Transforming evapotranspiration from hydrological variable to decision-ready dataset in water management: Challenges and pathways

Hongwei Zeng,[1,2] Hantian Wu,[3,*] Lu Sun,[3] Weiwei Zhu,[1] Jiangyuan Zeng,[1,2] Dongryeol Ryu,[4] and Bingfang Wu[1,*]

[1]State Key Laboratory of Remote Sensing and Digital Earth, Aerospace Information Research Institute, Chinese Academy of Sciences, Beijing 100101, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]China Institute of Geo-Environmental Monitoring, Beijing 100089, China
[4]Department of Infrastructure Engineering, The University of Melbourne, Parkville Victoria 3010, Australia
*Correspondence: wuht@mail.cgs.gov.cn (H.W.); wubf@aircas.ac.cn (B.W.)

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The planetary boundary for water has been transgressed,[1] posing increasing risks to ecosystem stability and resilience. This reveals a fundamental limitation of current water management, which is withdrawal-oriented and neglects water consumption and return flows. Consequently, poor control of water consumption reduces water availability, triggers the irrigation paradox, and exacerbates land degradation. Evapotranspiration (ET) is a complex process involving the atmosphere, vegetation, soil, and human water use. It represents the dominant pathway of terrestrial water loss and provides a physically based measure of human consumptive use that can be accounted for in water management. Recent advances in Earth observation (EO) and artificial intelligence (AI) have substantially improved ET estimation, positioning ET as a practical bridge between scientific understanding and water management (Figure 1).

DEFINITION OF DECISION-READY ET

ET reflects water exchange between land and atmosphere and is influenced by evaporative demand, vegetation, soil moisture, and land surface temperature. Decision-ready ET is defined as EO-based datasets directly usable for water consumption accounting, allocation, and regulation, meeting operational thresholds in spatial resolution (10–30 m for field-level irrigation by local managers, 300–500 m for basin-scale policy by decision-makers), temporal frequency (daily to weekly for irrigation, monthly to annually for policy), data latency (less than 24 h for high-frequency applications), and automated cloud-based distribution. Unlike research-oriented ET datasets, decision-ready ET quantifies human-driven water consumption and provides actionable guidance for enforcing withdrawals, optimizing irrigation, and managing groundwater, enabling ET to support water management across scales.

CHALLENGES AND SOLUTIONS FOR GENERATING AND UTILIZING DECISION-READY ET

Most mainstream ET models rely on the surface energy, where ET is estimated as the residual of the surface energy budget. These models rely on soil, vegetation, radiation, and thermal variables to estimate net radiation, soil heat flux, and sensible heat flux. Many of these variables can be retrieved from multi-source satellite data, substantially advancing the development of ET models. For example, ETWatch,[2] driven by remote sensing variables, has demonstrated good performance in regional applications. More recently, AI enhanced ET estimation by capturing nonlinear relationships with environmental parameters. Despite these advances, generating and utilizing decision-ready ET for water management still faces several challenges.

Reducing uncertainty in ET estimates

Current ET estimates exhibit pronounced uncertainties over heterogeneous landscapes. Most ET models rely on the assumption of surface homogeneity, which is often invalid in areas with mixed vegetation, complex land use, and rugged terrain. ET estimates are also highly sensitive to uncertainties in key inputs, particularly LST, near-surface air temperature, and atmospheric boundary layer (ABL) parameters. Satellite LST retrievals are limited by instantaneous observations, revisit intervals, view-angle inconsistencies, and cloud cover, causing typical uncertainties of 1–2 K which can propagate into 2%–10% ET errors. Near-surface air temperature measured in thermometer shelters may differ by 0.5–2 K, contributing 2%–8% ET errors, and simplifications or neglect of ABL processes can further bias ET by 5%–10%.

Reducing these uncertainties requires improvements in both models and observations. Future ET models should account for surface heterogeneity by

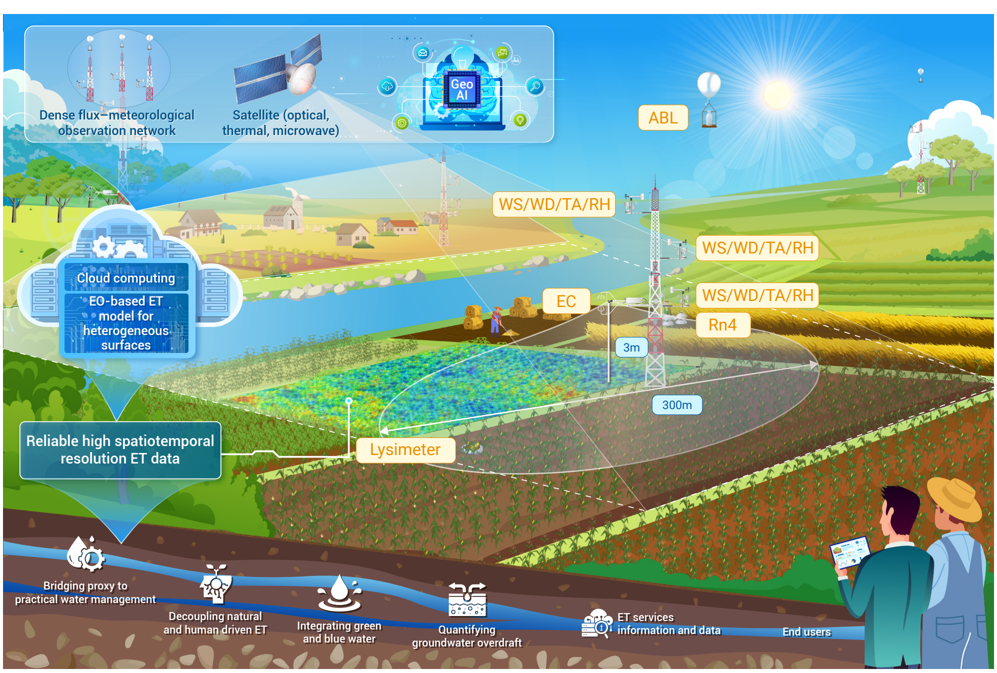

Figure 1. Conceptual framework for ET-based water consumption management EC, eddy covariance; Rn4, four-component radiation; ABL, atmospheric boundary layer; WS, wind speed; WD, wind direction; TA, air temperature; RH, relative humidity.

incorporating spatial variability of key land surface properties, integrating multi-source observations to capture ET dynamics, and exploring hybrid approaches combining physical and data-driven methods. Observational efforts should include vertical profiling from soil to the ABL and increased station density to improve representativeness.

Improving ET spatiotemporal resolution

Existing ET datasets often have coarse spatial resolution (100–10,000 m), limiting applicability for field-scale agricultural management. For example, the FAO's WaPOR dataset (version 3) offers actual ET at ~300 m globally (Level 1), 100 m regionally (Level 2), and ~20 m only in select pilot areas. In practice, irrigation planning and water allocation are conducted at the field level, making high-resolution ET data essential. OpenET partially addresses this need by providing 30 m ET for 17 western U.S. states with monthly and annual products readily available. Despite these advances, gaps remain for frequency and timeliness to high resolution ET.

Integrating multi-source high-resolution satellite imagery such as Planet, Sentinel, Landsat, MODIS with cloud computing improves ET estimates in spatial resolution, temporal frequency, and timeliness. However, upscaling or downscaling over heterogeneous surfaces can introduce nonlinear aggregation biases, underestimating ET in high-transpiration areas and overestimating it in low-transpiration areas. These biases affect the operational accuracy of ET for irrigation planning, water allocation, and policy compliance. Mitigation strategies include physically constrained downscaling, sub-grid heterogeneity modeling, and hybrid data-driven approaches to ensure decision-ready ET meets operational thresholds.

Decoupling natural and human-driven ET

A key limitation in current water management is that total ET includes both natural processes and human-induced water consumption. Current research primarily separates ET into vegetation transpiration, soil evaporation, and canopy interception, but provides limited guidance on quantifying the relative contributions of natural and human-driven ET from a management perspective. For example, agriculture accounts for over 87% of global freshwater use.[3] Its water consumption is influenced by irrigation methods, crop type and rotation, cropping intensity, and climate change. Decoupling natural and human-driven ET is therefore essential for irrigation management, water quotas, ecological compensation, and groundwater restoration.

A practical approach involves constructing a "natural baseline" using historical climate data to simulate ET under climate-only conditions. The deviation between observed ET and this baseline can then be attributed to human activities such as irrigation and land management. This attribution can be further refined by incorporating irrigation extent, crop types, and land use change. Such decoupling enables ET to serve as a direct measure of human water consumption, forming the basis for consumption-based water allocation and regulation.

Integrating green and blue water management

Current water management frameworks focus on regulating blue water withdrawals while largely overlooking green water (e.g., soil moisture and precipitation), which is predominantly lost through ET. As a result, existing management tracks and controls water in rivers, reservoirs, and groundwater systems but fails to account for the majority of actual consumptive water use, limiting the effectiveness of water scarcity mitigation and sustainable agricultural water management. This oversight has led to the transgression of the planetary boundary for green water,[4] posing serious risks to ecological stability and resilience.

To address these challenges, sustainable water management frameworks should adopt a landscape approach by establishing ET-based water consumption caps. These caps directly limit green water consumption and regulate total water withdrawals and are designed to ensure environmental flows and maintain ecosystem service functions. In practice, this approach can be implemented through cloud-based advisory systems or digital twin platforms, which integrate ET, soil moisture, and precipitation with environmental regulation, ecosystem management practices, and agricultural development, supporting optimized irrigation recommendations at the irrigation district scale and coordinated water resources planning at the basin level.

ET-based monitoring and regulation of groundwater overdraft

Groundwater, particularly in arid and semi-arid regions, is a critical resource for humans. Sustainable management requires treating surface water and groundwater as a single, interconnected resource.[5] Achieving a balance between groundwater extraction and recharge depends on precise quantification of both withdrawal and replenishment. Traditional methods, such as well measurements or flowmeters, have limited spatial coverage, cannot capture groundwater consumption at field or regional scales, and are costly to maintain.

To address these limitations, ET-based approaches are embedded in a multi-source evidence chain, combining ET with local rainfall, soil moisture, land cover, and irrigation data to more accurately estimate net groundwater extraction. By applying water balance or mass conservation principles, these methods quantify groundwater overdraft at the watershed scale, providing a foundation for regulation targets, guiding field-level irrigation planning, and supporting sustainable groundwater management. Moreover, ET-derived consumption caps can complement existing water withdrawal permits, forming enforceable regulatory metrics when remote sensing data meet certification and legal standards.

OUTLOOK

This commentary outlines pathways to transform ET from a hydrological variable into a decision-ready dataset for actionable water consumption management. By reducing uncertainties and improving spatiotemporal resolution through high-resolution satellites, cloud computing, and scale-aware modeling, ET provides a robust foundation for operational applications. Coupled with the separation of natural and human-driven ET, integration of blue and green water, and monitoring of groundwater overdraft, decision-ready ET can directly inform consumptive water accounting, irrigation planning, allocation, and regulatory enforcement. These advances position ET as a bridge between scientific understanding and practical water governance, offering policymakers and managers a quantitative, data-driven tool for sustainable and resilient water use.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.