.69 to 189.99 mm when higher temperatures lead to greater evaporative demand. The monsoon and post-monsoon months

exhibited relatively lower values ranging from 101.68 to 140.37 mm consistent with reduced temperature and increased cloudiness. The annual totals ranged between 1302.28 mm in 2016 and 1760.72 mm in 2018, indicating inter-annual variability influenced by climatic conditions. These results emphasize the importance of understanding seasonal evapotranspiration dynamics for effective water management in the micro-watershed especially where irrigation is being done using harvested water and pumping from bore wells strictly following irrigation scheduling and micro irrigation methods. The Hargreaves method in the present study showed comparatively higher ET_o values during summer months, which may be attributed to its strong dependence on temperature. Hargreaves depends mainly on temperature. Semi-arid regions have high temperature amplitude. Therefore overestimation occurs during hot months. Similar observations were reported in Berti. *et al.*, 2014 [6] studies where the uncalibrated Hargreaves method overestimated ET_o by about 18.9% with a mean error of 0.44 mm d^{-1} , and the discrepancies became more pronounced during summer, reaching nearly 1 mm d^{-1} . This indicates that although the Hargreaves method performs reasonably well in semi-arid conditions with limited climatic data, it tends to overestimate. s

The monthly and annual ET_o estimated using the Priestley-Taylor method are given in Table 3. The results reveal consistently high values ranging from 146.98 to 152.16 mm during the pre-monsoon summer months (March to May). This suggests a significant evaporative demand during the dry season, necessitating careful irrigation scheduling coupled with water

stress condition of crops. The lowest monthly values were observed during the monsoon and post-monsoon months (July to October), when increased atmospheric humidity and reduced net radiation limit evapotranspiration. The annual totals varied from 1065.36 mm in 2016 to 1460.91 mm in 2018, reflecting fluctuations in climatic factors such as temperature and radiation. Priestley-Taylor ignores aerodynamic term under semi-arid windy conditions, aerodynamic demand is important. Hence Priestley -Taylor underestimates ET_o . The obtained annual ET_o values are comparable with studies conducted by Aschonitis *et al.*, 2015 [5] in Italy, Similar findings were reported, where regions with extremely high ET_o values ($>1300 \text{ mm year}^{-1}$) were mainly observed in hot lowland areas, while mountainous regions exhibited much lower ET_o values ($<500 \text{ mm year}^{-1}$).

As shown in Fig.4 and Table.4, among the evaluated methods, the CROPWAT model showed the best performance with the lowest RMSE (68.02 mm) and MAE (60.64 mm) values along with the highest coefficient of determination ($R^2 = 0.9245$). The lower error statistics indicate a very close agreement between the CROPWAT model and the Penman-Monteith method. This strong relationship is expected because the CROPWAT software internally uses the FAO-56 Penman-Monteith equation for ET_o estimation. The high R^2 value suggests that the model can effectively explain the variability in evapotranspiration under the climatic conditions of the study area. Therefore, the CROPWAT model can be considered highly suitable for irrigation scheduling and crop water requirement estimation in the Halayapura-1 micro-watershed.

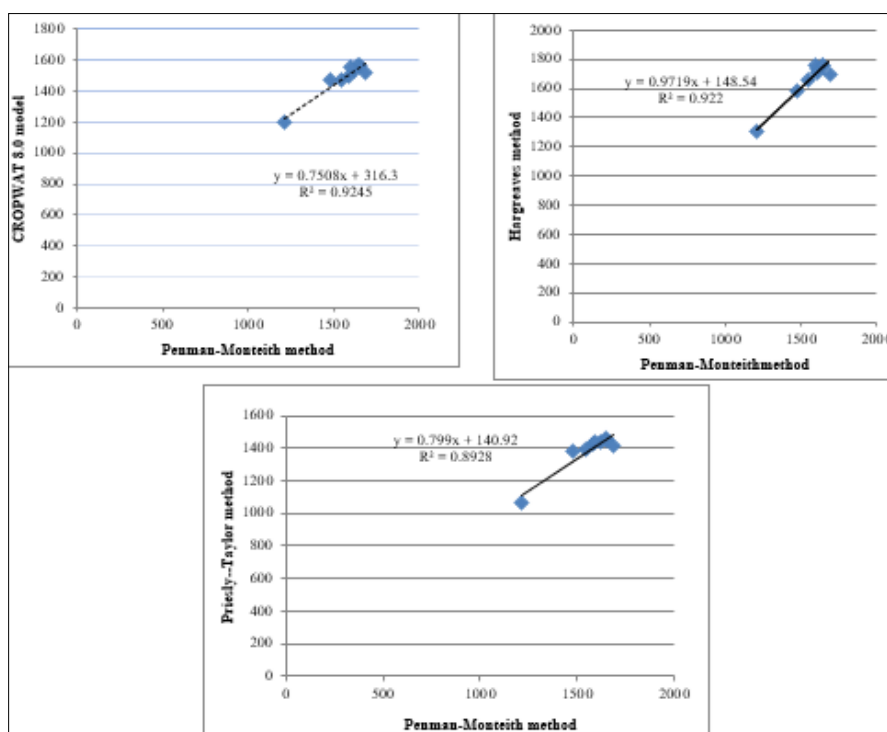


Fig 4: Correlation analysis of ET_o Estimation with Penman-Monteith method

Table 4: Statistical analysis

Method	RMSE	MAE	R^2
CROPWAT	68.02	60.64	0.9245
Hargreaves	117.71	115.96	0.922
Priestley-Taylor	163.71	161	0.8928

The Hargreaves method also demonstrated good agreement with the Penman-Monteith method, with an R^2 value of 0.922. However, the RMSE (117.71 mm) and MAE (115.96 mm) values

were comparatively higher than those of the CROPWAT model, indicating moderate deviation from the standard method. The relatively higher error values may be attributed to the temperature-based nature of the Hargreaves equation, which does not incorporate important aerodynamic parameters such as humidity and wind speed. Under semi-arid conditions, where temperature fluctuations are high, the method tends to overestimate evapotranspiration, particularly during summer months. Nevertheless, because of its simplicity and minimal

climatic data requirement, the Hargreaves method remains useful for data-scarce regions.

The Priestley-Taylor method recorded the highest RMSE (163.71 mm) and MAE (161 mm) values with the lowest R^2 value (0.8928) among the evaluated methods. These results indicate comparatively lower accuracy and weaker agreement with the Penman-Monteith method. The comparatively poor performance of the Priestley-Taylor method may be due to the exclusion of aerodynamic components in its formulation. In semi-arid and windy climatic conditions, aerodynamic effects significantly influence evapotranspiration processes, and neglecting these factors can lead to underestimation of ET_o values. Hence, the Priestley-Taylor method may be less reliable for estimating evapotranspiration in the study area without local calibration.

The estimation of reference evapotranspiration from 2016 to 2024 using different approaches highlights clear seasonal and annual variations in water demand within the study area. Higher ET_o values were observed during the summer months, indicating greater evaporative demand, while lower values occurred during the monsoon and post-monsoon periods. The annual totals showed noticeable inter-annual variability, reflecting the influence of changing climatic conditions. These results provide a reliable basis for understanding crop water requirements and planning irrigation schedules. Overall, the findings emphasize the importance of evapotranspiration studies for sustainable water resource management in the micro-watershed.

4. Conclusion

The present study evaluated and compared reference evapotranspiration (ET_o) estimated using the CROPWAT model, Penman-Monteith, Hargreaves, and Priestley-Taylor methods for the Halayapura-1 micro-watershed under semi-arid climatic conditions during the period 2016–2024. The results revealed clear seasonal and inter-annual variations in ET_o , with higher evapotranspiration observed during the summer months (March-May) due to elevated temperature and solar radiation, while lower values occurred during the monsoon and post-monsoon periods because of increased humidity and cloud cover.

Among the methods evaluated, the CROPWAT and Hargreaves methods produced comparatively higher annual ET_o values, indicating greater sensitivity to temperature variations and a tendency to overestimate evapotranspiration under hot semi-arid climatic conditions. In contrast, the Priestley-Taylor method generated relatively lower ET_o estimates because it primarily depends on radiation parameters and does not adequately account for aerodynamic effects. The FAO Penman-Monteith method, which incorporates multiple meteorological parameters, provided more reliable and physically based ET_o estimates and was therefore considered the standard method for comparison.

Regression analysis revealed strong agreement between all methods and the Penman-Monteith method, with coefficient of determination values greater than 0.89. Among the evaluated methods, the CROPWAT model showed the highest agreement with the Penman-Monteith method ($R^2 = 0.9245$), followed closely by the Hargreaves method ($R^2 = 0.922$), indicating that both methods are suitable for estimating reference evapotranspiration in data-scarce semi-arid regions.

Overall, the study demonstrates that all the evaluated methods can effectively estimate reference evapotranspiration under semi-arid conditions, although their performance varies depending on climatic factors. The findings provide useful information for irrigation scheduling, crop water requirement estimation, and sustainable water resource management in the micro-watershed. The study also highlights the importance of selecting appropriate

ET_o estimation methods for efficient utilization of limited water resources in semi-arid agricultural regions.

References

- Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper No. 56. Rome: Food and Agriculture Organization; 1998. p. 300.
- Al-Ghobari HM. Estimation of reference evapotranspiration for southern region of Saudi Arabia. *Irrigation Science*. 2000;19(2):81-86.
- Allen RG, Tasumi M, Trezza R. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC) model. *Journal of Irrigation and Drainage Engineering*. 2007;133(4):380-394.
- Andrade JAV, Ventura R. Estimation of reference evapotranspiration by Hargreaves-Samani and Penman-Monteith methods in Mediterranean environment (Portugal). *Finisterre*. 2024;59(127).
- Aschonitis V, Demertzi K, Papamichail D, Colombani N, Mastrocicco M. Revisiting the Priestley-Taylor method for the assessment of reference crop evapotranspiration in Italy. *Italian Journal of Agrometeorology*. 2015;20(2):5-18.
- Berti A, Tardivo G, Chiaudani A, Rech F, Borin M. Assessing reference evapotranspiration by the Hargreaves method in north-eastern Italy. *Agricultural Water Management*. 2014;140:20-25.
- Brutsaert W. Evaporation into the atmosphere. Dordrecht: Reidel Publishing Company; 1982.
- Chattopadhyay N, Hulme M. Evaporation and potential evapotranspiration in India under conditions of recent and future climatic change. *Agricultural and Forest Meteorology*. 1997;87:55-74.
- Feng Y, Cui N, Gong D, Wang H, Gao L. Estimating rainfed spring maize evapotranspiration using a modified dual crop coefficient approach based on leaf area index. *International Agricultural Engineering Journal*. 2016;25(3):99-108.
- Harbeck GE. A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory. U.S. Geological Survey Professional Paper 272-E. Washington (DC): U.S. Government Printing Office; 1962.
- Karimi S, Kisi O, Kim S, Nazemi AH, Shiri J. Modelling daily reference evapotranspiration in humid locations of South Korea using local and cross-station data management scenarios. *International Journal of Climatology*. 2017;37(7):3238-3246.
- Lang D, Zheng J, Shi J, Chen X, Ma X, Wang W, *et al.* A comparative study of potential evapotranspiration estimation by eight methods with the FAO Penman-Monteith method in southwestern China. *Water*. 2017;9(10):734.
- Legates DR, McCabe GJ. Evaluating the use of goodness-of-fit measures in hydrologic and hydroclimatic model validation. *Water Resources Research*. 1999;35(1):233-241.
- Lu J, Sun G, McNulty SG, Amatya DM. A comparison of six potential evapotranspiration methods for regional use in the southeastern United States. *Journal of the American Water Resources Association*. 2005;41(3):621-633.
- Mavi HS, Tupper GJ. *Agrometeorology: Principles and applications of climate studies in agriculture*. New York: Food Products Press; 2004. p. 364.
- Mousumi KA, Mojid MA, Ahmad T, Uddin MZ, Parvez MF. Climate-induced historical drift of reference evapotranspiration in the Mymensingh region of Bangladesh. *Journal of the Bangladesh Agricultural University*.

- 2019;17(2):258-264.
17. Pereira LS, Allen RG, Smith M, Raes D. Crop evapotranspiration estimation with FAO56: Past and future. *Agricultural Water Management*. 2015;147:4-20.
 18. Reddy A, Ganachari A, Lokesh K. Estimation of reference evapotranspiration using the CROPWAT model for the Raichur region, Karnataka. *Pharma Innovation Journal*. 2020;9(5):226-231.
 19. Rosenberg NJ, Blad BL, Verma SB. *Microclimate: The biological environment*. 2nd ed. New York: John Wiley and Sons; 1983. 495 p.
 20. Saha KA, Som PS, Kingra PK. Estimation of reference crop evapotranspiration of barley using the CROPWAT model in Punjab. *Agricultural Research Journal*. 2018;55(4):654-658.
 21. Shahid S. Impact of climate change on irrigation water demand of dry season Boro rice in northwest Bangladesh. *Climatic Change*. 2011;105(3):433-453.
 22. Tabari H, Hosseinzadeh Talaei P, Some'e BS. Spatial modelling of reference evapotranspiration using the adjusted Blaney-Criddle equation in an arid environment. *Hydrological Sciences Journal*. 2013;58(2):408-420.
 23. Thornthwaite CW. An approach toward a rational classification of climate. *Geographical Review*. 1948;38:55-94.
 24. Xu CY, Singh VP. Cross-comparison of mass-transfer, radiation- and temperature-based evaporation models. *Water Resources Management*. 2002;16:197-219.
 25. Zhao L, Xia J, Xu CY, Wang Z, Sobkowiak L, Long C. Evapotranspiration estimation methods in hydrological models. *Journal of Geographical Sciences*. 2013;23(2):359-369.