

FINAL REPORT

**RE-ASSESSMENT OF EVAPOTRANSPIRATION (*ETO*)
ESTIMATION FOR IRRIGATION PLANNING IN MADHYA
PRADESH**



A Joint Research Study by

**National Institute of Hydrology
Central India Hydrology Regional Centre, Bhopal**

&

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Madhya Pradesh Water Resources Department, Bhopal
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PREFACE

This report is intended to serve as a key input for effective irrigation planning and implementation in Madhya Pradesh, with a focus on estimating Evapotranspiration (ET_o), Crop Water Requirement (CWR), and Irrigation Requirement (IR), as guided by Technical Circular-25 (TC-25) issued by the Government of Madhya Pradesh in 1990. Recent assessments of irrigation projects across Madhya Pradesh have revealed that ET_o, CWR, IR are being overestimated under the current norms outlined in the TC-25. These discrepancies, assumed to be influenced by climatic changes, evolving agricultural practices, and anthropogenic factors, underscore the need for a thorough reassessment of ET_o estimation methods used in irrigation planning. Thus, this study focuses on verifying the causes behind the overestimations and recommends updates to TC-25. The Penman-Monteith method, supported by recent climatic data and the IMD gridded dataset, is proposed as a more accurate alternative to the currently used Modified Penman method. The Hargreaves method is also identified as a reliable cross-validation tool in data-scarce scenarios. Additionally, the revised TC-15 (2002) canal efficiency guidelines are recommended for improved planning accuracy. The study finds no significant changes in soil or cropping patterns affecting CWR and IR but highlights the pressing need for adaptive strategies in light of climate variability and climate change. This study provides recommendations for possible revisions to be made in TC-25 to improve the accuracy of ET_o, CWR, and IR estimations in Madhya Pradesh.

This research was jointly conducted by the National Institute of Hydrology (NIH), Central India Hydrology Regional Centre (CIHRC), Bhopal, and BODHI, Madhya Pradesh Water Resources Department. The study team included Dr. Ravi Galkate, Scientist-F, Dr. R.K. Jaiswal, Scientist-F, Dr A. K. Loani, Scientist-G, Er. Shashi P Indwar, Scientist-D, and Sh. Rahul Kumar, RA of NIH, CIHRC, Bhopal. The study team also included officers at the level of Assistant Directors from the State Dam Safety Organization and the State Water Data Centre of BODHI, MPWRD, Bhopal.

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1. INTRODUCTION

Irrigation is a crucial aspect in India, where 52% of the workforce depends on agriculture, contributing around 18% to GDP (Government of India, 2021). With 50% of cultivated land reliant on rainfall, irrigation ensures year-round crop production, reducing monsoon dependency (Shah, 2013). Madhya Pradesh has over 55 lakh hectares of irrigated land, with several minor, medium, and major irrigation projects boosting water availability (Singh et al., 2019). Scientific studies show irrigation increases crop yield by 30-50%, improving food security and farmer incomes (FAO, 2012). Approximately 64% of India's irrigation relies on groundwater, while in Madhya Pradesh, around 60% of irrigation depends on groundwater and the remaining 40% on surface water projects (CGWB, 2020). The state is actively expanding its canal networks to increase the area irrigated through surface water resources (MPWRD, 2021). Assured irrigation enables multiple cropping, enhancing productivity and profitability (Kumar & Singh, 2015). Advanced methods like drip and sprinkler irrigation reduce water wastage by 40-60% (Narayanamoorthy, 2018). Government schemes like Pradhan Mantri Krishi Sinchai Yojana (PMKSY) and Atal Bhujal Yojana promote irrigation infrastructure and groundwater conservation (DACFW, 2020). Irrigation helps farmers adapt to climate change, stabilizing agricultural output despite erratic rainfall (Aggarwal et al., 2019). Improved irrigation supports rural development, increasing farm incomes and fostering economic growth (World Bank, 2020).

Estimating crop water requirements is essential for efficient irrigation planning, ensuring optimal water use while preventing wastage (Allen et al., 1998). It helps in scheduling irrigation based on crop type, soil properties, and climate conditions, improving yield and resource management (Doorenbos & Pruitt, 1977). Proper estimation prevents over-irrigation, which can lead to waterlogging and soil degradation, and under-irrigation, which reduces crop productivity (Hanson et al., 2004). Scientific methods like evapotranspiration calculations and soil moisture monitoring enhance precision in water allocation (Allen et al., 2005). Effective estimation supports sustainable agriculture, conserving water while maximizing farm output (Goyal, 2004).

Crops require an appropriate quantity of water with specific time intervals for their normal growth and maximum yield. Hence, for irrigation planning, design, and operation, it is essential to estimate crop water requirements and irrigation requirements accurately. Crop water requirements of an area depend upon crop evapotranspiration, which can be estimated with the help of reference crop evapotranspiration (ET_o) (Allen et al., 1998). Different types of lysimeters are available and used for accurate measurements of ET_o; however, the lysimeter data is not readily accessible. Therefore, different methods of ET_o estimation are to be considered in different regions to select an appropriate estimation method. Some of the popular methods are the Blaney-Criddle method, Christian-Sen method, Thornthwaite method, Penman method, modified Penman method, and Penman-Monteith method (Jensen et al., 1990).

In Madhya Pradesh, the crop water requirement and irrigation water requirement are estimated as per the methodology suggested in Technical Circular-25 (TC-25) of the Government of Madhya Pradesh issued in June 1990 (MPWRD, 1990). The estimation of Potential or Reference Evapotranspiration (ET_o), Crop Evapotranspiration (ET_c), Crop Water Requirements (CWR), and Irrigation Requirement (IR) has to be done regularly based on historical data (Singh et al., 2021; Rao et al., 2022; Verma et al., 2021). In the present scenario, due to many climatic changes, biotic evolution, changing agricultural practices, and anthropogenic interferences, the ET_o estimates seem to be overestimated, which needs to be verified and reassessed for irrigation planning in Madhya Pradesh. Recent observations in several irrigation projects across Madhya Pradesh indicate that Evapotranspiration (ET_o), Crop Water Requirement (CWR), and Irrigation Requirement (IR) have been overestimated under the existing TC-25 norms. As a result, more area is being irrigated per unit of Million Cubic Meters (MCM) of water than initially planned. For instance, in the case of a lined canal, 240 hectares are being irrigated instead of the planned 200 hectares, highlighting the need for a reassessment of estimation methods.

Possible reasons for this discrepancy include changes in soil water holding capacity, cropping patterns, irrigation efficiencies, crop coefficient (K_c) values, and water use efficiency. Additionally, variations in effective rainfall, evolving agricultural practices, anthropogenic interferences, selection of ET_o estimation methods, and climatic changes may also contribute to this trend (Kashyap & Panda, 2001). Thus, this study aims to verify facts behind the change in the estimation of ET_o and irrigation requirements in the command area and suggest changes in TC-25 and accurate methods or software for the estimation of ET_o, which is free to access and available online under the constraint of data requirements and adaptable to new changes. In the present study, ET_o estimation was conducted across all eleven agro-climatic zones of Madhya Pradesh, with Kolar Dam selected as the case study area for detailed hydrological investigations.

Objectives:

- Assessment of ET_o using different methods
- Investigating reasons behind the change in ET_o, CWR, and IR estimation.
- Study of different online open-source software and development of an Excel-based dashboard for ET_o estimation in MP
- Suggestions and recommendations for modification in TC-25

2. REVIEW OF LITERATURE

Potential or Reference Evapotranspiration (ET_o) estimation methods are important for effective irrigation management and water conservation. Various methods have been developed over time, each with varying degrees of accuracy and applicability. Numerous researchers have developed various methods for estimating evapotranspiration (ET_o), each with differing applicability based on climatic conditions. Direct methods, such as the Lysimeter, Eddy Covariance, and Bowen Ratio methods, provide field-based measurements of ET. Rational methods, including the Modified Penman, Penman-Monteith, Priestley-Taylor, Turc, and FAO-56 models, are widely used due to their strong physical basis. Empirical approaches like the Hargreaves, Blaney-Criddle, and Thornthwaite methods rely on climatic data and are useful in data-scarce regions. Additionally, other techniques such as Pan Evaporation, Water Balance, Soil Moisture Depletion, Remote Sensing, and Radiation/Temperature-based models are employed in ET estimation. The accuracy and reliability of these methods, however, vary across different climatic zones, including arid, semi-arid, and humid regions.

A lysimeter is widely regarded as the most accurate method for estimating evapotranspiration (ET) under field conditions because it directly measures the water balance of a soil-plant system. It quantifies all water inputs such as rainfall and irrigation, and outputs like drainage and ET, allowing precise ET determination. Lysimeters closely replicate natural field conditions, making them ideal for calibrating and validating ET models (Allen et al., 1998). They are particularly valuable in research settings for assessing crop water use under varying climatic and soil conditions. The major strengths of lysimeters include high accuracy, direct measurement of ET, and their ability to evaluate water use efficiency. However, they have limitations like high installation and maintenance costs, limited spatial coverage, and the difficulty of simulating large-scale or heterogeneous field conditions (Howell et al., 1991). Moreover, data collection and analysis can be time-consuming.

To complement lysimeter data or when lysimeters are impractical, data-based, rational and empirical models are useful. Rational models, such as the FAO Penman-Monteith equation, use physical laws and meteorological data to estimate ET with high reliability (Allen et al., 1998). Empirical models like Hargreaves and Blaney-Criddle are simpler and rely on historical or regional data, making them suitable for data-scarce areas. These models, when calibrated properly, provide practical ET estimates and support effective water resource management.

A review of key studies (Allen et al., 1998; Jensen et al., 1990; Hargreaves & Samani, 1985; Shuttleworth, 1993; Pereira et al., 2015; Irmak et al., 2013) highlights the suitability of different evapotranspiration estimation methods across arid, semi-arid, and humid climates as given in Table 2.1. Physically based models like Penman-Monteith perform well across all regions, while empirical methods are more suited to data-scarce environments. These sources provide a reliable foundation for method selection based on climatic conditions and data availability.

Table 2.1: ETo estimation methods and their suitability in different climatic conditions

Method of ETo Estimation	Arid	Semi-arid	Humid
Direct Method			
Lysimeter Method	✓	✓	✓
Eddy Covariance Method	✓	✓	✓
Bowen Ratio Method	✓	✓	✓
Rational Method			
Modified Penman	✓	✓	✗
Penman-Monteith Method	✓	✓	✓
Priestley-Taylor Method	✗	✓	✓
Turc Method	✗	✓	✓
FAO-56 Method	✓	✓	✓
Empirical Method			
Hargreaves Method	✓	✓	✗
Blaney-Criddle Method	✓	✓	✗
Thornthwaite Method	✗	✓	✓
Other Methods			
Pan Evaporation Method	✓	✓	✓
Water Balance Method	✓	✓	✓
Soil Moisture Depletion Method	✓	✓	✓
Remote Sensing-Based Methods	✓	✓	✓
Empirical Radiation/Temp-Based Models	✓	✓	✓

Legend: ✓ Suitable and ✗ Less suitable or not recommended

In the early 1970s, the Food and Agriculture Organization (FAO) of the United Nations introduced a practical method and approach for estimating crop water requirements, which quickly became a widely recognized standard, especially in irrigation studies. However, since the publication of the FAO Irrigation and Drainage Paper, new research developments and evolving concepts have exposed certain limitations in the original methodology, prompting the need for its review and revision.

Commonly used ETo estimation methods include the Hargreaves Method, which is a simpler approach that relies on temperature data, making it effective in data-scarce regions but less reliable under varying climatic conditions (Jensen et al., 1990). Whereas, the Blaney-Criddle and Modified Penman Methods are frequently used in semi-arid regions but tend to overestimate ETo (Gupta et al., 2015). The Satellite-Based Models like SEBAL and METRIC use remote sensing techniques to estimate actual evapotranspiration and improve accuracy at larger scales (Bastiaanssen et al., 2005).

The Penman-Monteith method is widely regarded as the most accurate for ETo estimation as it incorporates multiple climatic parameters, such as temperature, wind speed, humidity, and solar radiation (Allen et al., 1998). Compared to traditional methods like the Modified Penman or Hargreaves models, it significantly reduces estimation errors (Gupta et al., 2019). However, the model's accuracy depends on the availability of high-quality climatic data.

Smith et al., (1998), in an expert consultation organized by the FAO, recommended the Penman-Monteith combination method as the new standard for calculating reference evapotranspiration, along with guidance on how to compute its various parameters. The method defines a hypothetical reference crop with specific characteristics in height, a surface resistance, and an albedo designed to simulate the evaporation from a well-watered, actively growing, uniform grass surface. This standardized approach addressed shortcomings in earlier methods and produced results that align more closely with observed crop water use across different regions. Additionally, procedures have been established for applying the FAO Penman-Monteith method even when only limited climatic data are available, reducing the reliance on alternative methods and ensuring a uniform, transparent framework for estimating crop water requirements globally.

According to Smith et al. (1998), the Modified Penman method, as introduced in FAO Irrigation and Drainage Paper No. 24, was often found to overestimate reference evapotranspiration. In contrast, the Penman-Monteith method addressed the limitations of earlier approaches by incorporating both aerodynamic resistance and canopy (or surface) resistance, providing a more accurate simulation of the effects of wind and atmospheric turbulence on evapotranspiration.

Major evapotranspiration estimation challenges in Madhya Pradesh are that the accuracy of ETo estimation methods in Madhya Pradesh requires improvement due to changing climate conditions and outdated models. Many traditional models have limitations. Studies indicate that traditional methods, such as the Modified Penman and Hargreaves models, may not capture regional variations effectively, leading to overestimations and inefficient irrigation planning (Sharma & Patel, 2021). The Technical Circular-25 (TC-25) method, used for ETo estimation in Madhya Pradesh, has become outdated and often leads to excessive irrigation allocation (Sharma et al., 2021).

Under the Climate change and variability scenarios, like rising temperatures, erratic rainfall patterns, and soil moisture variations, necessitate the adoption of climate-responsive models. The IPCC (2019) highlights that traditional models fail to integrate these dynamic factors, affecting water resource planning. Implementing AI-based models and integrating real-time weather data can improve predictive accuracy (Singh et al., 2022). There comes the role of Technology in improving ETo Estimation includes advanced computational tools, remote sensing, and AI-based models can enhance the accuracy of evapotranspiration estimation.

Remote Sensing and GIS integration, having Satellite-based models such as SEBAL and METRIC, have significantly improved ETo accuracy by using thermal imaging and vegetation indices (Bastiaanssen et al., 2005). GIS-based mapping allows for spatially distributed ETo data, optimizing irrigation planning in Madhya Pradesh (Kalma et al., 2008). Artificial Intelligence and Machine Learning Models are useful in quick assessment and prediction. AI-driven approaches, such as neural networks and support vector machines, provide highly accurate ETo predictions, even in regions with limited climatic data (Rahmati et al., 2020). These models can integrate remote sensing data, improving estimation reliability and supporting precision irrigation strategies.

Real-time data collection and automation with the help of automated weather stations and IoT-based sensors enhance ETo model precision by providing real-time climatic inputs (Goyal, 2014). Incorporating these advancements into Madhya Pradesh's irrigation framework can refine water allocation strategies and improve sustainability.

Accurate ETo estimation is crucial for sustainable agricultural productivity and water conservation. Proper irrigation planning helps reduce water wastage and enhance crop yield (Kumar et al., 2020). Traditional irrigation systems lead to excessive water consumption, necessitating the adoption of advanced scheduling techniques (FAO, 2019). The integration of remote sensing and GIS-based tools improves decision-making, ensuring optimal water use efficiency (Bastiaanssen et al., 2000). The canal irrigation system in Madhya Pradesh suffers from outdated efficiency models, leading to significant water losses. Research suggests updating efficiency values and incorporating real-time monitoring to enhance system performance (Sharma et al., 2021).

Water-use efficiency can be further improved by integrating real-time climate data and adopting modern irrigation techniques such as drip and sprinkler systems. The FAO (2019) reports that these methods can improve efficiency by 30–50%. A shift towards sustainable irrigation planning will ensure long-term agricultural stability in Madhya Pradesh.

Thus, from the review of literature, it could be summarized that the updating of ETo estimation models in Madhya Pradesh is essential for effective irrigation management and water conservation. Traditional methods, such as the Modified Penman and TC-25 models, tend to overestimate ETo, necessitating a transition to more accurate models like Penman-Monteith. Advanced remote sensing, AI-based models, and real-time climatic data integration can significantly improve ETo estimation accuracy, supporting efficient water resource management and sustainable agriculture. Future research should focus on implementing these advanced methods to optimize irrigation planning and ensure resilience against climate change and variability.

3. METHODOLOGY

In Madhya Pradesh, irrigation requirements are being estimated using the methodology outlined in the Design Series Technical Circular-25 (TC-25), issued in 1990. While this framework has guided irrigation planning for decades, recent observations from several irrigation projects across the state indicate that the estimates of potential evapotranspiration (ET₀), crop water requirement (CWR), and irrigation requirement (IR) may be significantly overestimated. These discrepancies highlight the need for a critical reassessment of the existing methodology to ensure water resources are managed efficiently and sustainably. The present study aims to evaluate the accuracy of ET₀ and IR estimates under current climatic and agricultural conditions and to recommend appropriate updates to the TC-25 methodology. The objective is to identify reliable, data-efficient, and freely accessible estimation methods or software tools that are adaptable to the evolving environmental and farming scenarios in the region.

To achieve this, ET₀ has been estimated using historical climatic data, covering all eleven agro-climatic zones of Madhya Pradesh. This broad analysis provides a comprehensive understanding of ET₀ variability across different geographic and climatic settings. However, certain factors such as changes in soil characteristics, cropping patterns, and farming practices require primary data collection, which is typically unavailable from secondary sources. To address these ground-level variables, Kolar Dam and its command area have been selected as a representative irrigation project for conducting detailed field surveys and hydrological assessments. This site enables validation of ET₀ estimates and supports the development of improved irrigation planning strategies aligned with current and future needs.

This section provides a detailed discussion on the Design Series Technical Circular-25 (TC-25), the methods used for estimating potential evapotranspiration (ET₀), the selected study areas, and the approach adopted for comparison and evaluation. It outlines the methodology for analyzing ET₀ estimates, the criteria for selecting representative regions, and the process used to assess and compare the accuracy and applicability of different estimation methods.

3.1 Design Series Technical Circular-25 (TC-25)

In Madhya Pradesh, crop water and irrigation requirements have traditionally been estimated using methodologies outlined in the Design Series Technical Circular-25 (TC-25) issued in 1990 vide Momo No. 205/BODHIR&C/TC/11/88/ Dated 20/06/1990 for “Estimation of Crop Water Requirement and Irrigation Water Requirement”. The procedure of ET₀ estimation is described briefly below.

- TC-25 has a Step-by-step procedure to compute fortnightly CWR and IR for a crop.
- Computation of gross irrigation requirement (considering system efficiency)
- Method Used for ET₀ estimation: Modified Penman
- Standard Tables:

- ✓ Planting dates and duration of crops
- ✓ Fortnightly ETo Values of all districts of MP using the Modified Penman method
- ✓ Values of Crop factors
- ✓ Average monthly effective rainfall w.r.t mean monthly rainfall
- ✓ Table of recommended efficiencies of a canal system
- In TC-25, the Crop Water Requirement (CWR) is represented as a “**Demand**” of the crop and expressed as given in Equation 3.1.

$$CWR = ETc + SPL + PL \quad \text{Equation 3.1}$$

ETc - Water required for consumptive use

SPL - Special needs like land preparation, palewa, nursery, and transplantation

PL - Percolation (needed only for ponded crops like paddy)

- The CWR could be met with by any one or more of the following sources, such as Irrigation water, Effective rainfall in the cropped area, Available soil moisture, and Ground water contribution, thus it is expressed as given in Equation 3.2.

$$CWR + LR = IR + ER + SM + GW \quad \text{Equation 3.2}$$

Where

IR - Irrigation water

ER - Effective rainfall in the cropped area

SM - Available soil moisture

GW - Ground water contribution

LR - Leaching requirement

- The Irrigation water requirement (IR) may be termed as “**Supply**” to the crops. Thus, it is expressed as given in Equation 3.3.

$$IR = CWR - ER - SM - GW + LR \quad \text{Equation 3.3}$$

In MP, for most of the crops, the depth of groundwater is deeper than the specific depth contribution to CWR by groundwater (GW) is ignored in the calculation. In MP, there is generally no problem of shallow groundwater table; therefore, the leaching requirement (LR) is generally ignored in calculations. Thus, in MP, the values of GW and LR are ignored in the CWR calculation.

The Technical Circular-25 (TC-25) provides comprehensive reference tables for crop planting dates and crop durations. It includes district-wise values of potential evapotranspiration (ETo) calculated using the Modified Penman method, crop coefficient (Kc) values, and average

monthly effective rainfall across Madhya Pradesh. The circular also presents several illustrative examples for estimating crop water requirements for various Kharif, Rabi, and summer crops, including different crop varieties with varying durations. These guidelines assist field engineers in formulating effective irrigation plans and developing appropriate irrigation schedules tailored to specific command areas within the state.

3.2 ET_o Estimation using Empirical and Rational Methods

In this study, four widely recognized methods for estimating potential evapotranspiration (ET_o), Blaney-Criddle, Hargreaves, Modified Penman, and FAO Penman-Monteith methods were employed for comprehensive analysis and comparison. The primary objective was to identify the most suitable method for application across the diverse eleven agro-climatic zones of Madhya Pradesh. Each method was evaluated based on its input requirements, adaptability to varying climatic conditions, and accuracy in ET_o estimation. These four methods are discussed in detail below.

3.2.1 Blaney-Criddle Method

The Blaney-Criddle method, developed by Harry F. Blaney and Wayne D. Criddle in the 1950s, is a semi-empirical approach for estimating potential evapotranspiration (ET_o) based on readily available air temperature data. The core principle underlying the Blaney-Criddle method is the idea that evapotranspiration is directly related to temperature-driven energy available for evaporation and a crop's ability to utilize that energy. The method assumes a proportional relationship between ET_o and mean monthly temperature, with adjustments made for day length and a crop coefficient. The Blaney-Criddle method is an empirical approach for estimating reference evapotranspiration (ET_o) as given in Equation 3.4, and it is primarily based on temperature and daylight hours. It is widely used in semi-arid and arid regions where more detailed meteorological data is unavailable.

$$ET_o = p (0.46T + 8.188) \quad \text{Equation 3.4}$$

Where,

ET_o = Reference evapotranspiration (mm/day)

p = Monthly percent of total daytime hours of the year (varies with latitude)

T = Mean daily temperature (°C) (average of daily maximum and minimum)

The Blaney-Criddle method estimates evapotranspiration by relating mean temperature and the percentage of annual daytime hours. It is a straightforward and practical approach for estimating ET_o, especially in semi-arid and arid regions where only temperature data is available. However, it lacks the accuracy of the Penman-Monteith method, particularly in humid or windy conditions. Despite its limitations, it remains a valuable tool for large-scale irrigation planning and water management.

This method has certain limitations. It is Less Accurate as it does not consider relative humidity, wind speed, or solar radiation, leading to lower accuracy in humid or windy climates. It is not suitable for Short-Term Predictions and is best for monthly or seasonal rather than daily estimates.

3.2.2 Hargreaves Method

The Hargreaves method is based on the concept that temperature and solar radiation are the primary drivers of evapotranspiration. The equation proposed by Hargreaves (Hargreaves and Samani, 1985) is based on the idea that the temperature range between the daily maximum and minimum values reflects the potential for evaporation. Additionally, solar radiation is considered a key factor in determining the energy available for evaporative processes, it is as expressed in Equation 3.5.

$$ET_0 = 0.0023 * \sqrt{T + 17.8} * (T_{\max} - T_{\min}) * (T + 17.8)^{0.5} \quad \text{Equation 3.5}$$

T_{\max} and T_{\min} are the daily maximum and minimum air temperatures (°C). The Hargreaves method is a simpler and empirical approach for estimating reference evapotranspiration (ET₀) based on temperature variations. It does not require detailed meteorological data such as wind speed, humidity, or radiation, making it useful in data-scarce regions. Though it lacks the precision of Penman-Monteith, it remains valuable for climate modeling, irrigation planning, and large-scale hydrological assessments.

3.2.3 Modified Penman Method

The Penman Equation, developed by Howard Penman in 1948, stands as a widely recognized method for estimating potential evaporation across diverse surfaces. This equation integrates both aerodynamic and energy balance components to furnish a comprehensive assessment of evaporation. In 1977, Doorenbos and Pruitt modified the Penman method, documented in FAO's Irrigation and Drainage Paper 24. This modification was grounded on the premise that evapotranspiration from grass predominantly responds to climatic conditions. Their adaptation, known as the Modified Penman method for grass reference evapotranspiration, simplifies the original equation for practical use, specifically in estimating evapotranspiration for well-watered, actively growing grass with fixed height.

The Modified Penman Method is an improved version of the original Penman equation, used to estimate evapotranspiration (ET₀), the sum of evaporation and plant transpiration. It is widely used in agriculture, hydrology, and water resource management for irrigation planning and water budgeting. The method integrates energy balance and aerodynamic approaches, accounting for net radiation, temperature, humidity, and wind speed. The Modified Penman Method Formula is given in Equation 3.6.

$$ET_0 = \frac{0.408 * \Delta * (R_n - G) + \gamma * \left(\frac{900}{T+273}\right) * U * e_s}{\Delta + \gamma * (1 + 0.34 * U)} \quad \text{Equation 3.6}$$

$$\Delta = \frac{4098 * (0.6108 * e^{\frac{(17.27 * T)}{(T + 237.3)}})}{(T + 237.3)^2}$$

Where,

- ET₀ is the reference evapotranspiration (mm/day),
- Δ is the slope vapor pressure curve (kPa/°C),
- R_n is the net radiation at the crop surface (MJ/m²/day),
- G is the soil heat flux density (MJ/m²/day),
- γ is the psychrometric constant (kPa/°C),
- T is the mean daily air temperature (°C),
- U is the wind speed at 2 meters above ground level (m/s),
- e_s is the saturation vapor pressure (kPa).

The Modified Penman Method remains a cornerstone in irrigation planning and hydrological modeling, ensuring efficient water use in both arid and humid regions.

3.2.4 FAO Penman-Monteith Method

The Penman-Monteith equation is a widely used method for calculating reference evapotranspiration (ET₀), which represents the evaporative demand of the atmosphere. Developed by Howard Penman and Roger Monteith, the Penman-Monteith equation integrates both aerodynamic and energy balance components to furnish a comprehensive assessment of evaporation.

The Penman-Monteith equation is a globally accepted standard for estimating reference evapotranspiration (ET₀). This method integrates multiple climatic parameters to estimate water loss due to both evaporation and transpiration from a reference surface (typically a well-watered grass field). The FAO-56 Penman-Monteith equation (Allen et al., 1998) is expressed as Equation 3.7.

$$ET_0 = \frac{0.408 * \Delta * (R_n - G) + \gamma * \frac{900}{(T + 273)} * U * (e_s - e_a)}{\Delta + \gamma * (1 + 0.34 * U)} \quad \text{Equation 3.7}$$

Where:

- ET₀ = Reference evapotranspiration (mm/day)
- R_n = Net radiation at crop surface (MJ/m²/day)
- G = Soil heat flux density (MJ/m²/day)
- T = Mean daily air temperature (°C)
- u₂ = Wind speed at 2 m height (m/s)

- e_s = Saturation vapor pressure (kPa)
- e_a = Actual vapor pressure (kPa)
- $e_s - e_a$ = Vapor pressure deficit (kPa)
- Δ = Slope of the saturation vapor pressure curve (kPa/°C)
- γ = Psychrometric constant (kPa/°C)

The Penman-Monteith equation is widely considered the most accurate method for ETo estimation due to its ability to account for multiple climatic factors. (Smith et al., 1998). It provides better precision compared to simpler methods. It adjusts for regional variations, making it suitable for humid, arid, and semi-arid regions. This is recommended by FAO-56; it serves as the standard for agricultural water management and irrigation planning. The Penman-Monteith method remains the gold standard for ETo estimation due to its precision and adaptability. Its integration with remote sensing, AI, and climate modeling ensures sustainable water resource management, particularly in semi-arid regions like Madhya Pradesh.

3.3 Study Area and Data Used

3.3.1 Study Area

In the present study, the ETo estimation was carried out for all eleven agro-climatic zones of Madhya Pradesh as shown in Figure 3.1. Madhya Pradesh, the second-largest state in India, spans a total geographical area of approximately 308,000 km² and is home to a population of around 75 million people, following the separation of Chhattisgarh. Geographically, the state is bisected by the sacred Narmada River, which flows east to west between the Vindhyan and Satpura mountain ranges. A significant portion of the state falls within the catchment areas of major tributaries of the Yamuna and Ganga rivers, including the Chambal, Betwa, Parvati, Kali Sindh, Son, Ton, Ken, and Dhasan rivers.

The state experiences a predominantly subtropical climate, typical of much of northern India. It is characterized by a hot, dry summer from April to June, followed by the southwest monsoon season from July to September, and a cooler, relatively dry winter from October to March. The average annual rainfall is about 1,371 mm, the majority of which is contributed by the southwest monsoon. The present research has been conducted across the state of Madhya Pradesh, with particular focus on its 11 distinct agroclimatic zones. This includes drought-prone regions such as Bundelkhand, Malwa, and the southern districts, which are particularly vulnerable to seasonal water stress. During drought years, the situation becomes even more severe, leading to acute water scarcity that impacts irrigation, domestic water usage, and industrial supply systems. The state exhibits a variety of soil types, including alluvial soil along river plains, black soil in the Malwa Plateau, and red and yellow soils in the Satpura and Vindhya Plateaus.

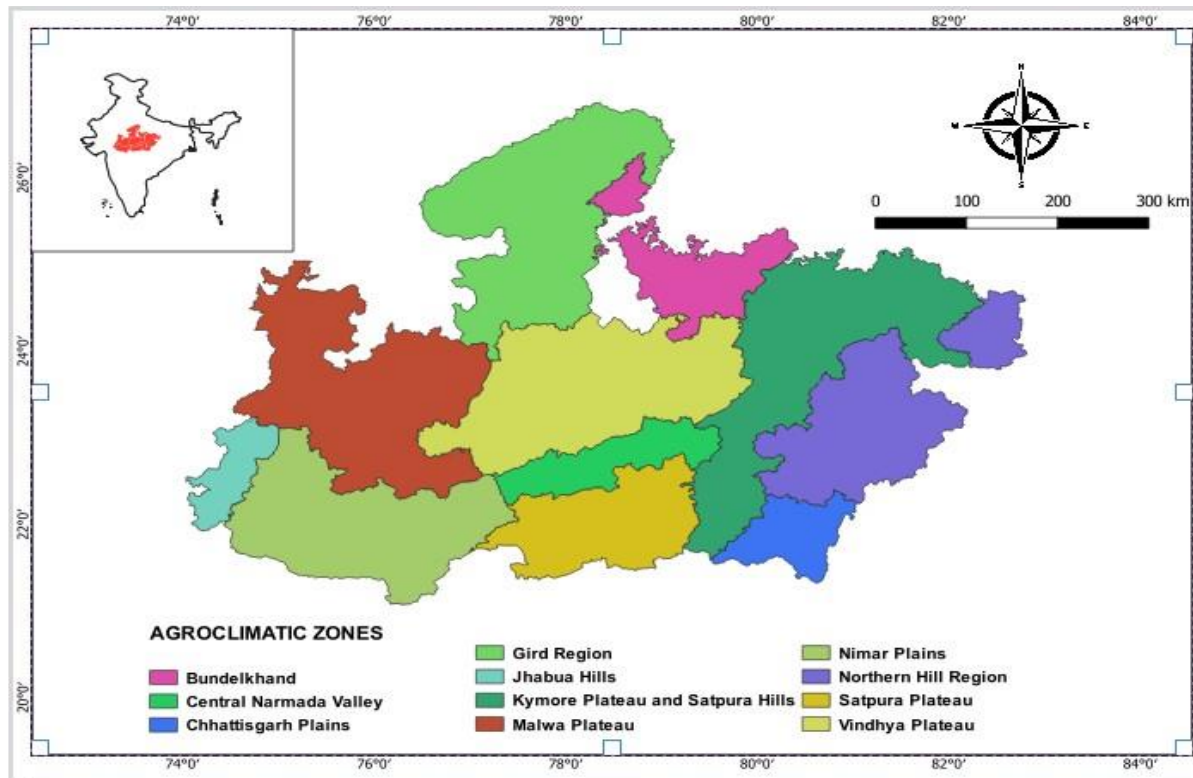


Figure 3.1 Agroclimatic Zones of Madhya Pradesh

Madhya Pradesh, with its diverse agro-climatic and topographical conditions, supports the cultivation of a wide range of cereals, pulses, oilseeds, and cash crops. The state is a leading producer of soybeans, wheat, gram, mustard, and linseed. It is divided into 11 agro-climatic zones based on rainfall, soil type, and cropping patterns. Crop distribution varies regionally: rice dominates the east, wheat and cotton the central region, and cotton and jowar the west. Major Kharif crops include soybean, chickpea, and pigeon pea, while Rabi crops include wheat, gram, lentil, mustard, and paddy. Zone-wise classifications, crop types, and rainfall ranges are detailed in Table 3.1.

3.3.2 Data Used

The study employs meteorological and agroclimatic data from 1990 to 2022, including temperature, humidity, wind speed, and solar radiation, collected from the NASA POWER website for all the districts of Madhya Pradesh. The IMD gridded data from 1960 to 2020 were also used as inputs for the Blaney-Cridde, Hargreaves, Modified Penman, and Penman-Monteith, and to estimate Reference Evapotranspiration (ET_o). The results were statistically analyzed to evaluate the performance of each method in capturing the region-specific climatic variations.

Table 3.1: Agroclimatic Zones of Madhya Pradesh

Zone No.	Agroclimatic zones	Rainfall range (mm)	Districts covered	Crop zones
I	Chhattisgarh plains	1200 to 1600	Balaghat	Rice
II	Northern Hill Region of Chhattisgarh	1200 to 1600	Shahdol, Mandla, Dindori, Anuppur, Umaria,	Rice
III	Kymore Plateau & Satpura Hills	1000 to 1400	Rewa, Satna, Panna, Jabalpur, Seoni, Katni, Sidhi (Partly), Singrauli	Wheat Rice
IV	Central Narmada Valley	1200 to 1600	Narsingpur, Hoshangabad	Wheat
V	Vindhya Plateau	1200 to 1400	Bhopal, Sagar, Damoh, Vidisha, Raisen (Partly), Sehore (Partly)	Wheat
VI	Gird Region	800 to 1000	Gwalior, Bhind, Morena, Sheopur, Shivpuri (Partly), Guna, Ashoknagar	Wheat- Jowar
VII	Bundelkhand	800 to 1400	Chhatarpur, Datia, Tikamgarh, Niwari	Wheat- Jowar
VIII	Satpura Plateau	1000 to 1200	Betul & Chhindwara	Wheat- Jowar
IX	Malwa Plateau	800 to 1200	Mandsaur, Neemach, Ratlam, Ujjain, Dewas, Indore, Shajapur, Rajgarh, Dhar (Partly), Agar	Cotton Jowar
X	Nimar Plains	800 to 1000	Khandwa, Burhanpur, Khargone, Barwani, Harda	Cotton Jowar
XI	Jhabua Hills	800 to 1000	Jhabua, Alirajpur	Cotton Jowar

3.4 Open-Source Software for ETo Estimation

In the present study, CROPWAT and ET Calculator, which are free Online softwares, were used for ETo estimation.

3.4.1 CROPWAT Software

CROPWAT is a widely used decision-support software developed by the Food and Agriculture Organization (FAO) of the United Nations. It is designed to assist in the planning and management of irrigation systems and agricultural water use. The software enables the estimation of crop water requirements (CWR), irrigation scheduling, and reference evapotranspiration (ET_0) using climatic, crop, and soil data as shown in Figure 3.2. Built around the principles outlined in FAO Irrigation and Drainage Paper No. 56, CROPWAT supports professionals, researchers, and policymakers in making informed decisions for efficient and sustainable agricultural water management.

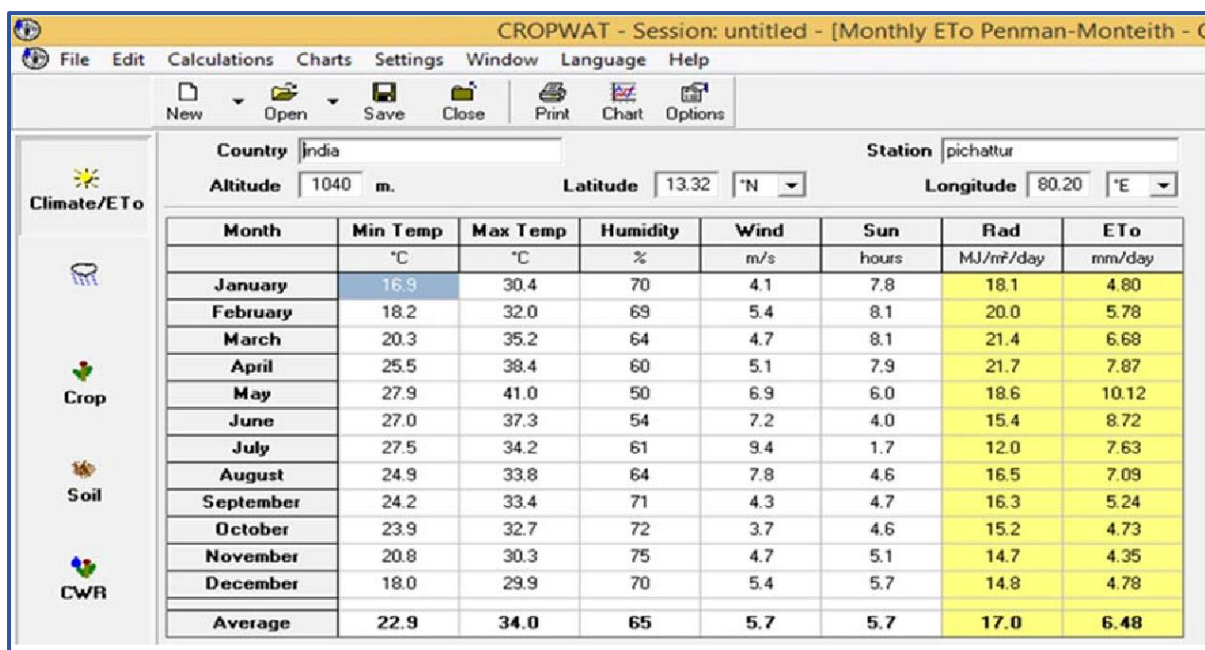


Figure 3.2: CROPWAT Software interface

CROPWAT uses the FAO Penman-Monteith method, a globally accepted standard for ETo estimation, ensuring consistency with international guidelines. It allows users to input climate parameters such as maximum and minimum temperature, relative humidity, wind speed, and sunshine hours to calculate ETo. From this, it derives crop evapotranspiration (ETc) using crop-specific coefficients (Kc) across different growth stages. The software also includes functions for estimating the study Area using methods like USDA or fixed percentages, helping refine irrigation requirements based on actual water availability from precipitation.

The software features built-in databases for a wide variety of crops and soils. Crop data includes growth stages, rooting depths, depletion fractions, and yield response factors (Ky), while soil data allows users to define moisture retention characteristics, infiltration rates, and allowable depletion. With this information, CROPWAT can develop detailed irrigation schedules, calculate yield reduction due to water stress, and help identify periods of water deficit during the crop growth cycle.

CROPWAT is applicable in a broad range of agricultural and water resource planning activities. It is commonly used for designing irrigation schedules for field crops, estimating seasonal irrigation water demand, and evaluating climatic impacts on crop water use. Its accessibility and ease of use make it a preferred tool in both government and development agency projects focused on sustainable agriculture.

CROPWAT is freely available for download from the official FAO website. It is a lightweight Windows-based application and can be installed easily on most personal computers. CROPWAT has several advantages that contribute to its widespread adoption. It is scientifically accurate, following FAO-56 guidelines for ETo and crop water estimation. The

software is user-friendly, with a simple interface that allows straightforward data input and output. It accommodates both basic and advanced data inputs, making it adaptable to data-rich and data-scarce environments. It includes a comprehensive crop and soil database, reducing the need for external datasets. CROPWAT is freely accessible, making it ideal for use in developing countries and educational institutions.

Despite its strengths, CROPWAT has a few limitations, such as its lack of integration with GIS tools, which restricts its use in spatial analysis or mapping applications. It does not support real-time data integration, such as importing automated weather data or sensor inputs. Visualization capabilities are limited, offering only basic tabular and graphical outputs.

3.4.2 ETo Calculator

The FAO ETo Calculator is a specialized software tool developed by the Food and Agriculture Organization (FAO) to estimate reference evapotranspiration (ET_0) using the standardized FAO Penman-Monteith method. It is designed for use in irrigation planning, crop modeling, water resource assessments, and agricultural research. The software provides a consistent and reliable means of calculating ET_0 based on available climatic data, forming the basis for more complex analyses such as crop water requirements (ET_c) and irrigation scheduling when used alongside tools like CROPWAT. The ETo Calculator Software interface is shown in Figure 3.3.

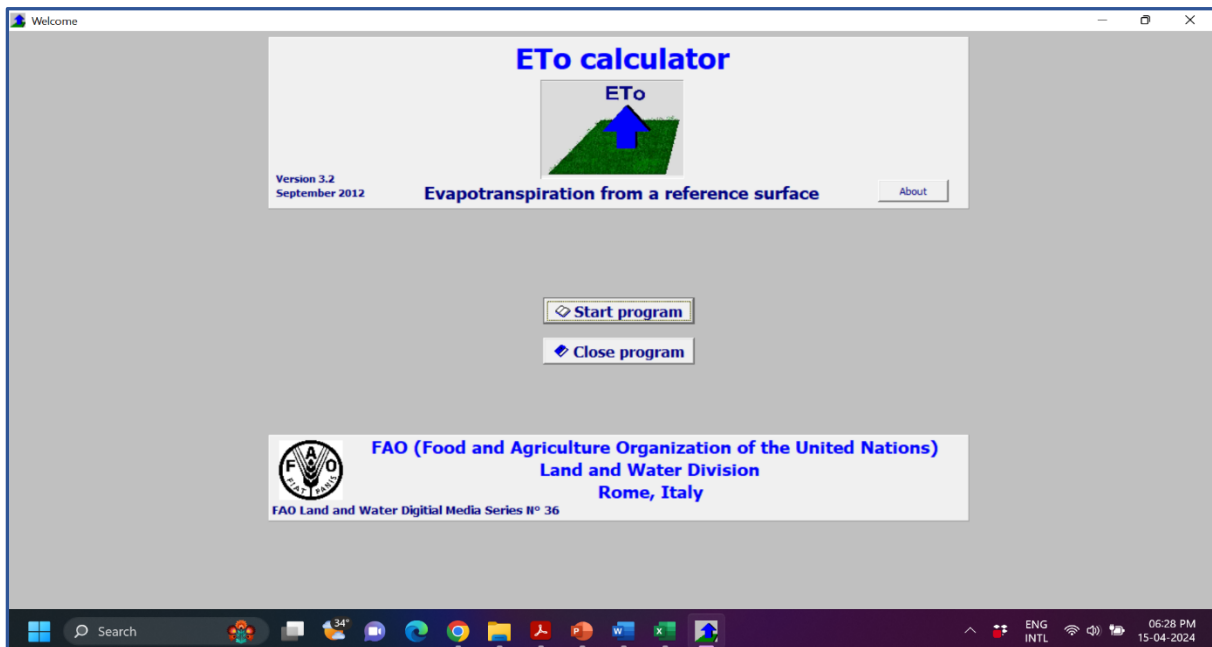


Figure 3.3: ETo Calculator Software interface

The primary function of the ET Calculator is to compute reference evapotranspiration, a key parameter in determining how much water crops require under standard conditions. ET_0 is calculated using the FAO-56 Penman-Monteith equation, which is recognized globally for its

accuracy and scientific rigor. The software uses standard meteorological inputs, including maximum and minimum temperature, relative humidity, wind speed, and solar radiation or sunshine hours. If solar radiation is unavailable, the tool can estimate it from sunshine hours or even infer it from temperature and latitude data. The software supports calculations over different time steps, daily, ten-day, and monthly, which allows users to tailor the analysis according to the needs of their irrigation schedule or research study.

FAO ET Calculator includes several built-in computational tools to automate important components of the ET_0 equation. These include:

- Atmospheric pressure estimation from elevation.
- Slope of the saturation vapor pressure curve, based on temperature.
- Psychrometric constant calculations using standard atmospheric conditions.
- Vapor pressure and saturation vapor pressure values.

The software also requires site-specific inputs such as latitude, altitude, and wind speed measurement height, which help adjust the climatic data to local conditions. The tool accepts manual data entry and allows users to create and save projects for different locations.

FAO ET Calculator is free to download and use, and does not require an internet connection after installation. It is a lightweight application compatible with Windows operating systems. It is ideal for users in areas with limited internet access or computing resources. The ET Calculator is a valuable tool for a wide range of applications, including irrigation scheduling and design, especially in areas where only climate data is available. It is also capable of water resource planning and allocation at a farm or regional level. It works for hydrological modeling where ET_0 is needed as an input variable. It is also helpful in agricultural and climate research, including drought analysis and agroclimatic zoning.

One of the major strengths of the ET Calculator is its scientific reliability. By strictly following FAO-56 guidelines, the software ensures that ET_0 estimates are compatible with global best practices. Its simple interface makes it user-friendly even for those with limited technical expertise. It is especially valuable in data-scarce environments, as it can estimate missing inputs such as solar radiation or vapor pressure. Furthermore, the software works without internet connectivity, making it ideal for field conditions and remote locations. It supports multiple time-step calculations and can handle long-term climate data series.

Despite its usefulness, the ET Calculator has certain limitations. It is limited to ET_0 calculation only and does not estimate crop evapotranspiration (ET_c), crop water requirement (CWR), or irrigation requirement (IR). The interface is dated, with minimal graphical or visualization capabilities. It lacks integration with GIS platforms or real-time weather stations. All data must be entered manually; there is no automated data import from meteorological APIs or online databases. It does not support spatial analysis or mobile/web-based usage.

3.4.3 Development of Excel-Based Dashboard for ETo Estimation

In the present study, the ETo estimation dashboard was developed as a computational tool to estimate daily potential evapotranspiration (ETo) for a specific geographic location using four established methods: FAO Penman-Monteith, Modified Penman, Hargreaves, and Blaney-Criddle, as shown in Figure 3.4. These methods represent a range of complexity, from physically based models to simpler empirical formulas, providing users with flexible options based on the availability and quality of meteorological data. The step-by-step process of developing the ETo estimation dashboard is discussed in detail below. The manual for the use of the ETo estimation dashboard is given in **Annexure I**

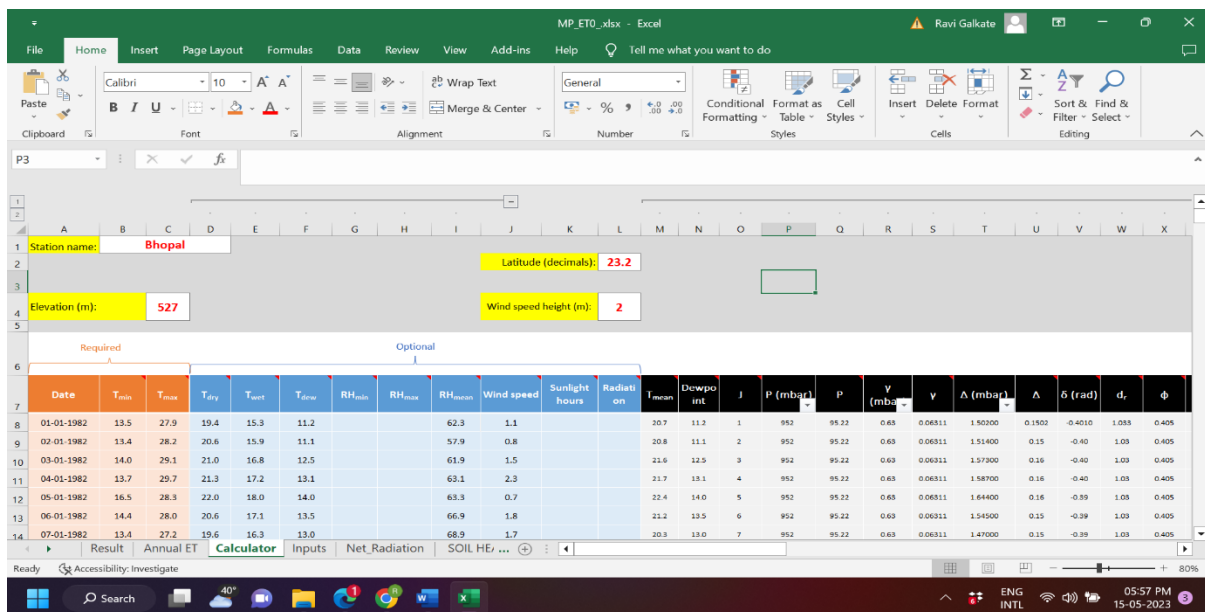


Figure 3.4: Excel-based dashboard for ETo estimation

3.4.3.1 Station configuration and geographical constants

At the core of the ETo calculations is the accurate specification of station-specific constants, which are manually entered by the user at the outset. These constants include:

- Station Name: A unique identifier for the data source.
- Latitude (decimal degrees): Used to determine solar geometry such as solar declination and daylight hours, which are crucial for radiation-based calculations.
- Elevation (m): Elevation above sea level is used to estimate atmospheric pressure, a critical factor in the psychrometric constant and related calculations.
- Wind Speed Measurement Height: Necessary to standardize wind speed measurements to the reference height of 2 meters, as required by some methods.

These geographic and station-specific parameters form the basis for several internally calculated variables used throughout the estimation process.

3.4.3.2 Meteorological input data and classification

The dashboard classifies input meteorological data into required and optional categories to accommodate varying levels of data availability:

- Required Inputs (essential for all or most methods):
 - ✓ Date: Used to compute the Julian day and track seasonal variations.
 - ✓ Maximum Temperature (T_{max}) in °C
 - ✓ Minimum Temperature (T_{min}) in °C
- Optional (but highly beneficial) Inputs:
 - ✓ Average Temperature (T_{avg}): Usually computed as $(T_{max} + T_{min}) / 2$.
 - ✓ Dew Point Temperature (T_{dew}): Either measured or estimated; vital for vapor pressure calculations.
 - ✓ Relative Humidity (RH_{max} , RH_{min} , RH_{mean}): Used in the computation of actual vapor pressure and radiation terms.
 - ✓ Wind Speed (U_{2m}): Measured at or adjusted to 2 m height.
 - ✓ Sunshine Hours (n): Useful for radiation-based methods like Penman and Hargreaves.

These input parameters are supplied by the user in a standardized format, allowing for automated processing within the dashboard.

3.4.3.3 Internal calculations and derived parameters

To support accurate ET_0 estimation, the dashboard automatically computes a range of derived parameters that are required by the various methods:

- Atmospheric Pressure (P): Estimated from the elevation using the barometric formula. This pressure is necessary for calculating the psychrometric constant, a key component in the Penman-based equations.
- Psychrometric Constant (γ): Computed using:
 - ✓ Specific heat of air (cp),
 - ✓ The molecular weight ratio of water vapor to dry air (ϵ),
 - ✓ Latent heat of vaporization (λ).

This constant reflects the relationship between heat and moisture in the air and is essential for modeling evapotranspiration under varying humidity conditions.

- Slope of Saturation Vapour Pressure Curve (Δ):

A temperature-dependent variable representing how rapidly vapor pressure changes with temperature. It plays a central role in the FAO Penman-Monteith method.

- Daylight Hours (N): Determined based on the Julian day and latitude, this parameter is used to estimate solar radiation and evaporation potential. Calculation steps include:
 - ✓ Determining solar declination (δ)
 - ✓ Calculating the sunset hour angle (ω_s)
 - ✓ Estimating extraterrestrial radiation (R_a)

- ✓ Final computation of N using astronomical equations.

- Dew Point Temperature (T_{dew}):

If not directly available, T_{dew} is estimated using the approximation:

- ✓ $T_{dew} = T_{min} - 2^{\circ}C$

This estimate is based on FAO guidelines and is particularly useful when humidity data is missing. These derived parameters enhance the accuracy of ET_0 estimation, especially when certain meteorological variables are not available.

3.4.3.4 Implementation of ET_0 estimation methods

The dashboard includes four ET_0 estimation techniques, each appropriate for a variety of data scenarios and covered in depth in this report:

- FAO Penman-Monteith Equation

This is the most comprehensive and recommended method, integrating the effects of radiation, temperature, wind speed, and humidity. It follows the FAO-56 guidelines and includes:

- ✓ Net radiation (R_n)
- ✓ Soil heat flux (G), typically set to 0 for daily time steps
- ✓ Saturation (e_s) and actual vapor pressure (e_a)
- ✓ Wind function at 2 meters

It provides the most accurate estimates when full meteorological data is available.

- Modified Penman Equation

An empirical variation of the original Penman method, it includes:

- ✓ A temperature and altitude-based weighting factor (W)
- ✓ A wind function $f(u)$

It is suitable when solar radiation and temperature data are available but relative humidity data may be limited.

- Hargreaves Equation

This method estimates ET_0 using:

- ✓ Maximum and minimum temperatures
- ✓ Extraterrestrial radiation

It is useful in data-sparse regions, requiring only basic temperature and location data. The radiation coefficient kR_s (typically 0.16 for interior regions) can be adjusted by the user.

- Blaney-Criddle Method

An older empirical method that uses:

- ✓ Average temperature
- ✓ Daylight percentage (p), which is derived from latitude and month

This method is simpler and can be used when radiation or wind speed data are unavailable.

Each method is implemented in a modular manner within the dashboard, allowing users to choose methods based on their data availability and accuracy needs.

3.4.3.5 Computational framework and embedded constants

To ensure accurate and standardized calculations, the dashboard uses well-established constants embedded into the algorithms, such as:

- Stefan-Boltzmann constant (σ): 4.90×10^{-9}
- Angstrom coefficients ($a_s = 0.25$, $b_s = 0.50$)
- Crop albedo (α): 0.23
- Specific heat of air (c_p): 0.001013 MJ/kg°C
- Psychrometric coefficient base value (ψ): 0.000665
- Adjustment factor (c): 1.06 for Modified Penman
- Radiation coefficient (k_R s): 0.16 for Hargreaves method

These constants ensure the dashboard adheres to internationally recognized practices in agrometeorological modeling.

3.4.3.6 Result compilation, comparison, and visualization

After calculations, the dashboard compiles the ET_0 values from all four methods into a centralized pivot table. This table supports:

- Daily comparison of ET_0 estimates across methods
- Temporal aggregation into monthly or seasonal summaries
- Statistical analysis to identify trends or anomalies
- Graphical visualization (if enabled), aiding decision-making for irrigation, crop modeling, or climate studies

This comprehensive output allows users not only to calculate ET_0 but also to critically analyze and compare different estimation approaches under variable climatic conditions. This methodological framework ensures that the ET_0 dashboard remains a robust, adaptable, and scientific tool for irrigation planning, water resource management, and climate impact assessment.

3.4.4 Comparison of ET_0 Estimation using Different Data Sets, Tools and Methods

In this study, multiple climatic datasets, software tools, and estimation methods were used to calculate reference evapotranspiration (ET_0) to identify the most accurate and user-friendly approach suitable for field-level application. The analysis utilized gridded data from the India Meteorological Department (IMD) from 1960 to 2020, as well as NASA POWER data from 1980 to 2020. To estimate ET_0 , three tools were employed: FAO's CROPWAT (desktop), FAO's ET Calculator (online), and a custom-developed Excel-based ET_0 Dashboard. These platforms applied four commonly used methods, Hargreaves, Blaney-Criddle, Modified Penman, and FAO Penman-Monteith methods, as shown in Figure 3.5.

The primary objective was to compare the performance, ease of use, and data requirements of each method and software to recommend a reliable and accessible approach that can be

effectively used by field officers with limited computing and internet resources. By cross-analyzing outputs from different methods and tools, the study aims to suggest the most practical and efficient solution for ETo estimation in the varied agro-climatic conditions of Madhya Pradesh.

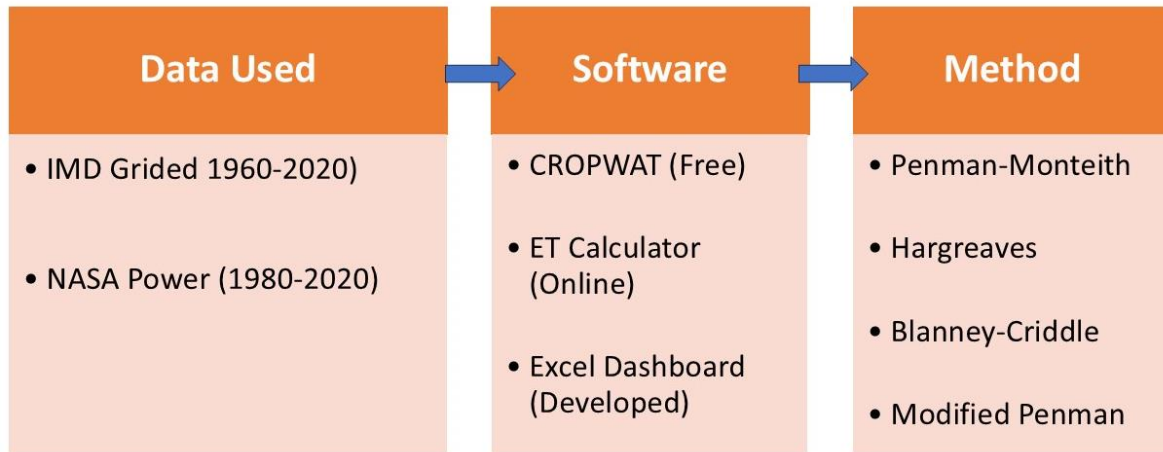


Figure 3.5: Multiple datasets, software tools, and estimation methods used for ETo Estimation

3.4.5 Climate Change Impacts on ETo Estimation.

Climate change refers to long-term alterations in temperature, precipitation patterns, and other aspects of Earth's climate system, primarily driven by increased greenhouse gas emissions from human activities such as fossil fuel combustion and deforestation (IPCC, 2021). In India, particularly in Central India and Madhya Pradesh, climate change has led to a noticeable rise in average temperatures (IMD, 2020). Warmer temperatures intensify heatwaves and increase the rate of evapotranspiration, affecting crop water requirements and irrigation demand (Jain et al., 2017). This can reduce soil moisture and stress crops, especially during dry spells, thereby increasing the need for supplemental irrigation. Additionally, climate change has disrupted monsoonal rainfall patterns, making precipitation more erratic and intense, which may affect the effective rainfall that governs the water requirement of crops (Mall et al., 2006).

The Central India region has experienced a paradoxical trend of declining rainy days but increasing rainfall intensity, leading to higher risks of both droughts and floods (Roxy et al., 2017). Such variability impacts agricultural productivity, water availability, and ecosystem stability. Projections suggest these trends may worsen, emphasizing the need for adaptive strategies and evidence-based policy decisions for irrigation planning in Madhya Pradesh. In this study, a comprehensive review of the literature will be conducted to assess the impact of climate change on irrigation and crop water requirements, thereby aiding informed policy formulation.

3.4.6 Field Survey (Primary Data Collection)

In the present study, understanding critical factors such as changes in soil characteristics, cropping patterns, and farming practices required the collection of primary data, as this information is generally not available through secondary sources. To address these ground-level variables, a sample survey was conducted in the Kolar Dam command area.

A total of 40 farmers were interviewed, representing a range of landholding sizes from marginal farmers (2 to 5 hectares) to large farmers (more than 5 hectares). A structured questionnaire was designed to gather comprehensive information on key aspects, including landholdings, water availability across the head, middle, and tail reaches of the canal system, canal conditions, irrigation methods adopted, cropping intensity, and changes in soil conditions observed over the past 20–25 years. Additional information was collected on cropping pattern shifts, leaching effects, groundwater table trends, and the role of Water User Associations (WUAs) in water management. The collected data was systematically analyzed using basic statistical techniques to extract required insights supporting the objectives of the study.

3.4.6.1 Study area for field survey: Kolar irrigation project

Kolar Dam is located near Birpur village in Sehore district, approximately 30 km from Bhopal, Madhya Pradesh. It is constructed across the Kolar River, a tributary of the Narmada. The Kolar dam lies within the Narmada basin, covering a catchment area of 502 km². It supports an irrigation potential of 45,040 ha with a Culturable Command Area (CCA) of 45,087 ha and a Gross Command Area of 62,752 ha, extending into Raisen, Dewas, and Bhopal districts.

The dam, a homogeneous earthen embankment, is 1,242 m long with a maximum height of 45 m and a live storage capacity of 265 MCM. Water is released to the Jholiapur barrage, from which two main canals, Right Bank Canal (42.1 km + 149 km distributaries) and Left Bank Canal (46.77 km + 204.76 km distributaries) are operated.

The region has a warm temperate climate with an average annual temperature of 25.3°C and rainfall of about 1,230 mm, mainly from the southwest monsoon. DEM analysis shows elevations ranging from 433 to 609 m, with the northwest being more elevated. Soils are predominantly black cotton soil, ideal for crops like wheat, cotton, millets, and jowar. Wheat is the major Rabi crop in the command area. The location map of Kolar dam, its catchment area, and the command area canal network are given in Figures 3.6 and 3.7.

3.4.6.2 Data used

Various datasets were used for the study, including SRTM DEM (30 m resolution), topographical maps (9 Survey of India toposheets), and 27 years of meteorological data from IMD, Bhopal (1987–2016). Using GIS tools (ArcSWAT and QGIS 3.16), stream networks, catchment areas, and canal command areas were delineated and analyzed for hydrological planning and water resource management.

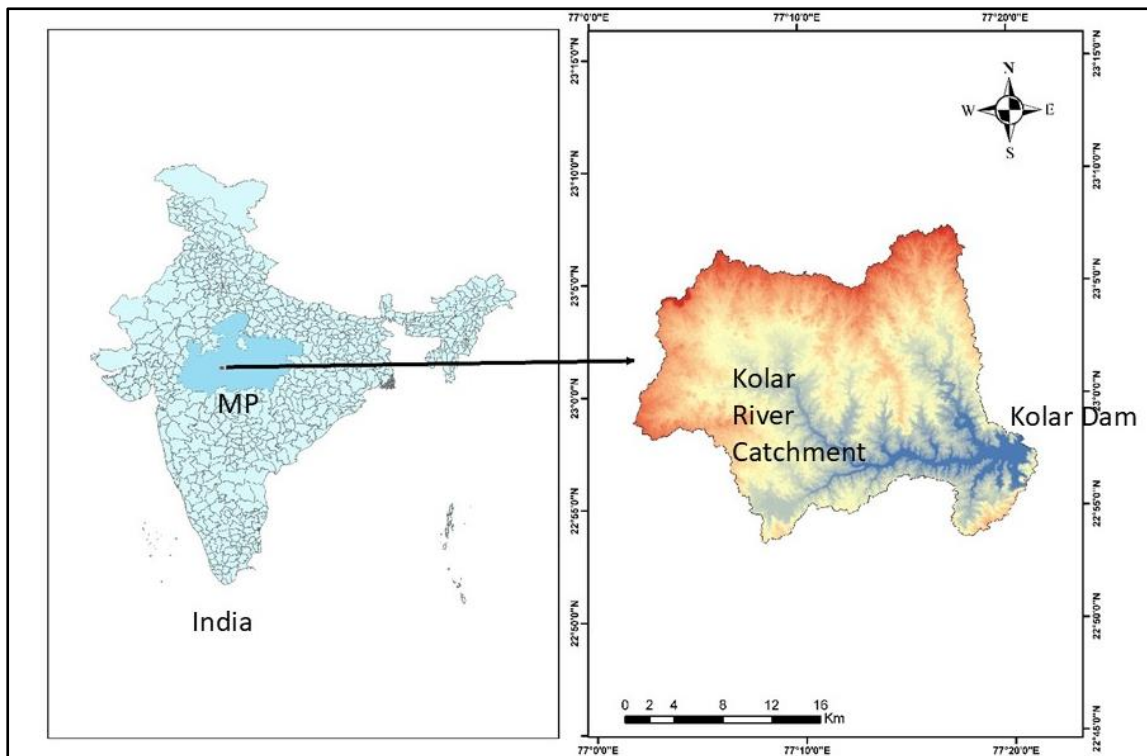


Figure 3.6: Location map of Kolar dam and its catchment area

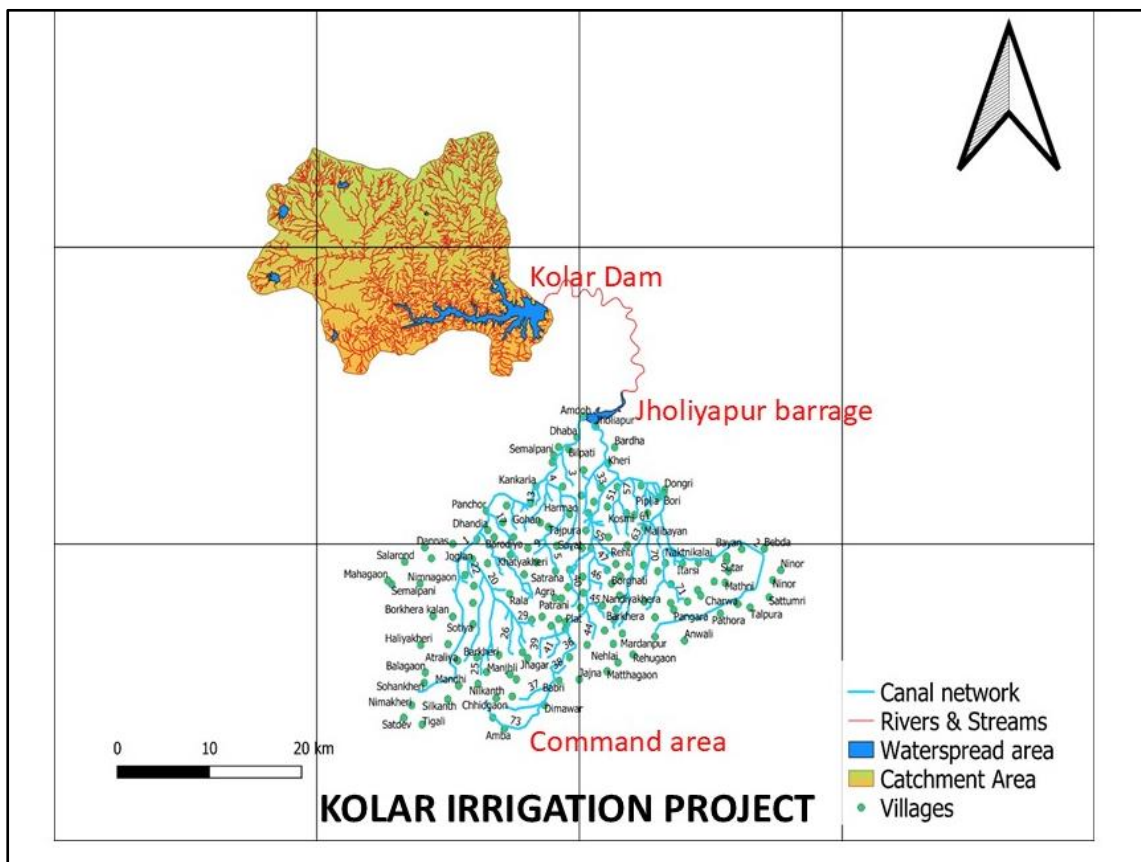


Figure 3.7: Kolar dam command area and canal network

4. RESULTS AND DISCUSSION

In Madhya Pradesh, crop water and irrigation requirements have been calculated using the methodology outlined in Technical Circular-25 (TC-25), issued by the Government of Madhya Pradesh in 1990. However, recent experiences across many irrigation projects in the state reveal that the current estimates for evapotranspiration (ET_o), crop water demand, and irrigation needs based on TC-25 are substantially overestimated. This overestimation has emerged as a significant constraint, limiting the state from expanding irrigated areas despite the availability of water in many reservoirs. As a result, the potential to extend irrigation coverage, support the cultivation of water-intensive but high-value crops, and ensure water supply for summer cropping has been adversely affected. Addressing these discrepancies is essential for enhancing water use efficiency and maximizing the benefits of existing irrigation infrastructure. The present study undertakes a detailed reassessment of ET_o values to ensure more accurate irrigation planning. The analysis confirms the overestimation under the existing norms and emphasizes the need for revision. Consequently, the study provides evidence-based recommendations to update TC-25, including the adoption of more accurate methodologies or software tools for ET_o estimation. These proposed changes aim to support field engineers in formulating precise irrigation schedules, thereby optimizing the use of available water resources in the state's irrigation systems.

4.1 ET_o Estimation using Empirical and Rational Methods

In this study, four widely recognized methods for estimating potential evapotranspiration (ET_o) were evaluated: the Blaney-Criddle, Hargreaves, Modified Penman, and FAO Penman-Monteith methods. A comprehensive comparative analysis was conducted to determine the most suitable method for application across the eleven diverse agro-climatic zones of Madhya Pradesh. To support this evaluation, extensive meteorological and agro-climatic data spanning from 1990 to 2022, including temperature, relative humidity, wind speed, and solar radiation, were sourced from the NASA POWER database for all districts of Madhya Pradesh. Additionally, long-term gridded climate data from the India Meteorological Department (IMD), covering the period from 1960 to 2020, were utilized to strengthen the historical perspective and reliability of the analysis.

Reference evapotranspiration (ET_o) was estimated for all eleven agro-climatic zones of Madhya Pradesh using two software tools: CROPWAT, a free decision-support tool developed by FAO, and the ET Calculator, an online application for evapotranspiration estimation. Statistical analyses were performed to assess the accuracy and sensitivity of each method in capturing spatial and temporal variations across different agro-climatic regions. The outcomes of this study aim to provide evidence-based guidance for selecting the most appropriate ET_o estimation method for improved irrigation planning and water resource management in Madhya Pradesh.

4.2 Development of Excel-based Dashboard for ETo Estimation

In the present study, an ETo Estimation Dashboard was developed as a computational tool designed to estimate daily potential evapotranspiration (ETo) for specific geographic locations using four established methods. The dashboard integrates the FAO Penman-Monteith, Modified Penman, Hargreaves, and Blaney-Criddle equations within a unified, user-friendly environment, enabling comprehensive analysis and comparison of these methods under varying climatic conditions.

The main part of ETo calculation process is the accurate input of station-specific constants, which are manually provided by the user at the start. These inputs include the station name, serving as a unique identifier for the data source; latitude (in decimal degrees), which is essential for determining solar geometry such as solar declination and day length key components in radiation-based methods; elevation above sea level (in meters), which is used to calculate atmospheric pressure and, subsequently, the psychrometric constant; and wind speed measurement height, which is necessary for adjusting wind speed data to the standard reference height of 2 meters, as required by certain methods.

The spatial variation in maximum and minimum temperature in Madhya Pradesh for the period from 1990 to 2022 is shown in Figure 4.1.

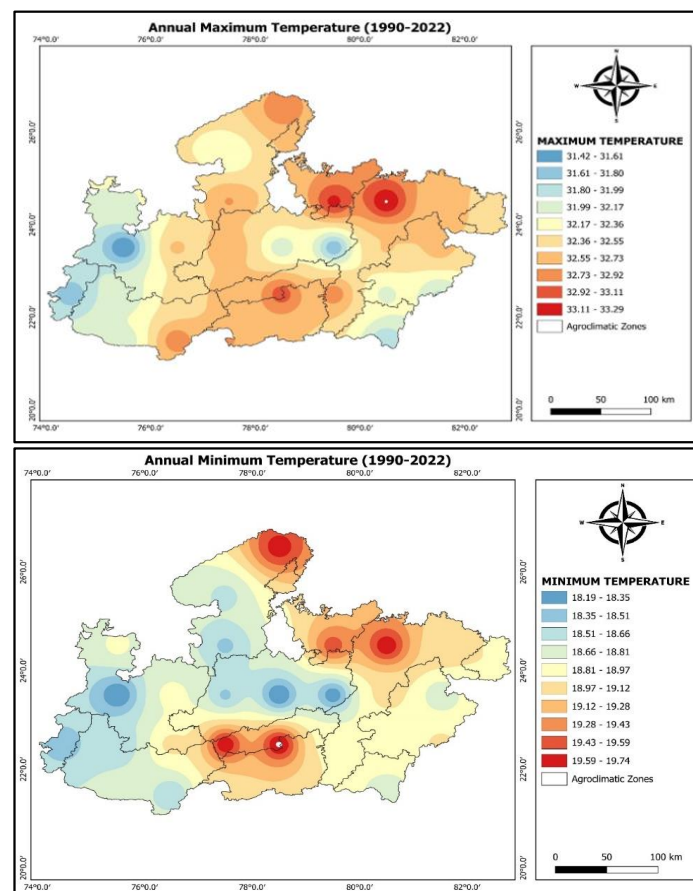


Figure 4.1: Mean annual maximum and minimum temperature in MP

Spatial analysis from Figures 4.1 reveals that the highest mean annual maximum temperatures were recorded in the Gird Region, Bundelkhand, and Satpura Plateau agro-climatic zones. Similarly, the highest mean annual minimum temperatures were observed in the Gird Region and Bundelkhand areas of Madhya Pradesh.

Figures 4.2 and 4.3 present a comparison of ETo values estimated using the developed Dashboard against those calculated with the ET Calculator and CROPWAT, the free online tools provided by the FAO.

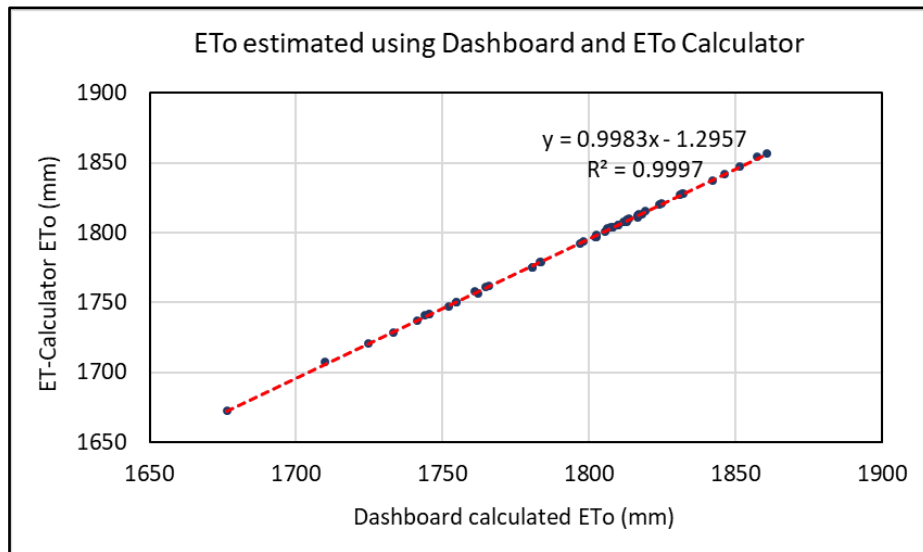


Figure 4.2: Comparison between ETo values estimated using Dashboard and ET Calculator

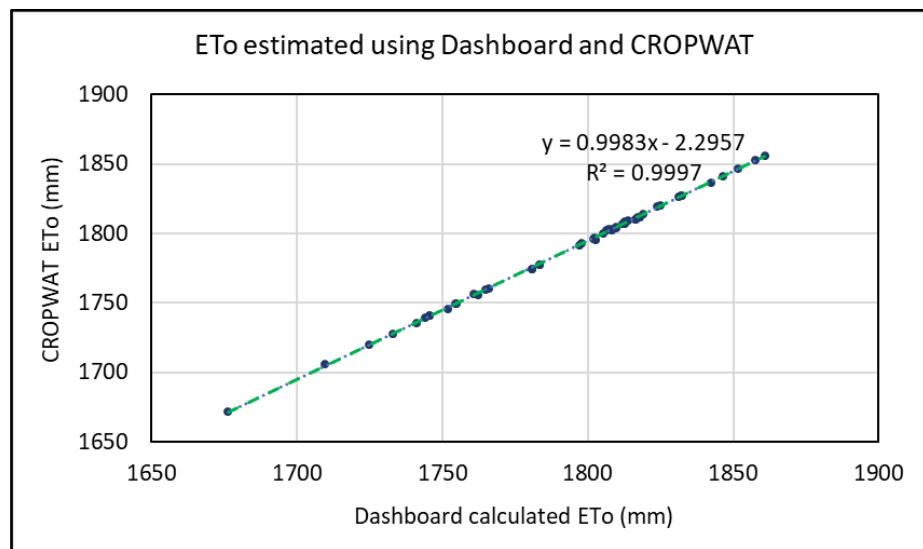


Figure 4.3: Comparison between ETo values estimated using Dashboard and CROPWAT

Figures 4.2 and 4.3 demonstrate a strong correlation between the ETo values estimated using the developed Excel Dashboard and those obtained from the ET Calculator and CROPWAT software. In both cases, the coefficient of determination (R^2) was observed to be 0.999,

indicating an almost perfect match. This high degree of accuracy validates the reliability and computational efficiency of the dashboard, confirming its suitability for precise ETo estimation. The results highlight the dashboard’s practical utility, particularly for field engineers who require a user-friendly and accurate tool for estimating ETo across various agro-climatic zones. Beyond its computational accuracy, the dashboard also offers the ability to critically analyze and compare multiple estimation methods, thereby supporting more informed decision-making in irrigation scheduling and water resource planning. This versatility makes the tool highly beneficial for a wide range of users, including engineers, researchers, and policymakers involved in agricultural water management in Madhya Pradesh.

4.3 Comparison of ETo Estimation using Different Datasets, Tools, and Methods

ETo estimates for the eleven agro-climatic zones using NASA Power and IMD gridded data are presented in Tables 4.1 and 4.2. Comparative graphs illustrating the results of all four estimation methods for both datasets are shown in Figures 4.4 and 4.5.

Table 4.1: ETo estimation using NASA Power Data in Dashboard

Zone No	Agro-climatic Zone	ETo Estimation method				Difference (mm) PM Vs MP	Difference (%) PM Vs MP
		Penman Monteith (mm)	Hargreaves (mm)	Blaney-Criddle (mm)	Modified Penman (mm)		
1	Chhattisgarh Plains	1870	1772	2030	2065	195	10.43
2	Northern Hill Region of Chhattisgarh	1795	1703	1993	1982	187	10.40
3	Kymore Plateau & Satpura Hills	1862	1744	2026	2054	193	10.35
4	Central Narmada Valley	1975	1790	2029	2186	211	10.69
5	Vindhya Plateau	1965	1783	2020	2179	214	10.89
6	Gird Region	2000	1812	2055	2220	220	11.02
7	Bundelkhand	1925	1788	2060	2130	205	10.67
8	Satpura Plateau	1878	1712	1994	2080	202	10.76
9	Malwa Plateau	2083	1819	2033	2317	235	11.26
10	Nimar Plains	2081	1866	2067	2308	228	10.94
11	Jhabua Hills	2105	1850	2063	2341	236	11.20
Average		1958	1786	2034	2169	211	11.00

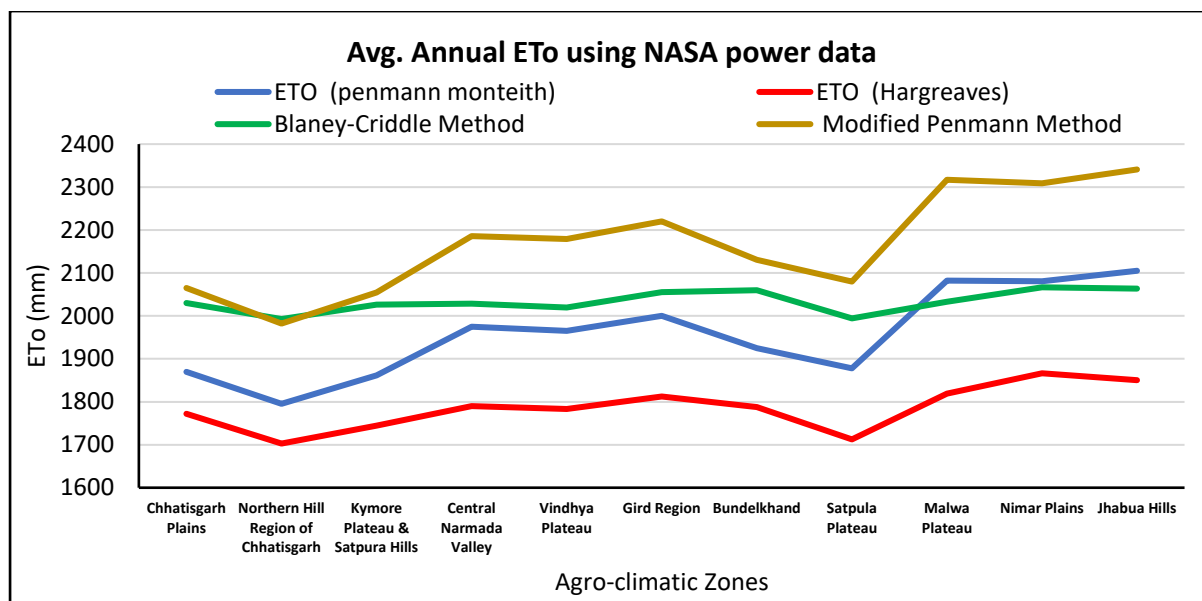


Figure 4.4: Graph showing comparison of all four methods for NASA Power data

Table 4.2: ETo estimation using IMD Grided Data in Dashboard

Zone No	Agro-climatic Zone	ETo Estimation method				Difference (mm) PM Vs MP	Difference (%) PM Vs MP
		Penman Monteith (mm)	Hargreaves (mm)	Blaney-Criddle (mm)	Modified Penman (mm)		
1	Chhatisgarh Plains	1775	1916	1787	2035	141	7.92
2	Northern Hill Region of Chhatisgarh	1753	1900	1764	1996	147	8.40
3	Kymore Plateau & Satpura Hills	1760	1980	1760	2020	220	12.53
4	Central Narmada Valley	1767	1920	1775	1982	153	8.68
5	Vindhya Plateau	1759	1970	1759	2010	211	11.96
6	Gird Region	1806	1957	1809	2019	151	8.36
7	Bundelkhand	1792	1932	1803	2023	140	7.81
8	Satpura Plateau	1795	1938	1806	2037	143	7.95
9	Malwa Plateau	1813	1966	1820	2011	153	8.44
10	Nimar Plains	1823	1971	1830	2037	149	8.15
11	Jhabua Hills	1805	1950	1812	2043	146	8.06
Average		1786	1945	1793	2019	159	8.93

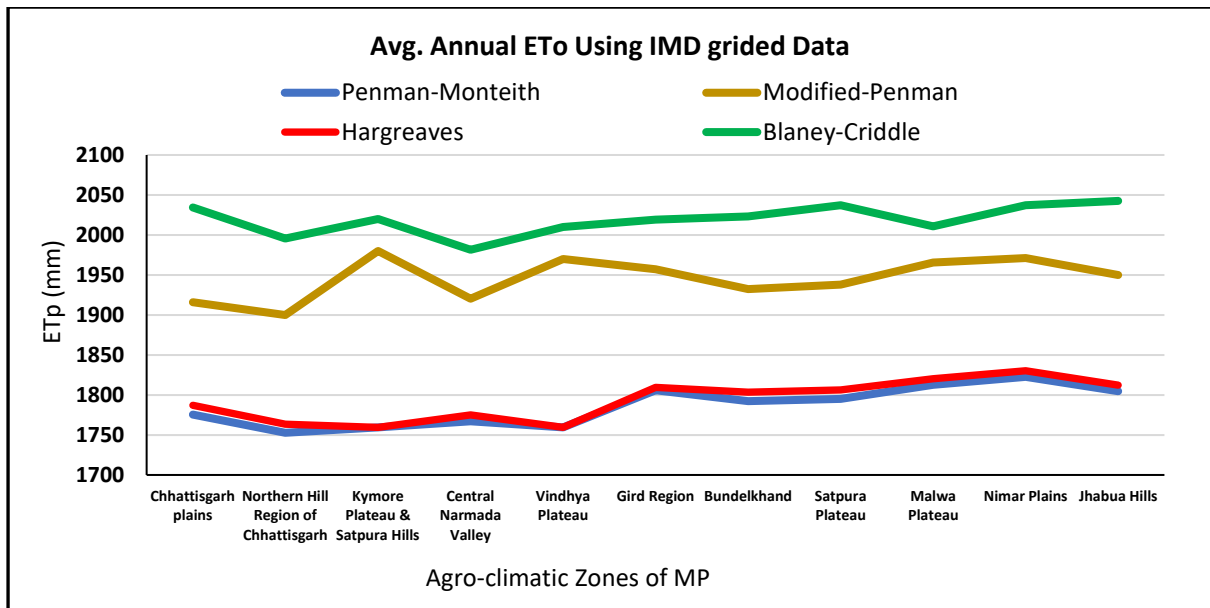


Figure 4.5: Graph showing comparison of all four methods for IMD Grided data (1960-2020)

A detailed analysis was conducted to estimate reference evapotranspiration (ET_o) using four different methods, Blaney-Criddle, Hargreaves, Modified Penman, and Penman-Monteith—across the 11 agro-climatic zones of Madhya Pradesh, using NASA Power data as shown in Table 4.1 and Figure 4.4. The ET_o estimation using IMD gridded weather data are shown in Table 4.2 and Figure 4.5. The IMD dataset was chosen over the NASA Power dataset due to its superior performance in ET_o estimation, as the NASA Power data tends to overestimate ET_o values. The ET_o results for both datasets revealed significant variations in ET_o estimates depending on both the agro-climatic zone and the method used. Among the methods, the Modified Penman consistently produced the highest annual average ET_o values, particularly in elevated regions such as the Jhabua Hills and Malwa Plateau, with estimates of 2341 mm and 2317 mm, respectively. This trend may be attributed to higher wind speeds and minimal variation between daily maximum and minimum temperatures in these areas. Conversely, the Hargreaves method yielded the lowest ET_o estimates, ranging from 1703 mm to 1850 mm, likely due to its reliance solely on temperature as the input parameter. These differences underscore the importance of selecting an appropriate ET_o estimation method tailored to specific regional conditions to ensure accurate irrigation planning and water resource management. Furthermore, the Penman-Monteith method indicated the highest ET_o values in the Malwa Plateau, Nimar Plains, and Jhabua Hills zones, characterized by warmer temperatures.

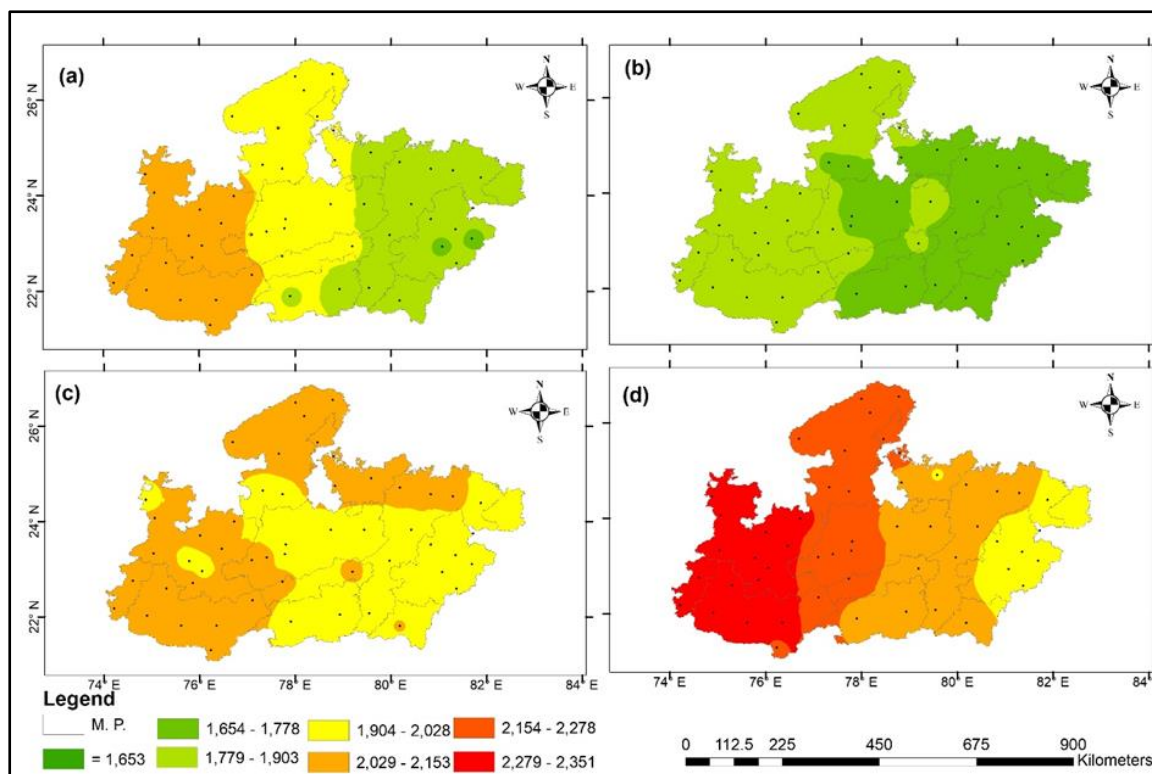


Figure 4.6: Spatial analysis of ETo estimation methods in 11 agroclimatic zones of M.P using Dashboard and IMD gridded data (a) Penman-Monteith, (b) Hargreave Method (c) Blaney-Criddle Method, (d) Modified Penman Method

Figure 4.6 illustrates that ETo values, as estimated by the Penman-Monteith method, are highest in the Malwa Plateau, Nimar Plains, and Jhabua Hills. These regions experience relatively warmer temperatures, lower humidity, and consistently high levels of sunshine, all of which contribute to increased evapotranspiration. In contrast, lower ETo values are observed in the Northern Hill Region, Kymore Plateau and Satpura Hills, and Satpura Plateau. These zones are characterized by higher elevations, cooler temperatures, higher humidity, and slightly reduced sunshine, resulting in lower evapotranspiration rates. Overall, the Penman-Monteith method provides moderate and consistent ETo estimates across the 11 agroclimatic zones, effectively capturing the climatic variation between regions.

4.4 Crop Water Requirement estimation using Modified Penman and Penman-Monteith methods in TC-25

Based on a thorough review of research papers and analysis of various ETo estimation methods, it was concluded that the Penman-Monteith method is more accurate and reliable than the Modified Penman method for estimating reference evapotranspiration (ETo). To assess the impact of selecting an appropriate ETo estimation method on crop water requirement (CWR) calculations, both the Modified Penman and Penman-Monteith methods were applied for an illustrative example given in *Annexure 13* of the TC-25, along with irrigation efficiency values

from TC-15. A comparison was made between the CWR estimation for the wheat crop using existing TC-25, which relies on the Modified Penman method, and the CWR calculated using ETo values derived from the Penman-Monteith method. This comparison has been detailed in Table 4.3, demonstrating the variation in results depending on the method used. Additionally, TC-15 was referenced to incorporate appropriate irrigation efficiency values in the estimation of irrigation requirements.

Table 4.3: Comparison between CWR estimation for Wheat (*Annexure-13 of TC-25*)

Crop Water Requirement –Wheat, Sowing Time Oct (19th Fortnight), Duration 135 days (All figures are in mm)														
S No	Particulars	Using Modified penman and TC- 15 (1988) Eff-58%										Using Modified Penman penman and TC- Month and 15 (1988) Eff 58% TC- 15 (2002) Eff 65%		
		Oct	Nov	Dec	Jan	Feb	Mar	Total	Total					
		19	20	21	22	23	24	1	2	3	4	5		
1	ETo	84	79	71	61	59	57	58	63	64	75		671	611
2	Kc	0.31	0.42	0.8	1	1.1	1.1	1.07	0.87	0.5	0			
3	ETc	26	33	57	61	65	63	62	55	32	0			
4	Plant Use Pre Sowing	60												
5	Soil Mos Adj.								-55	-32				
6	Gross Water Requirement	86	33	57	61	65	63	62	0	0	0		427	391
7	Rainfall	0	0	0	0	10	0	12	0	0	0			
8	Eff RF	0	0	0	0	0	0	0	0	0	0			
9	Net Irri Req (NIR)	86	33	57	61	65	63	62	0	0	0		427	391
10	GIR (with Eff %)	148	57	98	105	112	108	107	0	0	0		736	601

In Table 4.3, a specific example provided in *Annexure 13 of TC-25* estimated the crop water requirement (CWR) for wheat using the Modified Penman method. When this estimate was compared with the CWR values obtained using the Penman-Monteith method, along with the efficiency values outlined in TC-15, a significant difference was observed. Specifically, the reference evapotranspiration (ETo) was reduced from 671 mm to 611 mm, and the net irrigation requirement decreased from 391 mm to 247 mm. This analysis indicates that the use of the Penman-Monteith method effectively addresses the issue of ETo overestimation, which consequently leads to more accurate CWR estimates. Therefore, it is recommended that the Penman-Monteith method replace the Modified Penman approach in TC-25, and that the efficiency values from TC-15 be consistently applied. Updating the relevant tables and annexures in TC-25 accordingly will enhance the accuracy and reliability of ETo and CWR estimations.

4.5 Sample Survey Results

A sample survey was conducted in the Kolar command area to collect essential information not available through secondary data sources. The survey aimed to gather insights on aspects

such as changes in soil type, cropping patterns, irrigation methods, canal conditions, and grain production. The survey covered a total of 40 farmers across the Kolar command area.

The analysis of the survey data revealed several key findings. It was observed that water availability is generally sufficient in the head and middle reaches of the command area. However, in the tail-end regions, canal conditions are poor, prompting farmers to rely heavily on groundwater for irrigation. The predominant method of irrigation across the region is flooding.

In terms of cropping patterns, farmers primarily cultivate paddy and soybean during the Kharif season, while wheat and gram are grown during the Rabi season. Over the past 20 to 25 years, there has been no significant change in the cropping pattern or soil conditions in the area. Notably, grain production has shown an increase, despite the persistent use of traditional irrigation methods and unchanged cropping practices.

4.6 Climate Change Scenario

The trend analysis of rainfall and temperature data across the 11 agro-climatic zones of Madhya Pradesh reveals that there has been a consistent rise in average annual temperatures, with an increase of approximately 0.5°C to 1.2°C over the past three decades, especially in the Malwa Plateau and Bundelkhand regions. Annual rainfall patterns show significant variability, with the Nimar Plains and Satpura Plateau receiving the highest rainfall (average of 1200-1400 mm), while the Bundelkhand region experiences much lower rainfall (600-800 mm). Although total annual rainfall has remained relatively stable in several regions, rainfall intensity has increased, particularly in the Malwa Plateau, where heavy rainfall events have risen by 15-20%. Both drought and flood occurrences have increased in intensity, particularly in the Bundelkhand and Satpura Plateau zones, leading to more frequent crop water stress. The temperature rise in the Northern Hill Region has resulted in increased evapotranspiration, offsetting the effect of higher rainfall, particularly impacting wheat and paddy crops. Regions like Bundelkhand and the Northern Hill Region, with lower rainfall and higher temperature trends, face greater agricultural stress, requiring more supplemental irrigation. Future projections suggest continued warming across all zones, with temperature increases of up to 1.5°C by 2050, exacerbating the existing challenges of water availability and irrigation management.

5. CONCLUSIONS

The present study has been undertaken to support effective irrigation planning in Madhya Pradesh, with a primary focus on addressing the issue of ETo overestimation. By implementing scientifically sound estimation methods, the study aims to improve the accuracy of irrigation demand assessments and contribute to the expansion of the actual irrigated area across the state. The study involved a comprehensive assessment of ETo using multiple estimation methods, alongside an investigation into the factors influencing changes in ETo, Crop Water Requirement (CWR), and Irrigation Requirement (IR). Furthermore, it included an evaluation of various open-source online tools and led to the development of a user-friendly Excel-based dashboard tailored for ETo estimation in the context of Madhya Pradesh. Based on the findings, recommendations have also been proposed for revising TC-25 to enhance its accuracy and applicability in future irrigation planning initiatives.

The main conclusions drawn from the study are that the TC-25 currently utilizes the Modified Penman method, which tends to overestimate ETo. Therefore, it is recommended to revise TC-25 by adopting the Penman-Monteith method, using the latest available climatic data for more accurate ETo estimates. The Hargreaves method shows strong agreement with the Penman-Monteith method, making it a valuable tool for cross-validating ETo estimates, especially in situations where sufficient climate data is unavailable. The IMD dataset proves to be a more reliable source for ETo estimation compared to the NASA Power dataset, owing to its greater accuracy and reduced tendency to overestimate values.

The TC-15 (1988) table, which provides recommended efficiencies for canal systems in project planning, was revised in 2002 and should be utilized for more accurate irrigation planning in the state. Estimations of Crop Water Requirement (CWR) for wheat, when calculated using the Penman-Monteith method in conjunction with TC-15 (2002), show a reduction in values compared to previous estimates in TC-25, indicating a more accurate reflection of water needs. No significant changes have been observed in soil characteristics or cropping patterns over time that would affect CWR and irrigation requirements (IR). The Excel-based dashboard developed for ETo estimation has been seen to be a reliable and efficient tool for accurate reference evapotranspiration calculations. Climate change in Madhya Pradesh has led to rising temperatures, increased evapotranspiration, and erratic rainfall patterns, impacting crop water requirements and irrigation demand. These changes necessitate adaptive strategies for irrigation planning and policy formulation to ensure sustainable water management.

6. RECOMMENDATIONS

The following recommendations are proposed to address the issue of ETo overestimation in the state of Madhya Pradesh. These measures aim to support effective irrigation planning and contribute to the development of a robust policy framework for the optimal utilization of available water resources. Implementing these strategies will not only help in accurately assessing irrigation demand but also assist in expanding the actual irrigated area across the state.

- **Revise ETo Calculation:** TC-25 currently uses the Modified Penman method, which overestimates ETo. It should be updated to the Penman-Monteith method using recent climatic data for more accurate estimations.
- **Hargreaves Method Validation:** The Hargreaves method aligns well with the Penman-Monteith method and can be considered reliable for ETo estimation.
- **Use Updated Canal Efficiency Data:** The efficiency table for canal systems from TC-15 (1988), revised in 2002, should be used for irrigation planning.
- **Excel Dashboard:** The simple Excel-based dashboard developed by NIH has proven to be a reliable tool for ETo estimation.
- **Online Tools for ETo Calculation:** Free online tools like CROPWAT and ET Calculator of FAO provide accurate ETo estimations and can be adopted for ETo calculations.
- **Climate Change Consideration:** To improve irrigation planning amid changing climatic conditions, ETo estimation methods should be enhanced by incorporating real-time climatic data, while the TC-25 should be periodically updated to reflect the impacts of climate change.

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1. **Title of the Study:**
Re-assessment of evapotranspiration (*ETo*) estimation for irrigation planning in Madhya Pradesh

2. **Study Group: NIH, CIHRC, Bhopal and BODHI, MPWRD, Bhopal**

NIH RC Bhopal	PI : Dr. Ravi Galkate, Scientist F, CIHRC, Bhopal CO-PI : Dr. R.K. Jaiswal, Scientist F, CIHRC, Bhopal CO-PI : Dr A. K. Loani, Scientist G, NIH, Roorkee CO-PI : Er. Shashi P Indwar, Scientist D, CIHRC, Bhopal Memembr: Sh Rahul Kumar, RA.
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3. **Type of Study:** In-house collaborative study

4. **Nature of Study:** Applied Research

5. **Duration of study:** 3 Years (Nov 2021 to Oct 2024)

Manual for Calculation of Potential Evapotranspiration (ET₀) using Excel-Based Dashboard

Overview

This dashboard is designed to compute daily potential evapotranspiration (ET₀) for a selected station using multiple empirical and physically based methods:

1. FAO Penman-Monteith
2. Modified Penman
3. Hargreaves
4. Blaney-Criddle

It integrates meteorological input data with geographic constants and uses internally calculated parameters such as daylight hours and atmospheric pressure. A pivot table compiles the final ET₀ values for comparative or analytical purposes. Press **Link ****** to download the ET₀ Estimation Dashboard.

Station name: <input type="text" value="Bhopal"/>		Latitude (decimals): <input type="text" value="23.2"/>																											
Elevation (m): <input type="text" value="527"/>		Wind speed height (m): <input type="text" value="2"/>																											
Required										Optional																			
Date	T _{min}	T _{max}	T _{dry}	T _{wet}	T _{sw}	RH _{min}	RH _{max}	RH _{mean}	Wind speed	Sunlight hours	Radiation	T _{mean}	Dewpoint t	J	P (mm)	P	y (mm)	y	Δ (mm)	Δ	δ (rad)	α	φ	ω _s	ρ _a	N	e ^s (T _{min})	e ^s (T _{max})	e ^s (T _{mean})
01/01/20	13.5	27.9	19.4	15.3	11.2			62.3	1.1			20.7	11.2	1	92	95.22	0.03	0.0002	1.50200	0.202	-0.4020	1.033	0.405	1.39	24.02	33.60	1.544	3.756	1.739
02/01/20	13.4	28.2	20.6	15.9	11.1			57.9	0.8			20.8	11.1	2	92	95.22	0.03	0.0002	1.51400	0.15	-0.40	1.03	0.405	1.39	24.07	33.61	1.54	3.83	1.833
03/01/20	14.0	29.1	21.0	16.8	12.5			61.9	1.5			21.6	12.5	3	92	95.22	0.03	0.0002	1.57000	0.36	-0.40	1.03	0.405	1.39	24.12	33.62	1.60	4.03	1.938
04/01/20	13.7	29.7	21.3	17.2	13.1			63.1	2.3			21.7	13.1	4	92	95.22	0.03	0.0002	1.58700	0.36	-0.40	1.03	0.405	1.39	24.17	33.62	1.57	4.17	1.959
05/01/20	16.5	28.3	22.0	18.0	14.0			63.3	0.7			22.4	14.0	5	92	95.22	0.03	0.0002	1.64000	0.36	-0.39	1.03	0.405	1.39	24.23	33.63	1.87	3.84	2.063
06/01/20	14.4	28.0	20.6	17.1	13.5			66.9	1.8			22.2	13.5	6	92	95.22	0.03	0.0002	1.56000	0.15	-0.39	1.03	0.405	1.39	24.29	33.64	1.64	3.78	1.945
07/01/20	13.4	27.2	19.6	16.3	13.0			68.9	1.7			20.3	13.0	7	92	95.22	0.03	0.0002	1.47000	0.15	-0.39	1.03	0.405	1.39	24.36	33.64	1.53	3.61	1.850
08/01/20	12.7	28.3	19.9	16.0	12.0			63.8	1.8			20.5	12.0	8	92	95.22	0.03	0.0002	1.48900	0.15	-0.39	1.03	0.405	1.39	24.43	33.65	1.47	3.85	1.812
09/01/20	15.1	28.6	21.3	17.7	14.1			67.1	1.9			21.8	14.1	9	92	95.22	0.03	0.0002	1.59000	0.36	-0.39	1.03	0.405	1.40	24.50	33.66	1.71	3.91	2.024
10/01/20	14.7	24.2	19.3	17.1	14.9			77.1	1.1			19.5	12.7	10	92	95.22	0.03	0.0002	1.43000	0.14	-0.38	1.03	0.405	1.40	24.58	33.67	1.68	3.92	1.949
11/01/20	12.5	25.5	17.6	14.8	11.9			73.5	1.5			19.9	11.9	11	92	95.22	0.03	0.0002	1.37000	0.14	-0.38	1.03	0.405	1.40	24.66	33.68	1.45	3.97	1.679
12/01/20	10.8	24.1	16.7	14.5	12.3			77.5	1.7			17.4	9.8	12	92	95.22	0.03	0.0002	1.25000	0.13	-0.38	1.03	0.405	1.40	24.74	33.69	1.29	3.99	1.622
13/01/20	13.3	23.0	17.5	15.9	14.4			82.9	2.0			18.2	11.3	13	92	95.22	0.03	0.0002	1.33000	0.13	-0.38	1.03	0.405	1.40	24.83	33.70	1.53	3.91	1.838
14/01/20	13.9	23.1	17.1	15.7	14.3			84.9	2.1			18.5	11.9	14	92	95.22	0.03	0.0002	1.33000	0.13	-0.37	1.03	0.405	1.40	24.91	33.71	1.59	3.82	1.783
15/01/20	12.7	22.5	17.0	15.7	14.4			85.6	1.4			17.6	10.7	15	92	95.22	0.03	0.0002	1.28000	0.13	-0.37	1.03	0.405	1.40	25.01	33.72	1.46	3.73	1.706
16/01/20	12.1	26.5	18.9	16.5	14.1			76.3	1.5			19.3	10.1	16	92	95.22	0.03	0.0002	1.39500	0.14	-0.37	1.03	0.405	1.41	25.11	33.73	1.41	3.47	1.876
17/01/20	14.2	26.5	19.5	16.1	12.8			67.1	1.5			20.4	12.8	17	92	95.22	0.03	0.0002	1.47500	0.15	-0.36	1.03	0.405	1.41	25.20	33.75	1.62	3.47	1.833
18/01/20	11.0	27.4	18.8	14.9	11.0			64.1	1.7			18.2	9.9	18	92	95.22	0.03	0.0002	1.36000	0.14	-0.36	1.03	0.405	1.41	25.30	33.76	1.31	3.65	1.694
19/01/20	13.3	28.3	20.2	16.9	13.5			68.4	1.4			20.8	11.3	19	92	95.22	0.03	0.0002	1.52000	0.15	-0.36	1.03	0.405	1.41	25.41	33.77	1.53	3.85	1.921
20/01/20	11.4	27.6	18.5	15.1	10.6			61.1	1.3			19.1	10.6	20	92	95.22	0.03	0.0002	1.48000	0.14	-0.35	1.03	0.405	1.41	25.52	33.78	1.35	3.68	1.711

Station Information and Constants

- **Station Name:** Manually entered.
- **Latitude (decimal degrees):** Required for calculating solar geometry (e.g., solar declination, daylight hours).

- **Elevation (m):** Required for computing atmospheric pressure, which influences the psychrometric constant and hence the Penman-Monteith equation.
- **Wind Speed Height**

A	B	C	D	E	F	G	H	I	J	K	L		
Station name:	Bhopal											Latitude (decimals):	23.2
Elevation (m):	527											Wind speed height (m):	2
Required			Optional										
Date	T _{min}	T _{max}	T _{dry}	T _{wet}	T _{dew}	RH _{min}	RH _{max}	RH _{mean}	Wind speed	Sunlight hours	Radiation		

Input Data and Classification

The input data is grouped into **required** and **optional** categories:

1. Required Input Parameters

These are essential for calculating ET₀ using all or most of the methods:

Parameter	Symbol	Unit	Description
Date	-	-	Daily record
Max temperature	T _{max}	°C	Daily maximum air temperature
Min temperature	T _{min}	°C	Daily minimum air temperature

Optional (But Useful) Parameters

These are used in Penman-Monteith and other methods for improved accuracy:

Parameter	Symbol	Unit	Description
Average temperature	T _{avg}	°C	$(T_{max} + T_{min}) / 2$
Dew point temperature	T _{dew}	°C	Estimated or derived from T _{min}
RH _{max} , RH _{min} , RH _{mean}	%	Max and min relative humidity	
Wind speed	U _{2m}	m/s	Measured at 2 m height
Sunshine hours	n	hours	Actual sunshine duration

Required			Optional								
Date	T _{min}	T _{max}	T _{dry}	T _{wet}	T _{dew}	RH _{min}	RH _{max}	RH _{mean}	Wind speed	Sunlight hours	Radiation
01/01/82	13.5	27.9	19.4	15.3	11.2			62.3	1.1		
02/01/82	13.4	28.2	20.6	15.9	11.1			57.9	0.8		
03/01/82	14.0	29.1	21.0	16.8	12.5			61.9	1.5		
04/01/82	13.7	29.7	21.3	17.2	13.1			63.1	2.3		
05/01/82	16.5	28.3	22.0	18.0	14.0			63.3	0.7		
06/01/82	14.4	28.0	20.6	17.1	13.5			66.9	1.8		
07/01/82	13.4	27.2	19.6	16.3	13.0			68.9	1.7		
08/01/82	12.7	28.3	19.9	16.0	12.0			63.8	1.8		
09/01/82	15.1	28.6	21.3	17.7	14.1			67.1	1.9		
10/01/82	14.7	24.2	19.3	17.1	14.9			77.1	1.1		
11/01/82	12.5	25.5	17.6	14.8	11.9			73.5	1.5		
12/01/82	10.8	24.1	16.7	14.5	12.3			77.5	1.7		
13/01/82	13.3	23.0	17.5	15.9	14.4			82.9	2.0		

Derived Parameters and Internal Calculations

1. Atmospheric Pressure (P)

Estimated using elevation (z) via the barometric formula:

$$P = 101.3 \left(\frac{293 - 0.0065z}{293} \right)^{5.26}$$

Where:

- z is elevation (m)
- P is atmospheric pressure in kPa

This value is crucial for calculating the **psychrometric constant** (γ).

2. Psychrometric Constant (γ)

$$\gamma = \frac{c_p \cdot P}{\varepsilon \cdot \lambda} = 0.000665 \cdot P$$

Where:

c_p : specific heat of air at constant pressure (0.001013 MJ/kg°C)

ε : ratio of molecular weight of water vapor/dry air (0.622)

λ : latent heat of vaporization (2.45 MJ/kg)

γ plays a central role in the Penman-Monteith method.

2. Slope of Saturation Vapour Pressure Curve (Δ)

$$\Delta = \frac{4098 \cdot 0.6108 \cdot \exp\left(\frac{17.27 \cdot T_{mean}}{T_{mean} + 237.3}\right)}{(T_{mean} + 237.3)^2}$$

This temperature-dependent parameter is used in the Penman-Monteith equation and determines how sensitive vapor pressure is to temperature.

4. Daylight Hours (N)

Automatically calculated using **latitude** and **Julian day**, using the following steps:

- Solar declination (δ)
- Sunset hour angle (ω_s)
- Extraterrestrial radiation (R_a)
- Then compute N using:

$$N = \frac{24}{\pi} \cdot \omega_s$$

5. Dew Point Temperature (T_{dew})

If RH data is unavailable, it is estimated as:

$$T_{dew} = T_{min} - 2$$

Where 2°C is a typical adjustment value based on FAO guidelines.

Key Equations for ET_0 Estimation

1. FAO Penman-Monteith Equation (Primary Method)

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

- R_n : Net radiation (MJ/m²/day)
- G : Soil heat flux (assumed 0 for daily time steps)
- e_s, e_a : Saturation and actual vapor pressure

This method integrates **solar radiation, wind speed, humidity, and temperature**.

2. Modified Penman Equation

It uses similar inputs to Penman-Monteith, with empirical adjustments using radiation and temperature:

$$ET_0 = W \cdot R_n + (1 - W) \cdot f(u) \cdot (e_s - e_a)$$

Where:

- W : Weighting factor depending on temperature and altitude
- $f(u)$: Wind function

3. Hargreaves Equation

$$ET_0 = k_{Rs} \cdot (T_{avg} + 17.8) \cdot (T_{max} - T_{min})^{0.5} \cdot R_a$$

- Uses temperature and extraterrestrial radiation only
- $k_{Rs} \approx 0.16$ for interior stations (user-defined)

4. Blaney-Criddle Method

$$ET_0 = p \cdot (0.46 \cdot T_{avg} + 8)$$

Where p is a monthly mean daylight percentage, based on latitude and month.

Constants and Empirical Coefficients

Constant	Value	Description
σ	4.90×10^{-9}	Stefan-Boltzmann constant
a_s	0.25	Angstrom coefficient
b_s	0.50	Angstrom coefficient
α	0.23	Albedo of reference crop
c_p	0.001013	Specific heat
k_{Rs}	0.16	Hargreaves radiation coefficient
a_{psy}	0.000665	For psychrometric constant
c (Adjustment)	1.06	Used in Modified Penman

Result Compilation

At the final stage, ET_0 values from all methods are compiled via a **pivot table** for ease of comparison, statistical analysis, and temporal aggregation (daily/monthly/seasonal).
