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A Comprehensive Review: Climate Change Impacts on Reference Evapotranspiration (ET_0)

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***Abstract*— *Reference Evapotranspiration (ET_0) is a key component of the hydrological cycle and strongly influenced by climate variability, land use change, and anthropogenic activities. Accurate ET_0 estimation is vital for water resource management, irrigation planning, and climate adaptation strategies. This review synthesizes findings from global studies spanning 2000–2025, covering agricultural systems, wetlands, lakes, and urban environments. Traditional estimation methods such as the FAO-56 Penman–Monteith model remain the standard, while empirical, energy balance, and machine learning approaches offer useful alternatives when data are limited. Remote sensing advances have improved spatiotemporal monitoring, yet challenges remain in calibration, validation, and uncertainty management. The reviewed literature highlights that ET_0 trends are highly sensitive to factors such as sunshine duration, wind speed, and vegetation cover, with marked regional variability. Urbanization and impervious surface expansion further intensify ET_0 fluctuations by enhancing heat island effects. Research gaps include short-duration datasets, limited interdisciplinary integration, and uncertainties in large-scale modelling. Future directions emphasize hybrid modelling, long-term climate records, and improved satellite-based observations to strengthen ET_0 predictions under climate change scenarios.*

I. INTRODUCTION

Reference Evapotranspiration (ET_0), the combined process of evaporation from soil and water surfaces and transpiration from vegetation, is a key driver of hydrological and climatic interactions. It influences water balance, soil moisture, atmospheric energy exchange, and local climate regulation, while in wetlands it further controls water retention and vegetation dynamics. However, anthropogenic pressures such as urbanization and the spread of impervious surfaces disrupt ET_0 processes, intensifying urban heat island effects, ecosystem degradation, and water scarcity. Understanding these mechanisms is therefore essential for developing effective water conservation and management strategies. Traditional methods of measurement, including lysimeters, eddy covariance systems, and pan evaporation techniques, provide reliable results but are often limited by meteorological data requirements, site-specific constraints, and high operational costs. Advances in remote sensing, such as satellite-based thermal imaging, microwave sensing, and multispectral analysis, now enable large-scale ET_0 assessments with greater accuracy. This review examines the role of ET_0 in sustaining ecosystems and water bodies, evaluates contemporary measurement approaches, and discusses their implications for long-term water security

From the literature study, the Penman-Monteith equation with crop coefficients (Kc) based on Acala cotton growth stages was used to estimate the crop water requirements (CWR) in Sudan's Gezira region. Results were compared with the traditional Penman evaporation (EO) method using crop factors (Kf) from Farbrother (1970). Actual ET data from Fadl (1978-1979) validated the findings. The Penman-Monteith method showed higher accuracy in predicting CWR, with better correlation, regression slope, and lower error than the Farbrother method. Weather data from 1966 to 1993 showed increased ET_0 during the rainy season due to drought, highlighting the need for caution when predicting CWR. Abdelhadi et. al (2000) [1]. Evapotranspiration is vital for agriculture, water management, and drought monitoring, but direct measurement is costly and limited in many regions. Estimation is essential, especially in water-scarce areas. Researchers use empirical and physics-based models to calculate reference evapotranspiration, crucial for crop water needs. Forecasting with climate data aids irrigation planning and resource management. Methods range from traditional statistical models to advanced deep learning techniques. This review explores various estimation and forecasting approaches, covering both conventional and modern predictive methods. Ali et. al (2025) [2]. This study estimated regional evapotranspiration (ET) for Fenéki "Pond" (FP) in Hungary's Kis-Balaton wetland from 1997 to 2012, considering five macrophyte classes and open water. Using land cover classification and the Penman–Monteith (FAO-56) equation, ET variations were analysed based on vegetation type and climate data. The 16-year mean annual ET ranged from 876.8 mm/year for common reed to 662.8 mm/year for woody deciduous species, with a weighted average of 802.1 mm/year. Winter ET accounted for 17.1% of annual totals. Daily ET rates varied, with common reed at 4.0 mm/day and woody deciduous species at 2.9 mm/day. Open water, often covered by seaweed, had 7% higher evaporation than standard measurements. Modelling with SARIMA (1,0,0)(0,1,1)12 preserved seasonal ET patterns through 2020. The study emphasized the need to consider multiple macrophyte species, as relying solely on dominant species could lead to overestimations of regional ET by over 10%. Anda et. al (2015) [3]. Alpine wetlands on the Qinghai-Tibet Plateau are vital for water regulation and ecological stability. This study analysed evapotranspiration (ET) in lakeside and headwater ecosystems of the Qinghai Lake basin over two years. The lakeside ecosystem showed a double peak ET pattern, while the headwater had a multiple peak pattern. Monthly ET ranged from 9.88 to 111.56 mm (lakeside) and 0.23 to 75.5 mm (headwater), with annual ET in the lakeside area 1.89 times higher than in the headwater. Net radiation (Rn) and leaf area index (LAI) explained 96% of monthly ET variation in the lakeside ecosystem, while Rn and wind speed (WS) accounted for 94% in the headwater. These results highlight ET variability and confirm net radiation as the key influencing factor. Cao et. al (2020) [4]. A study evaluated the SIMETAW model using monthly climate data from four Iranian stations-Bushehr, Tabriz, Zahedan, and Mashhad-to assess climate change impacts on reference evapotranspiration (ET). SIMETAW generates daily weather data from monthly averages, aiding climate research. Future climate variables (temperature, dew point, rainfall, and wind speed) were downscaled from HadCM3 outputs under A2 and B2 emission scenarios for 2020-2050 and 2050-2080. SIMETAW accurately simulated temperature and rainfall but struggled with daily wind speed. ET is projected to increase at most stations. For 2050-2080 under B2, ET may rise from 164.7 to 181.2 mm/month in Bushehr, 125.4 to 137.5 mm/month in Tabriz, 182.7 to 197.5 mm/month in Zahedan, and 118.3 to 128.8 mm/month in Mashhad. Ebrahimpour et. al (2014) [5]. Measuring open water evaporation is challenging but crucial for understanding changes in lakes, reservoirs, and inland seas. This study evaluated the AquaSEBS algorithm, used by ECOSTRESS and OpenET, against data from 19 global sites using MODIS and Landsat imagery. Results showed reasonable accuracy when controlling for high wind events ($r^2 = 0.71$; bias = 13%; RMSE = 38%). However, high winds (>7.5 m/s) reduced accuracy ($r^2 = 0.47$; bias = 36%; RMSE = 62%). Temporal integration improved precision, lowering daily RMSE to 1.2–1.5 mm/day. AquaSEBS performed comparably to 11 machine learning models, suggesting errors stem from in situ data, input variables, or scaling issues. The study confirms the reliability of remotely sensed open water evaporation data, despite some uncertainties, and provides a basis for future improvements. Fisher et. al (2023) [6]. This study illustrates the sensitivity of FAO-56 Penman–Monteith ET_0 estimates to climate variable uncertainties at Bangalore (Sub-humid) and Bellary (Hot semi-arid) in Karnataka. Results highlight the importance of sunshine hours, wind speed, and relative humidity in ET_0 estimation. Bangalore's ET_0 is most affected by sunshine hours, while Bellary's is more sensitive to wind speed. Trend analysis shows increasing sunshine hours at Bangalore but declining at Bellary, providing key insights for climate-based water management. Mahadeva et. al (2024) [7]. Water bodies in urban areas help cool the surroundings through evaporation, reducing the Urban Heat Island (UHI) effect, where cities are warmer than rural areas. Studies show water bodies can be 2 to 6°C cooler than surrounding urban spaces. Increasing evapotranspiration from vegetation and water can effectively lower urban temperatures. However, the impact of water bodies, especially differences in daytime and nighttime cooling, and the role of urban design in maximizing these benefits remain underexplored. This paper reviews existing research and provides a theoretical background on the topic. Manteghi et. al (2015) [8]. In water-scarce mountainous regions, afforestation increases evapotranspiration, reducing water availability for downstream users. This study evaluates the impact of vegetation restoration on water consumption and potential restoration levels in the Haihe River Basin, where water demand is rising. Using the Penman-Monteith-Leuning model and a de-trending data series. Between 2000 and 2019, average precipitation and actual evapotranspiration (AET) were 508 mm and 317 mm, respectively, both showing an increasing trend. Vegetation restoration raised AET significantly in six sub-basins, with cumulative increases ranging from 175 mm (DQHMB) to 429 mm (BSHMB). Maximum LAI recovery levels were estimated, with LHMB, YDHMB, ZYHMB, and ZWHMB still having restoration potential, reaching up to 1.83 cm^3/cm^3. Sustainable afforestation should balance ecological and human water needs. This method can guide vegetation restoration in other water-limited regions. Qingming et. al (2022) [9]. The urban heat island effect (UHI) is the temperature difference between urban and non-urban areas. Evapotranspiration (ET) consumes 21.74% of solar energy, far exceeding human energy use (0.33%). Vegetation ET helps cool cities, reducing temperatures by 0.5 to 4.0°C, while green roofs and water bodies also lower temperatures. Green roofs reduce ambient temperatures by 0.24–4.0°C and roof surfaces by 0.8–60.0°C. Water bodies can be 2–6°C cooler than built areas, cooling 2,826 m^3 of air by 1°C per 16 m^2 of water surface. Increasing ET through vegetation, urban agriculture, and water bodies effectively mitigates UHI. QIU et. al (2013) [10]. This study assessed aquatic plant evapotranspiration (ET) in Edfina Drain, Nile Delta, using an in-stream treatment wetland. A field-scale approach measured water loss from evaporation and plant water consumption in floating tanks. Results showed that ETp and crop coefficients (Kc) varied with plant leaf area and growth stage. Water hyacinth had the highest ETp, followed by cattail, reeds, torpedo grass, and duckweed, with all ETp values exceedingly twice the open water evaporation rate. Kc values were nearly double those of FAO Penman-Monteith due to local climate effects. Total water loss from the wetland treatment system remained low, at only 0.55% of the drain discharge. Rashed (2014) [11]. This study examines how vegetation greening influences evapotranspiration (ET) in Siberia using the Penman–Monteith–Leuning (PML) model. It also assesses the effects of water vapor pressure deficit, surface net radiation (Rn), and wind speed (Um) on ET. From 2000 to 2020, the annual ET averaged 248.2 ± 94.1 mm, with a rising trend of 0.54 ± 1.38 mm per year. Greening was the primary driver, contributing 0.79 ± 0.76 mm per year (37%). Surface net radiation and wind speed contributed 33% and 19%, respectively, while the water vapor pressure deficit had minimal influence (11%), indicating that water availability did not significantly limit ET. These findings highlight the role of greening in ET changes and improve understanding of Arctic water cycle variations under "Arctic amplification. Shi et. al (2022) [12]. This study examines evaporation and evapotranspiration at Căldăruşani Lake and their impact on water volume. Analysing data from 2009 to 2014, it explores temporal variations, influencing climatic factors, and water loss estimates. Results show evapotranspiration (10.3 mm/day) exceeds evaporation (4.3 mm/day). In 2014, these processes led to a water loss of about 2.9 million cubic meters, nearly one-third of the lake's volume. Stan et. al (2016) [13].

II. ESTIMATION METHODS

The FAO-56 Penman–Monteith equation remains the most widely accepted standard for reference evapotranspiration (ET_0) estimation. It combines the Penman method, which is based on the Bowen ratio principle involving radiation, wind, and humidity factors, with the Monteith method, which incorporates resistance terms such as surface and aerodynamic resistance. Allen et al. [14] applied the equation on an hourly basis using a constant resistance value of 70 s/m and recommended the FAO-56 Penman–Monteith equation as the global standard wherever sufficient meteorological data are available. The equation is expressed as:

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

where ET_0 is the reference evapotranspiration (mm/day), Rn is the net radiation at the crop surface ($MJ/m^2/day$), G is the soil heat flux density ($MJ/m^2/day$), T is the mean daily air temperature at 2 m height (°C), U_2 is the wind speed at 2 m height (m/s), es is the saturation vapour pressure (kPa), ea is the actual vapour pressure (kPa), Δ is the slope of the vapour pressure curve (kPa/°C), and γ is the psychrometric constant (kPa/°C). Beyond the FAO-56 model, multiple approaches have been developed for ET_0 quantification, ranging from empirical and analytical methods to physically based and machine-driven models.

Empirical models, such as the Hargreaves–Samani and Thornthwaite equations, establish statistical relationships between meteorological parameters, particularly temperature and radiation. Physically based models, such as Penman–Monteith, remain the benchmark for accuracy but require comprehensive climatic inputs. Energy balance models, including SEBAL and METRIC, integrate surface energy dynamics with remote sensing data to improve ET_0 estimation across heterogeneous landscapes. In recent years, artificial intelligence and data-driven models, including deep learning techniques, have emerged as promising alternatives to refine predictions and address data limitations.

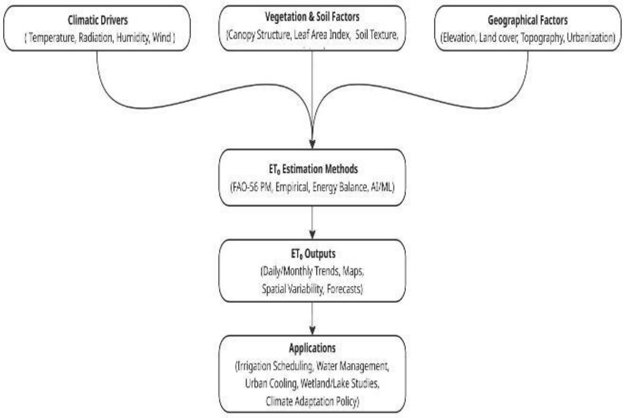

Fig. 1: Schematic Representation of ET_0 Estimation Pathways

2.1 Factors Influencing Evapotranspiration

The rate of ET_0 is governed by a complex interplay of atmospheric, biological, and geographical influences. Climatic conditions such as temperature fluctuations, solar radiation, humidity, and wind speed directly affect evapotranspiration levels. Vegetation characteristics also play a critical role, as species-specific transpiration capacities and canopy structures determine water loss rates. Soil properties, including moisture retention, texture, and composition, regulate evaporation potential and thereby influence overall ET_0. Geographic factors such as elevation, land cover, and topography introduce further spatial variability, making the estimation of ET_0 highly site-specific.

III. APPLICATIONS

Accurate estimation of ET_0 is fundamental to a wide range of environmental and agricultural applications. In water resource management, ET_0 estimates support efficient allocation, drought planning, and conservation strategies. In agriculture, they underpin irrigation scheduling and contribute to enhanced water use efficiency, which is critical in water-limited regions. In climate research, ET_0 provides a valuable indicator of hydrological responses to global warming and offers insight into long-term water security. Reliable ET_0 data are also indispensable for assessing changes under climate change scenarios and developing adaptive strategies that can sustain ecosystems and human water demands. Future research should therefore focus on integrating multiple estimation techniques to minimize the limitations of individual approaches. Expanding the availability of high-quality datasets, improving the performance of machine learning models, and advancing hybrid methods that combine remote sensing with ground-based sensor networks could further improve the accuracy and applicability of ET_0 assessments across diverse ecosystems, including wetlands, forests, and urban landscapes.

IV. RESEARCH GAPS

Despite these advances, significant research gaps remain. Much of the existing work on ET_0 has concentrated on specific climatic conditions and vegetation types, thereby limiting the generalizability of findings. Regional variations in ET_0 underscore the need for localized studies, while the reliance on short-term datasets constrains understanding of long-term climate impacts. Extended observational records for water bodies such as lakes, reservoirs, and wetlands are scarce, complicating the development of reliable predictive models. Although artificial intelligence and remote sensing approaches show great promise, challenges persist in sensor calibration, data processing, and the ability to distinguish between open-water evaporation and vegetation-driven transpiration, particularly in urban environments. Furthermore, many hydrological and climate models still rely on generalized assumptions regarding ET_0, reducing the accuracy of predictions related to water availability and ecological outcomes. Finally, there remains insufficient research into how climate change differentially impacts evapotranspiration across various regions and water body types, highlighting the need for broader and more integrated investigations.

V. METHODOLOGY

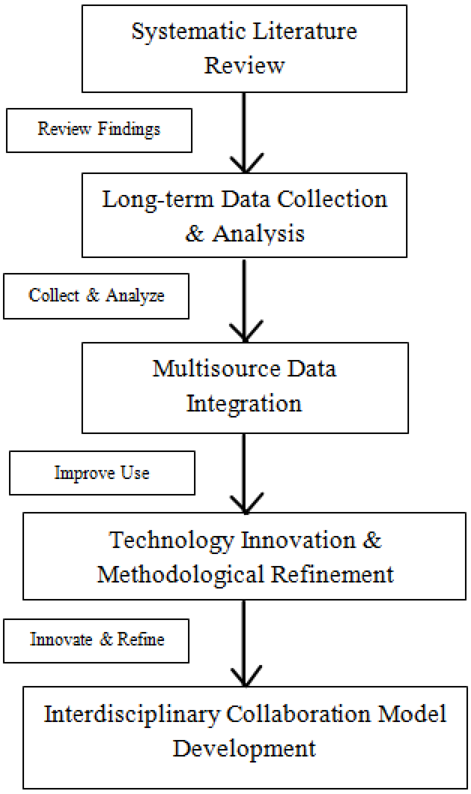

Fig. 2: Methodological Refinement and Collaboration Cycle

VI. RESULTS AND DISCUSSION

To systematically address existing research gaps and enhance the precision of evapotranspiration (ET_0) evaluations, a comprehensive and methodologically rigorous framework is essential. This framework should adopt a multi-faceted strategy that combines empirical data acquisition, technological innovations, and interdisciplinary collaboration. By integrating diverse analytical approaches, the aim is to refine ET_0 estimation techniques, expand knowledge of climatic influences, and support adaptive water management strategies. The inclusion of empirical observations alongside advanced computational models ensures more reliable assessments of ET_0 dynamics across diverse ecosystems and climatic zones. Furthermore, fostering collaboration among hydrologists, climatologists, ecologists, and data scientists strengthens the methodological base. Through systematic literature evaluation, model validation, and the application of remote sensing and machine learning techniques, this approach seeks to improve the accuracy, scalability, and applicability of ET_0 research while advancing water resource management and climate adaptation efforts.

6.1. Systematic Literature Review:

A rigorous literature review forms the foundation for understanding the complexity of ET_0 processes. This requires a careful examination of studies conducted across different climatic regions and ecological settings to identify existing knowledge gaps. Primary sources should include peer-reviewed journal articles, hydrological studies, and climate modelling research, supplemented by government reports, technical documents, and case studies from international organizations. Such breadth ensures a comprehensive understanding of ET_0 dynamics and their implications.

Special attention must be given to research on ET_0 within aquatic environments such as lakes, reservoirs, wetlands, and urban systems. Examining these diverse settings provides insight into the influence of temperature fluctuations, land cover changes, and hydrological interactions on ET_0 variability. A chronological evaluation of long-term ET_0 trends is equally important for capturing the impacts of climate change and human activities. Furthermore, meta-analytical techniques can be applied to consolidate results from multiple studies, thereby improving reliability and highlighting inconsistencies in existing models. This approach strengthens the evidence base for future ET_0 assessments and ensures that research builds on a robust, well-informed foundation.

6.2. Long-Term Data Collection and Analysis:

The accuracy of ET_0 assessments depends on systematic long-term data collection and analysis. Establishing consistent monitoring across diverse geographical regions and climatic conditions enables researchers to capture both localized and large-scale variability. Ground-based hydrological stations, remote sensing platforms, and in situ observational methods should be combined within an integrated monitoring framework.

Consistency across locations requires standardized protocols for data collection, reducing discrepancies caused by differences in techniques, instruments, or environmental conditions. Internationally recognized hydrological monitoring standards provide a basis for comparability across regions. Satellite-based datasets, including those from MODIS, Sentinel-2, and Landsat TIRS, provide critical information on temperature, vegetation, and water balance, while global networks such as FLUXNET, NASA EOS, and NOAA Climate Data Records enhance temporal and spatial coverage.

Equally important are in situ measurements, which validate satellite-derived estimates. Hydrometeorological stations and flux towers provide high-resolution data on climatic and soil conditions, bridging the gap between large-scale observations and localized processes.

Maintaining high-quality, long-term datasets allows for comparative analyses that capture climate-induced variability, including temperature shifts, precipitation anomalies, and extreme events. Incorporating such datasets into hydrological models enhances predictive capacity, supporting more reliable future projections of ET_0 and informing water management and climate resilience planning.

6.3. Technological Innovations and Methodological Refinement:

Advancing ET_0 estimation requires the use of emerging technologies such as artificial intelligence, remote sensing, and advanced computational modelling. These tools enhance precision, reduce error margins, and improve the scalability of hydrological research. Evaluating their performance across agricultural, urban, and natural environments provides insights into their robustness under diverse conditions.

Artificial intelligence, particularly deep learning and neural networks, has proven effective for processing large and complex ET_0 datasets. Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) models incorporate historical and real-time data to improve predictive accuracy, while hybrid AI approaches integrate meteorological, hydrological, and land cover parameters for a more holistic estimation framework. Remote sensing has also transformed ET_0 monitoring, with thermal sensors such as Landsat TIRS enabling precise surface temperature measurements and UAV- or LiDAR-based systems improving spatial resolution.

However, challenges remain in ensuring the consistency of measurements. Sensor calibration, atmospheric interference, and processing variations can introduce uncertainty, making rigorous calibration and standardized data-processing protocols essential. Computational models such as Penman–Monteith, SEBAL, and METRIC continue to provide essential tools for ET_0 assessment, though their reliability depends on the quality of input variables and calibration strategies. Comparative evaluations of these models are therefore necessary to identify uncertainties and improve prediction accuracy.

6.4. Multi-Source Data Integration:

Integrating data from multiple sources enhances the precision of ET_0 assessments by linking theoretical models with real-world observations. A hybrid framework combining satellite imagery, climate simulations, and ground-based hydrological measurements minimizes inconsistencies and captures the full complexity of ET_0 processes.

Ground-based meteorological stations provide key climatic variables such as temperature, wind speed, and radiation, which, when integrated with satellite datasets, improve model calibration and validation. Flux towers within global networks like FLUXNET further provide high-precision ET_0 measurements through eddy covariance techniques, enabling robust cross-comparisons. Climate models contribute long-term projections of ET_0 under different scenarios, although their generalized assumptions may limit local applicability. Integrating model outputs with real-time observational data can reduce these limitations and improve forecasting.

Adopting a multi-source integration strategy supports both methodological accuracy and practical water management applications. This approach not only strengthens the reliability of ET_0 estimation but also informs adaptive strategies for addressing climate variability and resource sustainability. Future efforts should focus on expanding monitoring networks, refining data fusion approaches, and incorporating machine learning to further improve integration and forecasting capacity.

6.5. Interdisciplinary Collaboration and Model Development:

The complexity of ET_0 processes underscores the need for interdisciplinary collaboration. Since ET_0 is influenced by atmospheric, hydrological, and ecological factors, collaboration among climatologists, hydrologists, engineers, and data scientists is vital for developing more accurate models. By combining domain-specific expertise, research can address both local-scale processes and global-scale patterns.

Refining hydrological models remains a central objective. Existing models often rely on generalized assumptions that fail to capture regional differences. Hybrid models that integrate high-resolution climate inputs, observational data, and AI-based methods hold promise for improving predictive accuracy. Standardized calibration methods are equally important, particularly in validating remote sensing results against flux tower measurements. Cross-referencing different datasets enhances reliability by reducing parameterization errors and highlighting model discrepancies.

Collaboration with policymakers is also critical to ensure that ET_0 modelling advances are translated into water conservation, irrigation scheduling, and ecosystem management practices. Case studies demonstrating successful applications can serve as models for broader implementation. To sustain progress, researchers should prioritize standardized data-sharing protocols, open-access repositories, and international partnerships. Workshops, training programs, and collaborative projects can further strengthen cross-disciplinary knowledge exchange, ensuring the continued refinement of ET_0 estimation techniques.

VII. SUMMARY AND CONCLUSION

Evapotranspiration (ET_0) remains a cornerstone of hydrological and ecological research, shaping water availability, agricultural planning, and climate adaptation strategies. This review highlights that while the FAO-56 Penman–Monteith equation continues to serve as the global reference standard, diverse empirical, physically based, and computational models provide complementary value across varying climates and data conditions. Advances in remote sensing, energy balance modelling, and artificial intelligence have expanded the capacity to monitor ET_0 with improved spatial and temporal resolution. Nonetheless, persistent challenges—ranging from calibration errors and sensor limitations to region-specific variability—underscore the need for refined methods and stronger data foundations.

Addressing these gaps requires a multifaceted approach that combines methodological innovation, long-term data expansion, and interdisciplinary collaboration. Researchers should broaden the scope of ET_0 studies by incorporating diverse climate conditions and vegetation types, thereby enhancing the universality of findings. Systematic collection of long-term datasets across regions and water bodies such as lakes, reservoirs, and wetlands would allow for more comprehensive assessments of climate impacts over extended periods. Advancements in technology must be matched by efforts to refine and calibrate existing tools. Artificial intelligence and remote sensing, for instance, should be further developed to improve sensor capabilities and overcome challenges in urban settings. Enhanced calibration methods and standardized processing protocols are critical for reducing errors, particularly in distinguishing open-water evaporation from vegetation transpiration. Integrating data from multiple sources—satellite observations, in situ measurements, and model simulations—can bridge the gap between theoretical predictions and real-world dynamics. Collaborative efforts among climatologists, hydrologists, data scientists, and engineers will also foster the development of sophisticated hybrid models that capture local nuances while maintaining global relevance. In doing so, these models can mitigate the limitations of generalized assumptions in hydrological and climate frameworks, ultimately leading to more accurate predictions of water availability and ecological impacts under diverse climate change scenarios.

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