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ASSESSMENT OF REFERENCE EVAPOTRANSPIRATION UNDER CLIMATE CHANGE CONDITIONS: METHOD COMPARISON AND PRACTICAL APPLICATIONS

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Abstract: This study provides a comprehensive evaluation of methods for estimating reference evapotranspiration (ET_0) under climate change conditions. The analysis compares several widely used approaches, including the Hargreaves, Turc, Blaney–Criddle, and FAO-56 Penman–Monteith methods, as well as the satellite-based Manna application. Meteorological data from the Tuyabog'iz meteorological station located in the Tashkent region of Uzbekistan were analyzed for the period 2021–2023. The methods were assessed in terms of estimation accuracy, data requirements, and their suitability for application under local arid climatic conditions. The results indicate that the PM-CROPWAT method estimated seasonal reference evapotranspiration at 935.68 mm, whereas the Manna application produced a value of 706.60 mm, corresponding to a difference of −24.5%. The Hargreaves and Turc methods significantly overestimated ET_0 values by approximately +87% and +77%, respectively. A strong statistical relationship was observed between the monthly values obtained from Manna and CROPWAT, with a coefficient of determination of $R^2=0.913$. The findings demonstrate that the FAO CROPWAT 8.0 software represents an effective tool for the practical calculation of reference evapotranspiration and irrigation scheduling. The results of this research contribute to improving water resource management and optimizing irrigation practices under conditions of increasing climatic variability.

Keywords: reference evapotranspiration, climate change, Penman–Monteith method, Hargreaves method, satellite data, CROPWAT, irrigation scheduling.

ИҚЛИМ ЎЗГАРИШИ ШАРОИТИДА ЭТАЛОН ЭВАПОТРАНСПИРАЦИЯНИ ҲИСОБЛАШ: УСУЛЛАР ТАҚҚОСЛАНИШИ ВА АМАЛИЙ ЁНДАШУВЛАР

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Annotatsiya: Ушбу тадқиқотда иқлим ўзгариши шароитида эталон эвапотранспирацияни (ET_0) баҳолаш усулларининг самарадорлиги ва аниқлиги комплекс тарзда таҳлил қилинди. Тадқиқотда Харгривз, Турк, Блэни–Криддл ҳамда Пенман–Монтейт (FAO-56) усуллари, шунингдек сунъий йўлдош маълумотларига асосланган Manna иловаси натижалари ўзаро таққосланди. Таҳлиллар 2021–2023 йиллар давомида Тошкент вилояти Ўрта Чирчиқ туманида жойлашган Туябоғиз метеорологик станцияси маълумотлари асосида амалга оширилди. Усуллар ҳисоблаш аниқлиги, талаб этиладиган маълумотлар ҳажми ҳамда маҳаллий арид иқлим шароитида қўллаш имкониятлари бўйича баҳоланди. Натижаларга кўра, PM-CROPWAT усули бўйича вегетация давридаги эталон эвапотранспирация миқдори 935,68 мм ни ташкил этди, Manna иловаси эса 706,60 мм қийматни кўрсатди (фарқ −24,5%). Харгривз ва Турк усуллари мос равишда +87% ва +77% даражада юқори баҳолашни кўрсатди. Manna ва CROPWAT натижалари ўртасидаги корреляция коэффициенти R^2=0,913 бўлиб, бу улар ўртасида юқори боғлиқлик мавжудлигини кўрсатади. Тадқиқот натижалари шуни кўрсатадики, FAO CROPWAT 8.0 дастури эталон эвапотранспирацияни ҳисоблаш ва суғориш режимларини режалаштиришда самарали инструмент ҳисобланади. Олинган натижалар сув ресурсларидан оқилона фойдаланиш ва замонавий суғориш тизимларини оптимал бошқариш учун муҳим амалий аҳамиятга эга.

Kalit so‘zlar: эталон эвапотранспирация, иқлим ўзгариши, Пенман–Монтейт усули, Харгривз усули, сунъий йўлдош маълумотлари, CROPWAT, суғоришни режалаштириш

ОЦЕНКА ЭТАЛОННОЙ ЭВАПОТРАНСПИРАЦИИ В УСЛОВИЯХ КЛИМАТИЧЕСКИХ ИЗМЕНЕНИЙ: СРАВНИТЕЛЬНЫЙ АНАЛИЗ МЕТОДОВ И ПРАКТИЧЕСКИЕ ПОДХОДЫ

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Аннотация: В данном исследовании проведена комплексная оценка методов расчёта эталонной эвапотранспирации (ET_0) в условиях изменения климата. Рассмотрены и сопоставлены широко применяемые методы Харгривза, Турка, Блейни–Криддла и Пенмана–Монтейта (FAO-56), а также приложение Manna, основанное на спутниковых данных. Анализ выполнен на основе метеорологических данных метеорологической станции Туябоғиз, расположенной в Ташкентской области Республики Узбекистан, за период 2021–2023 гг. Методы оценивались по точности расчётов, требованиям к исходным данным и пригодности для применения в условиях аридного климата региона. Полученные результаты показали, что по методу PM-CROPWAT величина сезонной эталонной эвапотранспирации составила 935,68 мм, тогда как приложение Manna показало значение 706,60 мм (разница −24,5%). Методы Харгривза и Турка продемонстрировали завышение результатов на +87% и +77% соответственно. Между значениями, полученными с использованием Manna и CROPWAT, установлена высокая корреляционная зависимость с коэффициентом детерминации R^2=0,913. Результаты исследования показывают, что программное обеспечение FAO CROPWAT 8.0 является эффективным инструментом для практического расчёта эталонной эвапотранспирации и планирования режимов орошения. Полученные выводы имеют важное значение для повышения эффективности управления водными ресурсами и оптимизации ирригационных технологий в условиях изменяющегося климата.

Ключевые слова: эталонная эвапотранспирация, изменение климата, метод Пенмана–Монтейта, метод Харгривза, спутниковые данные, CROPWAT, планирование орошения.

INTRODUCTION

Irrigated agriculture accounts for more than 90% of total freshwater withdrawals in Uzbekistan, yet the operational efficiency of irrigation systems remains at approximately 0.63 [1]. Against the backdrop of accelerating global climate change, the strategic importance of precise water management has increased significantly across Central Asia. IPCC (2022) projections suggest that mean temperatures may increase by 2.5–4.0°C and annual precipitation may decline by 15–20% in arid and semi-arid regions by 2050 [2], further intensifying pressure on limited water resources.

Reference evapotranspiration (ET_0) is a cornerstone parameter in estimating crop water requirements, irrigation scheduling, and water allocation optimisation [3,5]. Systematic errors in ET_0 estimation may lead to over- or under-irrigation of 20–35%, resulting in negative consequences such as soil salinisation, yield reduction, and groundwater table rise [3,4,5]. Therefore, the selection of an appropriate ET_0 estimation method compatible with locally available meteorological data is essential for sustainable irrigation management [9,15].

Over the past seven decades, numerous methods have been developed to estimate ET_0, ranging from physically based multi-parameter approaches to simplified temperature-based equations. The FAO-56 Penman–Monteith (PM) equation is widely recognised as the international reference standard [5]; however, its application requires a complete set of meteorological data that is often unavailable in data-scarce regions. Temperature-based methods such as Hargreaves [6] and Blaney–Criddle [7], as well as radiation–temperature approaches such as the Turc method [19], provide practical alternatives. Nevertheless, their performance under arid climatic conditions may deviate significantly from PM estimates [10,11]. More recently, satellite-based platforms such as Manna have emerged as powerful tools for operational evapotranspiration estimation, utilising datasets derived from Sentinel-2, MODIS, and ERA5 to provide field-scale daily ET estimates [8,13].

Despite these advances, systematic evaluations that combine satellite-based ET products with classical empirical methods under the specific hydroclimatic conditions of Uzbekistan's irrigated lowlands remain limited. The present study addresses this gap through a rigorous three-year comparative analysis conducted at the Tuyabog'iz meteorological station. The analysis provides station-specific performance indicators and practical recommendations for irrigation management.

The main objectives of this study are as follows: to evaluate seasonal and monthly performance of five ET_0 estimation methods relative to the FAO-56 Penman–Monteith standard; to quantify systematic bias and correlation of each method relative to PM-CROPWAT estimates; to develop a tiered methodological framework adapted to different levels of meteorological data availability.

LITERATURE REVIEW

Penman-Monteith Method. The FAO-56 Penman–Monteith (PM) equation, formulated by Allen et al. (1998), integrates both aerodynamic and radiative energy balance components and is recommended by FAO as the standard method for estimating reference evapotranspiration (ET_0) worldwide [5]:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where: Δ = slope of vapour pressure curve (kPa $°C^{-1}$); Rn = net radiation (MJ m^{-2} day^{-1}); G = soil heat flux (MJ m^{-2} day^{-1}); γ = psychrometric constant (kPa $°C^{-1}$); T = mean air temperature (°C); u_2 = wind speed at 2 m (m s^{-1}); es − ea = vapour pressure deficit (kPa).

The PM method has been extensively validated across a wide range of climatic zones and is currently considered the most reliable standard for ET_0 estimation in more than 100 countries [5,9].

Hargreaves and Turc Temperature-Based Methods. The Hargreaves–Samani (1985) equation requires only maximum and minimum air temperature values (Tmax and Tmin), making it particularly suitable for regions with limited meteorological observations [6]:

$$ET_0 = 0,0023 \cdot R_a \cdot (T_{mean} + 17,8) \cdot (T_{max} - T_{min})^{0,5}$$

where: Ra = extraterrestrial radiation; T_{mean} = mean temperature; $T_{max} - T_{min}$ = temperature range.

The Turc method (1961) is based on temperature and solar radiation:

$$ET_0 = 0,013 \cdot \frac{T_{mean}}{T_{mean} + 15} \cdot (R_s + 50)$$

The Turc (1961) method additionally incorporates solar radiation as a key variable in estimating evapotranspiration. Several studies have evaluated the performance of simplified temperature-based methods under arid climatic conditions. For example, Tabari et al. (2013) and Jensen et al. (1990) reported that the Hargreaves method may overestimate ET_0 by approximately 20–50% relative to the Penman–Monteith method in arid regions, indicating the need for regional calibration [10,11]. Furthermore, Droogers and Allen (2002) recommended the application of regional correction coefficients when simplified empirical methods are used outside the climatic conditions in which they were originally developed [19]

Blaney–Criddle Method. The Blaney–Criddle (1950) method estimates reference evapotranspiration as a function of mean air temperature and the percentage of annual daytime hours occurring during a given period [7]. Although an improved version for arid and semi-arid conditions was later proposed by Doorenbos and Pruitt (FAO, 1977), studies conducted in Central Asia indicate that the method may underestimate seasonal ET_0 values by approximately 20–30% under the climatic conditions of Uzbekistan [17].

Manna Satellite-based ET platform. The Manna platform estimates daily actual evapotranspiration using satellite-derived datasets from Sentinel-2, MODIS, and ERA5 through the application of energy balance and surface temperature algorithms [8]. Previous studies have demonstrated high agreement between Manna-derived evapotranspiration estimates and reference methods. For instance, Garrido-Rubio et al. (2020) reported a coefficient of determination of R^2=0.95 between Manna and the Penman–Monteith method in Mediterranean Spain [13], while Liu et al. (2022) observed an agreement within ±8–12% in arid regions of northwestern China [14]. Since the Manna platform estimates actual evapotranspiration rather than reference evapotranspiration, systematic differences relative to PM estimates may occur and should be considered when applying the results for irrigation scheduling.

Regional Context. Previous studies conducted in Uzbekistan have highlighted the importance of accurate ET_0 estimation for irrigation water management. Sherov and Amanov (2022) recommended the FAO-56 Penman–Monteith method as the primary reference standard for irrigated agriculture in Uzbekistan [17]. Amanov and Gulomov (2025) investigated the spatial zoning of water-saving irrigation technologies based on the aridity index under regional climatic conditions [20].

The novelty of the present study lies in the systematic integration of satellite-based evapotranspiration products (Manna) with classical empirical ET_0 estimation methods using data from a specific meteorological station in Uzbekistan. This approach enables a direct quantitative comparison of different methods within a consistent three-year dataset and provides practical recommendations for irrigation water management.

MATERIALS AND METHODS

The study was conducted using meteorological data obtained from the Tuyabog'iz meteorological station located in the Urta Chirchiq district of Tashkent region, Uzbekistan. The study area belongs to a semi-arid climatic zone. The calculations were performed based on meteorological observations collected during the period 2021–2023.

Reference evapotranspiration (ET_0) values using the Penman–Monteith method were calculated with the FAO CROPWAT 8.0 software. The Hargreaves, Turc, and Blaney–Criddle methods were calculated using Microsoft Excel based on the available meteorological parameters.

RESULTS

PM-CROPWAT estimated mean daily ET_0 from 0.61 mm day^{-1} (January) to 6.82 mm day^{-1} (July) — an eleven-fold seasonal amplitude driven by the strong radiative and thermal forcing of the continental semi-arid climate (Table 1). The near-perfect agreement between PM-CROPWAT and PM-FAO (maximum monthly difference: 0.14 mm day^{-1}) confirms the internal consistency of the FAO-56 algorithm under local conditions.

Hargreaves and Turc systematically overestimated ET_0 from March onwards, peaking in July at 12.22 and 12.30 mm day^{-1} compared with 6.82 mm day^{-1} (PM-CROPWAT) — deviations of +79% and +80%, respectively. This overestimation is consistent with the documented behaviour of temperature-based methods in arid environments, where low humidity and strong advective heat transport cause these equations to over-weight the temperature signal. Manna daily values were 20–30% below PM-CROPWAT, reflecting the fundamental distinction between actual ET (Manna's energy balance output) and reference ET (PM's conceptual grass surface).

Table 1. Mean daily ET_0 (mm day^{-1}) by method and month, 2021–2023 average

Month	PM-ET_0 (CROPWAT)	PM-ET_0 (FAO-56)	Manna ET_0	BC-ET_0	H-ET_0	T-ET_0
Jan	0.61	0.48	–	2.15	2.15	2.08
Feb	1.19	1.13	–	3.46	3.16	3.16
Mar	3.15	2.87	–	5.90	7.73	6.50
Apr	3.69	3.59	3.40	6.34	8.11	6.88
May	5.04	5.25	2.66	6.73	9.74	8.65

Jun	6.53	6.74	4.70	8.66	11.81	11.78
Jul	6.82	6.96	5.37	9.56	12.22	12.30
Aug	5.85	5.66	4.86	8.69	10.62	10.45
Sep	4.22	3.93	3.49	7.05	7.83	6.85
Oct	2.62	2.19	2.54	5.84	6.89	5.83
Nov	1.70	1.23	–	4.27	4.29	3.57
Dec	0.93	0.57	–	1.73	1.84	1.79

Note: PM=Penman–Monteith; BC=Blaney–Criddle; H=Hargreaves; T=Turc; M=Manna (growing season only). Decimal: period.

DISCUSSION

Seasonal (April–October) ET_0 cumulative totals varied substantially across methods (Table 2). PM-CROPWAT (935.68 mm) and PM-FAO (933.20 mm) differed by only 0.3%, confirming near-perfect agreement. Manna accumulated 706.60 mm (−24.5%), implying that operational use without a correction factor would leave approximately 229 mm of crop water demand unmet per season — sufficient to cause significant yield reduction in summer crops.

Blaney–Criddle overestimated by +46.2% (1367.98 mm), Hargreaves by +87.1% (1750.40 mm), and Turc by +77.5% (1660.45 mm). These systematic biases indicate that uncalibrated Hargreaves or Turc methods would prescribe 432–815 mm of excess irrigation per season, increasing waterlogging and secondary salinisation risk. The largest monthly divergences occurred in July, confirming that bias is most critical precisely when irrigation demand is at its highest.

Table 2. Monthly and seasonal cumulative ET_0 (mm month^{-1}) during the growing season, 2021–2023 average

Month	PM-ET_0 (CROPWAT)	PM-ET_0 (FAO-56)	Manna ET_0	BC-ET_0	H-ET_0	T-ET_0
Apr	40.59	39.49	37.4	69.74	89.21	75.68
May	156.24	162.75	82.7	208.63	301.94	268.15
Jun	195.90	202.35	141.2	259.80	354.30	353.40
Jul	211.42	215.80	166.7	296.36	378.82	381.30
Aug	181.35	175.32	150.8	269.39	329.22	323.95
Sep	126.60	117.76	104.9	211.50	234.90	205.50
Oct	23.58	19.73	22.9	52.56	62.01	52.47
Total	**935.68**	**933.20**	**706.60**	**1367.98**	**1750.40**	**1660.45**

Figure 1 shows monthly mean daily ET_0 for all methods. PM-CROPWAT and PM-FAO are virtually indistinguishable throughout the year. Hargreaves and Turc run systematically above PM from March onwards, converging with PM only in winter when temperature range narrows.

Manna tracks the PM seasonal pattern with a consistent downward displacement throughout the growing season.

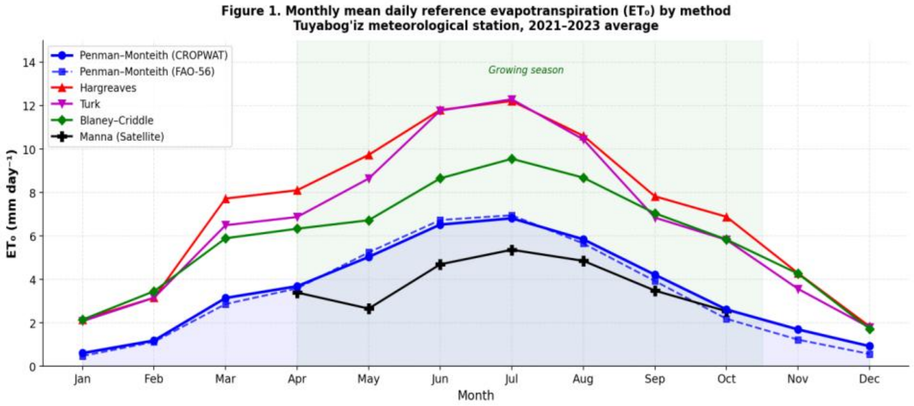

Figure 1. Monthly mean daily ET_0 (mm day^{-1}) by estimation method. Tuyabog'iz station, 2021–2023 average. Shaded band: growing season (April–October).

Figure 2 presents growing season monthly cumulative ET_0 as grouped bar charts. The divergence is most pronounced in June–July, when Hargreaves and Turc bars reach 1.7–1.8× the PM-CROPWAT values. Blaney–Criddle consistently exceeds PM by a moderate margin, while Manna remains the lowest throughout the season.

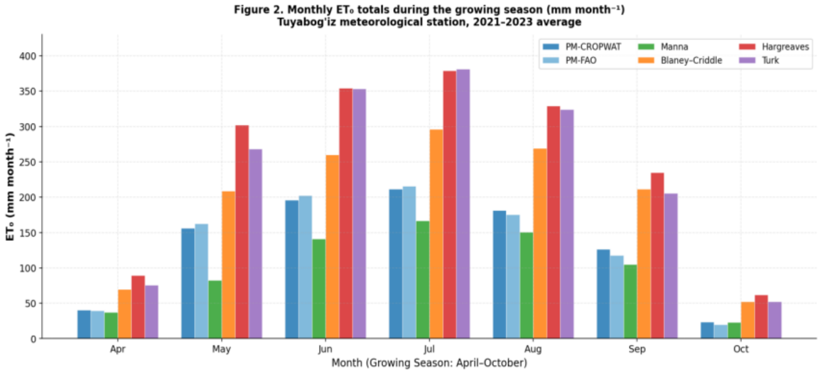

Figure 2. Monthly ET_0 cumulative totals (mm month^{-1}) during the growing season. Tuyabog'iz station, 2021–2023 average.

Figure 3a summarises seasonal ET_0 totals with PM-CROPWAT as the reference baseline. Figure 3b displays the percentage deviation of each method, colour-coded by bias category: green (≤±5%: PM-FAO), orange (moderate: Manna, BC), red (high: Hargreaves, Turc). Only PM-FAO falls within an operationally acceptable deviation; all alternative methods require correction prior to use in irrigation scheduling.

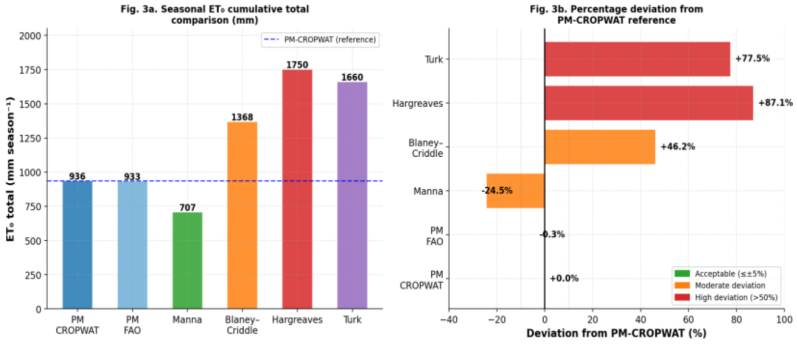

Figure 3. (a) Seasonal cumulative ET_0 comparison (mm season^{-1}); (b) Percentage deviation from PM-CROPWAT. Green ≤±5%; orange = moderate deviation; red >50%.

Figure 4 shows the scatter plot of monthly Manna vs. PM-CROPWAT values (R^2 = 0.913; y = 0.718x + 5.0). The high R^2 confirms that Manna reliably tracks the seasonal pattern of reference ET_0 despite systematic underestimation. The slope of 0.718 (< 1.0) reflects the Manna-PM methodological distinction: a seasonal correction factor of 1/0.718 ≈ 1.39 may be applied to Manna monthly cumulative values to approximate PM-CROPWAT estimates under the hydroclimatic conditions of this site.

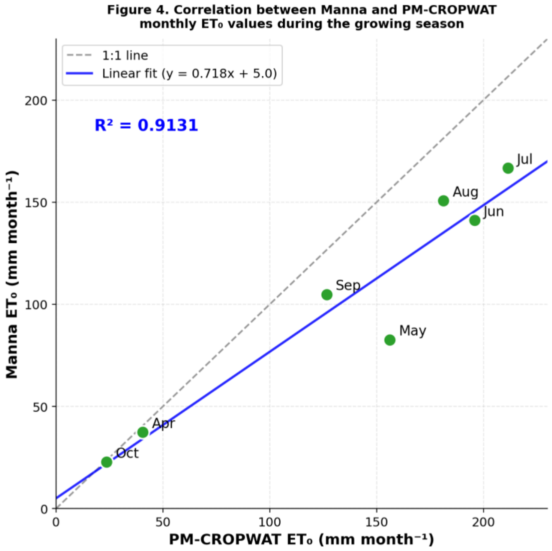

Figure 4. Correlation between monthly Manna and PM-CROPWAT ET_0 values during the growing season. R^2 = 0.913; linear regression: y = 0.718x + 5.0 (n = 21 monthly data points over 3 years).

A three-tier framework is proposed for ET_0 estimation in the semi-arid irrigated lowlands of Uzbekistan:

– Tier 1 — Reference standard: PM-FAO-56 + CROPWAT 8.0. Recommended when a full suite of meteorological variables is available. Provides highest accuracy; mandatory basis for official irrigation norms and hydrological planning.

– Tier 2 — Operational satellite tool: Manna application, with a regional correction factor of ≈1.39. Suitable for real-time daily irrigation scheduling at farm or irrigation district level when ground station data are unavailable (R^2 = 0.913 with PM-CROPWAT).

– Tier 3 — Rapid estimation with local calibration: Hargreaves or Blaney–Criddle. Applicable only when temperature data alone are available; uncalibrated application will produce systematic errors of +46% to +87%.

CONCLUSION

This study conducted a systematic comparative analysis of five reference evapotranspiration (ET_0) estimation methods using three years of data (2021–2023) from the Tuyabog'iz Meteorological Station, Tashkent Province, Uzbekistan. The results provide clear evidence of substantial methodological differences under semi-arid climatic conditions.

The main findings are as follows:

The **FAO-56 Penman–Monteith (PM)** method implemented in **CROPWAT 8.0** remains the definitive reference standard for ET_0 estimation. PM-FAO and PM-CROPWAT demonstrated near-perfect agreement, differing by only 0.3% over the full growing season.

The **Manna satellite-based platform** exhibited strong seasonal correlation with PM-CROPWAT (R^2=0.913), confirming its reliability in tracking temporal dynamics. However, it systematically underestimated seasonal cumulative ET_0 by 24.5% (229 mm season^{-1}). Application of a regional correction factor of approximately **1.39** significantly improves its compatibility with PM-based estimates, making it a viable operational tool for irrigation scheduling where complete meteorological datasets are unavailable.

The **Hargreaves (+87.1%)** and **Turc (+77.5%)** methods substantially overestimated seasonal ET_0 and require local calibration before application in semi-arid conditions of Uzbekistan. Uncalibrated use may result in 432–815 mm of excess irrigation per season, increasing risks of waterlogging and secondary soil salinisation.

The **Blaney–Criddle (+46.2%)** method also showed considerable deviation from the PM standard and should not be used as a standalone planning tool without regional correction.

Based on these findings, the following recommendations are proposed for irrigation water management in Uzbekistan:

1. Adopt **PM-FAO-56 combined with CROPWAT 8.0** as the national and regional reference standard for irrigation planning, hydrological modelling, and policy development.
2. Implement the **Manna platform**, applying a regional correction factor of approximately 1.39, for operational daily irrigation management at farm and irrigation-district levels.
3. Develop and publish **local calibration coefficients** for Hargreaves, Turc, and Blaney–Criddle methods for each agro-climatic zone, using PM-CROPWAT as the benchmark.
4. Establish an integrated network of **automatic meteorological stations linked with CROPWAT** to support real-time ET_0 advisory services for farmers.

Overall, the integration of satellite-based evapotranspiration products with the FAO reference framework provides a scientifically robust pathway toward improving irrigation efficiency and enhancing sustainable water resource management in Uzbekistan under climate change conditions.

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