# The Role of Geoinformatics in Irrigation Performance and Water Conservation: A Review

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**ABSTRACT:** Irrigation infrastructure forms the backbone of food production in water-stressed and monsoon-reliant regions, yet a large share of canal irrigation projects fall short of their designed potential. Delivery inefficiencies, skewed water distribution, and weak monitoring frameworks are recurring culprits. Traditional field-based methods struggle to bridge these gaps because they capture only scattered shots of what are, in reality, dynamic systems operating over vast areas. Over the past three decades, Remote Sensing (RS) and Geographic Information System (GIS) technologies have steadily filled this void, offering continuous, spatially coherent views of land-surface processes tied to irrigation. This review draws on close to some peer-reviewed studies to trace how RS–GIS methods have matured, from early crop-mapping experiments to integrated frameworks for evaluating water productivity and estimating savings. Core performance indicators examined include the Normalized Difference Vegetation Index (NDVI), actual evapotranspiration (AET), irrigation intensity, adequacy, equity, and output per unit of water consumed. Particular attention is given to large canal commands in India, where the stakes are highest. The paper closes by pointing to persistent data gaps, methodological hurdles, and the directions most likely to advance sustainable irrigation governance.

**Keywords**: Satellite monitoring, irrigation efficiency, NDVI, remote sensing and GIS, sustainable agriculture, Water Productivity.

## INTRODUCTION

Canal irrigation has long underpinned food security across South Asia. India, in particular, has channeled enormous resources into major and medium irrigation schemes, banking on them to stabilize yields and buffer rain-dependent farming against seasonal uncertainty. The physical infrastructure reservoirs, headworks, main canals, distributaries is impressive by any measure. What is less impressive is how much water actually reaches the crop roots it was intended to serve. Walking through almost any large command area exposes a familiar contradiction: elaborate works built to nourish millions of hectares, yet chronic shortfalls at the tail end and wasteful excess near the head. Some fields are waterlogged while neighboring plots stay parched. These are not isolated anomalies; they reflect a systemic lack of visibility into where water goes once it leaves the main canal. Addressing that invisibility is, in essence, what irrigation performance assessment is about.

Conventional assessment tools canal discharge gauges, farmer-reported crop data, periodic field surveys have real value but are stretched thin across large command areas. They generate point observations in systems that behave differently from one reach to the next, and they rarely capture changes fast enough to guide timely management decisions. High operational costs compound the problem, leaving managers to act on incomplete pictures. Satellite-based Earth observation began changing this situation in the 1990s. Ramesh and Dennis (1995) showed that NDVI-derived climatological models could reliably separate irrigated land from rainfed and natural vegetation, opening a practical path to large-area crop mapping. Richards (1996) followed with careful work on accuracy assessment, reminding the community that a map is only as trustworthy as its validation. These methodological

anchors proved durable. Bastiaanssen *et al.* (1998) then connected satellite-derived evapotranspiration patterns directly to wheat yield variation in the Bhakra command, making explicit what had been largely theoretical: that RS indicators could diagnose irrigation performance. Chwenming and Muhrong (1998) reinforced this by linking NDVI and spectral reflectance to rice growth stages, confirming multispectral data as a viable window on crop physiology.

In the years since, Earth observation satellites have grown more capable, more numerous, and easier to process. Cloud computing platforms now allow analysts to handle imagery archives that would once have overwhelmed any workstation. GIS environments have become more intuitive, enabling non-specialists to explore spatial patterns and test management scenarios. Together, these advances have shifted the question from whether RS & GIS can contribute to irrigation management to how best to deploy these tools at operational scale. This review synthesizes what the literature has established, identifies where significant gaps remain, and outlines the most promising avenues for translating research into practical water management gains.

## RESOURCE INVENTORY AND CROP CHARACTERIZATION USING REMOTE SENSING

The earliest RS applications in irrigation were rooted in a simple but powerful observation: crops that receive water behave differently in the electromagnetic spectrum from those that do not. Irrigated vegetation, even during dry spells, maintains higher chlorophyll concentrations and greater leaf water content, generating distinctive near-infrared reflectance signatures. NDVI was the tool that made this observation operational at scale.

Ramesh and Dennis (1995) demonstrated that irrigated croplands sustain consistently higher NDVI values during dry periods compared with rainfed or fallow land. That spectral contrast, stable across a growing season, allowed satellite sensors to trace irrigation extent over entire river basins a task that would require thousands of field inspectors to replicate on the ground. Methodological credibility required rigorous accuracy assessment, as Richards (1996) emphasized; without careful validation against ground truth, classification maps risk misleading the very managers they are meant to help. A more significant leap came when researchers moved beyond single-date imagery and began mining time-series data for phenological signals. Bastiaanssen *et al.* (1998) found that spatially variable evapotranspiration, derived from multi-date satellite observations, tracked wheat yield variation across the Bhakra command with notable fidelity. The implication was far-reaching: actual ET, retrievable from space, could serve as an integrative proxy for crop water use and health, condensing complex irrigation-plant interactions into a single, mappable variable.

Chwenming and Muhrong (1998) extended this line of inquiry to rice, showing that NDVI correlated closely with phenological stage, offering a way to monitor crop development without setting foot in a field. Multi-

temporal analysis proved similarly valuable for classification accuracy. Beltran and Belmonte (2001) demonstrated that blending NDVI-derived phenological trajectories with supervised classification dramatically reduced misidentification of irrigated crops. Kamthonkiat *et al.* (2005) refined the approach further by coupling time-series NDVI with rainfall data to separate irrigated from rainfed rice an important distinction for water accounting, since only the irrigated fraction represents managed water use. Collectively, this body of work established that irrigation leaves lasting, measurable imprints on vegetation behaviour that satellites can read reliably across seasons and regions. Research attention then shifted from proving detection feasibility to building the accurate, large-scale resource inventories needed for practical irrigation management.

## IRRIGATION PERFORMANCE EVALUATION USING REMOTE SENSING AND GIS

Knowing where irrigation occurs matters, but knowing how well an irrigation system serves its users matters far more. Early performance evaluation was the domain of hydraulic engineers who measured water delivery through canal networks and compared it against designed targets. Molden and Gates (1990) gave this tradition intellectual structure by formalizing four performance indicators adequacy, efficiency, equity, and dependability that together describe whether water reaches fields in the right amounts, at the right times, and with fair distribution across users. Those indicators remain foundational. Wolters (1992); Bos *et al.* (1994) broadened the scope, incorporating environmental sustainability and institutional performance alongside hydraulic metrics. This was an important conceptual shift: a canal that delivers water efficiently today but degrades its surrounding landscape is not performing well in any meaningful long-term sense. Despite the conceptual appeal, applying these frameworks across large systems required monitoring networks that few irrigation agencies could sustain. Remote sensing entered the performance evaluation arena through work by Bastiaanssen and Bos (1999), who argued that satellite-derived AET could substitute for conventional flow measurements in many evaluation contexts. The logic was compelling: while canal discharge data are often patchy or unreliable, AET reflects what vegetation actually consumed the biological endpoint that justifies irrigation in the first place. Mapping AET across a command area thus provided a direct, spatially complete view of irrigation outcomes.

Ray *et al.* (2002) applied this reasoning to the Mahi command in Gujarat. Their analysis laid bare a pattern that field surveys had only hinted at: systematic over-supply at the head end and persistent undersupply at the tail. Satellite data transformed these inequities from anecdotal complaints into documented, mappable spatial facts. Ramana (2007) pursued similar investigations at distributary and command scales, consistently finding head–tail disparities, inefficient water use, and underutilized irrigation potential findings that become compelling precisely because they are visible to anyone who examines the map. More recent frameworks have

made these assessments more actionable. Avilkumar *et al.* (2014) combined relative water supply, irrigation intensity, and water productivity into integrated scorecards that give canal managers a clear basis for targeting interventions. By connecting water delivery with actual crop response, these indicators shift the conversation from inputs to outcomes from how much water entered the canal to how much agricultural benefit it produced.

Furthermore, this evolution reflects a broader intellectual movement in irrigation science: away from infrastructure metrics and toward biologically grounded, spatially explicit assessments in which crops themselves serve as performance indicators.

## EVAPOTRANSPIRATION AND WATER PRODUCTIVITY ASSESSMENT USING REMOTE SENSING

Evapotranspiration is the process through which plants draw water from soil, move it through their vascular tissue, and release it to the atmosphere via leaf stomata. It also supports photosynthesis and regulates canopy temperature. For irrigation managers, ET is not merely a biophysical curiosity; it is the mechanism that connects water delivery to agricultural production. Quantifying it accurately is therefore central to any serious assessment of irrigation efficiency. Ground-based ET measurement is genuinely demanding. Lysimeters, eddy covariance towers, and Bowen ratio systems all require precision instrumentation, skilled operators, and regular calibration. They also provide point estimates that are notoriously difficult to scale across heterogeneous fields spanning tens or hundreds of thousands of hectares. Even networks of well-maintained stations introduce substantial interpolation error at the edges of their coverage.

Energy balance algorithms resolved much of this scaling problem by grounding ET estimation in physical principles observable from orbit. Incoming solar radiation partitions into soil heat flux, sensible heat flux, and latent heat the last of which corresponds to ET. Algorithms like SEBAL and METRIC draw on satellite measurements of surface temperature, spectral reflectance, and vegetation indices to compute this partition spatially, producing ET maps rather than ET points. Ahmad *et al*. (2009) demonstrated that MODIS imagery was up to the task in large irrigation schemes where ground networks were thin or unreliable, yielding AET estimates with sufficient spatial coverage to support regional management decisions.

Water productivity relating crop yield to water consumed extends the utility of ET estimation into the realm of agricultural economics. Droogers *et al.* (1999) ; Molden *et al*. (1998) formalized productivity metrics that distinguish water used productively by crops from water lost to bare-soil evaporation, canal seepage, or fallow land. This distinction matters enormously for targeting conservation efforts: it is futile to squeeze a field that is already operating near peak efficiency while ignoring an adjacent fallow plot evaporating water to no agricultural purpose. Taghvaeian *et al.* (2018) demonstrated how SEBAL outputs could be used to map zones of water stress, over-irrigation, and management inefficiency across a California irrigation scheme, offering managers a spatially explicit audit of system performance. Rather than asking how much water left the reservoir, satellite-derived ET asks a more fundamental question: how much water reached a crop and how productively was it used? That shift in perspective is what gives RS-based assessments their practical power.

## ESTIMATION OF WATER SAVING POTENTIAL USING REMOTE SENSING AND GIS

Identifying where water is being wasted may be the most consequential application of remote sensing in irrigation management. Developing new water supplies has grown progressively harder, more expensive, and more contentious. Meanwhile, substantial volumes of water circulate through existing irrigation systems without reaching a crop root lost through excessive application, ill-timed releases, or conveyance inefficiencies. The challenge is not recognizing that losses exist; it is locating and measuring them precisely enough to justify targeted intervention. Santhi *et al*. (2005) took an early step by coupling GIS with the SWAT hydrological model to estimate irrigation demand and potential savings at regional scale. The analysis revealed pronounced spatial heterogeneity, with subregions experiencing persistent surpluses coexisting alongside areas facing chronic deficits. This variability was not evident in aggregate statistics but became apparent through spatially explicit analysis, enabling targeted and actionable insights.

Later work exploited satellite-derived ET directly for savings estimation. Peng *et al*. (2009, 2019) compared actual evapotranspiration maps against crop water requirement estimates to pinpoint areas where applied water consistently exceeded agronomic need. The excess, mapped continuously across command areas, provided a defensible estimate of recoverable savings. The approach also allowed priority ranking of intervention zones, directing attention to where efficiency improvements would yield the greatest water recovery. Hao *et al*. (2018) took a different but complementary angle by optimizing cropping patterns under uncertain water availability. Remote sensing contributed realistic inputs actual crop distributions and phenological states that strengthened scenario modeling and helped identify cropping adjustments capable of reducing water demand without eroding yields. Wei *et al*. (2022) focused on paddy rice, where the distinction between necessary transpiration and avoidable evaporation or seepage is particularly consequential. Rice cultivation accounts for a disproportionate share of global irrigation withdrawals, and even modest improvements in water management can translate into large absolute savings. Their remote sensing framework enabled that fine-grained differentiation at scales relevant to practical water allocation decisions.

Wang *et al.* (2020) highlighted a related opportunity: near-real-time satellite monitoring of vegetation condition and stress can inform short-term release scheduling, allowing canal managers to adjust deliveries

dynamically rather than adhering to rigid seasonal averages. Under variable water availability, that responsiveness is increasingly valuable. The cumulative message from these studies is that RS–GIS assessment transforms water conservation from a general aspiration into a spatially targeted, evidence-based practice. By revealing where water is consumed productively, where it is lost, and where it is over-applied, satellite data give irrigation agencies the information they need to intervene with precision.

## CHALLENGES, RESEARCH GAPS, AND FUTURE DIRECTIONS

Progress in RS–GIS applications for irrigation has been substantial, but the technology confronts real limitations that temper what it can achieve operationally. Cloud cover is perhaps the most frustrating of these: optical and thermal sensors go blind during monsoon periods, precisely when monitoring would be most informative. Synthetic aperture radar offers partial relief because it penetrates cloud cover, but processing SAR data into irrigation-relevant products remains technically demanding and is not yet routine in most agencies.

Mixed pixels present a related challenge. Where fields are small and fragmented common across Indian command areas a single satellite pixel may blend cropland, fallow ground, canal banks, and village settlement. Classification algorithms then face an ambiguous signal, and errors propagate into ET estimates and performance indicators derived from them. Finer spatial resolution sensors help, but higher resolution typically means narrower swaths and less frequent revisit, trading one problem for another. Scale mismatch is a subtler but equally persistent issue. Many satellite datasets operate at resolutions of 250 m to 1000 m, while irrigation management decisions are made at distributary and field scales measured in tens of meters. Translating coarse observations into fine-scale guidance requires downscaling approaches whose uncertainties are not always well-characterized. Validation compounds this difficulty: reliable ground measurements of ET, yield, and water productivity are expensive to collect and spatially sparse, constraining meaningful verification of satellite products across diverse agro-climatic settings.

A more fundamental limitation is that remote sensing captures biophysical processes but says little about the institutional, economic, and behavioural factors that actually govern irrigation outcomes. A satellite can show that tail-end fields receive less water than head-reach fields, but it cannot explain whether that inequity reflects physical infrastructure constraints, management choices, governance failures, or farmer adaptations. Understanding cause is as important as mapping effect if interventions are to be well-designed and lasting.

Future work should pursue several directions. High-resolution sensors like Sentinel-2, long-term MODIS archives, and platforms like Google Earth Engine are already enabling analyses at scales and frequencies that were impractical a decade ago. Realizing their potential for operational irrigation management will require integrating RS outputs with socio-economic and institutional datasets, improving uncertainty quantification, and involving farmers and irrigation managers in validation and interpretation. Machine learning approaches that extract crop-specific performance signals from multi-sensor time series are promising but need rigorous testing across diverse systems before they can be trusted for policy.

Ultimately, the goal is not to replace ground-based monitoring but to multiply its reach and sharpen its focus. Satellite observations provide the spatial coverage and temporal regularity that field measurement cannot match; ground truth provides the calibration anchor and contextual understanding that satellites cannot supply. A more deliberate integration of the two will be essential for converting research advances into durable operational tools.

## CONCLUSION

Remote sensing and GIS have meaningfully changed what is possible in irrigation performance assessment. Satellite-derived indicators especially NDVI and actual evapotranspiration have proven reliable proxies for diagnosing delivery inefficiencies and distributional inequities that conventional monitoring consistently misses. When these RS outputs are combined with standard hydraulic performance metrics, the result is an evaluation framework that is both spatially comprehensive and practically grounded, capable of supporting water management decisions across the full extent of large canal commands.

The challenges are real cloud cover, mixed pixels, scale mismatch, limited ground validation, and the persistent gap between biophysical observation and institutional understanding. But advances in high-resolution sensors, long-term satellite archives, and cloud-based geospatial computing are steadily narrowing these constraints. What once required months of computational work can now be accomplished in hours, opening the door to near-operational monitoring.

From a policy perspective, the most important contribution of RS & GIS tools is that they make inefficiency visible and locatable transforming vague awareness of system underperformance into specific, mappable targets for intervention. As water scarcity deepens and irrigation systems face rising demands with constrained supplies, that capacity for targeted, evidence-based management will only grow in importance. Embedding satellite-based monitoring into routine irrigation practice is no longer a research aspiration; it is a practical necessity for systems that must do more with less.

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