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Editorial

Editorial for Special Issue "Geographic Information System (GIS) Techniques and Applications for Sustainable Water Resource Management in Agriculture"

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1. Overview of Recent Developments in the Field

Geographic Information Systems (GISs) and remote sensing technologies have undergone transformative advances over the past decade, fundamentally reshaping how hydrologists and water managers approach agricultural water resource challenges [1–12]. Given the increasing pressure on freshwater supplies in the context of climate change, the application of GISs has empowered experts and hydrologists to provide scalable, near-real-time, remote-sensing-based and cost-effective solutions to several issues related to water resource management in the agricultural sector. The integration of satellite-based remote sensing with GIS analytical frameworks has revolutionized the transition from traditional point-based monitoring systems to spatially continuous and temporally dynamic assessment tools [13–17]. This integrative approach has gained particular emphasis in recent literature, where researchers highlight its potential to bridge data gaps across scales, enhance the accuracy of hydrological modeling, and support evidence-based decision-making for sustainable agricultural water management under changing climatic and socioeconomic conditions [18–29]. Modern satellite platforms—including optical sensors like Sentinel-2 and Landsat, and radar-based systems such as Sentinel-1—now provide unprecedented data accessibility through cloud computing platforms like Google Earth Engine [30]. The democratization of geospatial technology has enabled near-real-time monitoring at operational scales previously attainable only through extensive, costly and time-consuming field surveys [31,32].

Simultaneously, ecosystem service valuation frameworks such as the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model have matured to provide spatially explicit quantification of water provisioning at fine resolutions [33]. Semi-distributed hydrological models (e.g., HEC-HMS, U.S. Army Software; HYDRUS, USDA Software) have become increasingly sophisticated in representing complex landscapes including terraced agroecosystems and heterogeneous agricultural mosaics [34]. The development of composite drought indices through multivariate statistical approaches—particularly Principal Component Analysis (PCA) and the combination of indices integrating precipitation, temperature, vegetation, and soil moisture—has enhanced drought characterization beyond single-variable metrics [34,35]. Furthermore, advances in machine learning and deep learning methodologies, coupled with remote sensing data, have opened pathways for predictive water quality monitoring and streamflow forecasting [36,37].

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These technological advances arrive at a critical juncture. Globally, freshwater scarcity intensifies due to climate variability and anthropogenic pressures, while agricultural water demand remains the dominant sectoral consumer of freshwater resources [31]. In recent years, several unprecedented drought events have impacted agricultural areas all over the world. Sri Lanka experienced a 40% rice yield decrease in 2016 due to an extensive lack of rain [34]. The water yield of the Hani Rice Terraces (China) dropped by 31% between 2018 and 2020 due to insufficient precipitation and land-use fragmentation, thus causing the abandonment of specific crop types [33]. The Po Valley (Northern Italy), one of Europe's most economically productive agricultural regions, was hit by an exceptional drought in 2022, identified as the worst in 216 years of records, that devastated agricultural production and threatened hydroelectric generation [38]. Island states like Indonesia were also recently affected by droughts that impacted rice and perennial crops, such as rubber trees [39]. All the listed studies underscore the urgency of improving agricultural water management capabilities. The possibility to map water dynamics, optimize irrigation networks, predict extreme events, and integrate hydrological assessment with socio-cultural water governance has become not merely advantageous but essential for agricultural resilience and food security.

2. Knowledge Gaps Addressed by This Special Issue

Despite remarkable technological advances, significant knowledge gaps persist in GIS and remote sensing applications to agricultural water challenges. These challenges include coarse-resolution hydrological assessments (30–50 km), which obscure local variability and lead to insufficient point measurements [40]; underexplored fine-scale mapping of water yield, streamflow, and drought impacts across heterogeneous landscapes like terraced agroecosystems, complex irrigation networks, and cloud-covered tropical mosaics [33,34]; and poorly quantified interactions of land-use fragmentation, topography, and climate gradients [33]. Fragmented evaluation limits multi-sensor complementarity among indices (NDVI, NDMI, NDWI, RDI, FAI) for water stress, soil moisture, blooms, and drought, particularly radar–optical synergies (VV/VH and DpRVI with NDMI/NDWI/RDI) in tropical/arid/Mediterranean contexts [31,39,41]. Reactive monitoring dominates, with underdeveloped predictive frameworks integrating remote sensing and modeling for proactive management such as streamflow forecasting or irrigation adjustment in data-scarce regions [42–47]. GIS and remote sensing techniques hold immense potential to advance emerging socio-hydrological frameworks by integrating biophysical assessments with cultural governance, heritage conservation, and equity considerations beyond traditional optimization [33,48–53], while ongoing efforts enhance operational scalability by overcoming technical barriers to deliver accessible tools for water managers and communities in resource-constrained settings [54].

3. How This Special Issue Addresses These Gaps

The present editorial synthesizes cutting-edge advancements that have the potential to improve agricultural water management amid climate variability. Moreover, it underlines the importance of multi-sensor integration as a paradigm shift toward scalable methodologies that are particularly suitable in data-scarce environments.

The five articles published in this Special Issue provide innovative solutions to the highlighted knowledge gaps, proposing diverse methodological approaches suitable for several geographical contexts.

Collectively, these studies illuminate interconnected challenges, such as drought, stress, eutrophication, yield decline, and irrigation precision, while pioneering hybrid

frameworks that bridge biophysical modeling, machine learning, and policy for sustainable agroecosystems, transforming reactive monitoring into proactive governance.

3.1. Fine-Scale Water Yield Mapping and Heritage Conservation

Huang et al. [33] demonstrated the application of the InVEST ecosystem service model combined with geodetector spatial analysis to map water–yield dynamics in the Honghe Hani Rice Terraces, a UNESCO World Heritage site in southwestern China. Operating at 30 m resolution over a decadal period (2010–2020), their framework quantifies how land-use fragmentation and climate variability interact to drive water availability in vertically zoned agroecosystems. A critical innovation is the systematic integration of hydrological modeling with socio-cultural insights, demonstrating that land-use pattern accounts for 80–95% of water yield variability. The study reveals that forests delivered 68.7 million m^3 of water over the decade while simultaneously highlighting the hydrological consequences of tourism-driven land conversion and cropland fragmentation. Reforestation in critical recharge zones, terrace restoration, and regulated tourism integrating rainwater harvesting emerged as management strategies balancing water security with cultural heritage preservation. The study demonstrates the potential of GIS beyond biophysical optimization, moving toward integrated socio-ecological sustainability.

3.2. Remote Sensing for Water Pollution Prevention and Monitoring

Podsosonnaya et al. [41] address algal bloom detection in estuarine systems using multispectral satellite imagery and spectral index-based classification. Their systematic comparative analysis of six spectral indices (TVI, NDVI, FAI, NDAI, NRSI, ABI) for algal bloom detection in the Tuggerah Lakes estuary (New South Wales, Australia) establishes the Floating Algae Index (FAI) as the most effective one (accuracy 0.711) for shallow, optically complex waters. By implementing logistic regression modeling calibrated through bootstrapping with probability thresholds optimized via cross-validation, the authors developed a cost-effective, scalable tool for monitoring macroalgal blooms, a critical indicator of nutrient pollution and eutrophication. This work addresses a fundamental gap: while nutrient runoff from agriculture represents a widespread water quality threat globally, operational monitoring systems that can detect algal blooms across large areas remain limited. The framework demonstrates that satellite-derived indices, when systematically selected and validated against ground-truth data, can support early detection of water pollution events, enable proactive management of agricultural nutrient losses and help protect downstream water resources and coastal ecosystems.

3.3. Smart Irrigation and Distributed Soil Moisture Estimation

Sánchez-Fernández et al. [55] present an integrated approach combining intelligent weather condition adjustment based on spatial features (IWeCASF) with fuzzy estimation for decision-making (FEADM) to estimate regional soil moisture. The innovation directly addresses a critical bottleneck in operational irrigation management: the complexity and cost of deploying extensive soil moisture sensor networks. Rather than requiring multiple measurement points—which are costly to install and maintain—their framework estimates soil moisture at multiple checkpoints by measuring weather conditions at a single primary location and intelligently adjusting for local spatial features (topography, vegetation, land use) using fuzzy inference systems. The integration of fuzzy logic handles the inherent imprecision in hydrological estimation, making the approach particularly valuable for regions with limited data availability. By incorporating actual irrigation water records, the framework extends beyond rainfall-based models to include human water management actions, a critical missing link in many operational systems, thus addressing the gap between theoretical water availability and practical irrigation scheduling, and demonstrating

how GIS-derived spatial analysis can simplify and substantially reduce the cost of smart irrigation systems while maintaining accuracy.

3.4. Drought Impact Assessment and Streamflow Prediction

Srimali et al. [34] developed a novel Combined Drought Index (CDI) integrating multiple remote sensing variables—Standardized Precipitation Evapotranspiration Index (SPEI), Temperature Condition Index (TCI), Vegetation Condition Index (VCI), and Soil Moisture Condition Index (SMCI)—through Principal Component Analysis. Applied to the Giriulla sub-basin of Sri Lanka's Maha Oya River Basin, their framework couples remote sensing with semi-distributed hydrological modeling (HEC-HMS) to assess how spatial drought variability influences streamflow across sub-catchments. A critical finding—that upstream sub-catchments exhibit greater drought sensitivity than downstream areas, and that drought impacts differ between high- and low-flow conditions—provides essential insights for reservoir operation and water allocation strategies. The CDI achieved a Pearson correlation coefficient of 0.74 with standardized streamflow and successfully captured major drought and flood events (2015–2023). The work fills a significant gap identified in recent drought literature reviews: while temporal patterns of drought have been extensively studied, the spatial dimension of drought and how localized water stress propagates through hydrological systems remain underexplored. The framework provides also a scalable methodology for data-scarce regions vulnerable to climate variability, integrating remote sensing with hydrological modeling in a manner generalizable across diverse basins.

3.5. Near-Real-Time Water Stress Monitoring in Heterogeneous Landscapes

Holik et al. [39] presented a comprehensive framework for near-real-time water stress monitoring in tropical agricultural mosaics by integrating radar-derived and optical remote sensing indices through Google Earth Engine. Their analysis of paddy, sugarcane, and rubber plantations in Banyuwangi, Indonesia, demonstrates strong complementarity between radar structural indices (vertical transmit/vertical receive–vertical transmit/horizontal receive VV/VH ratio ranging 4.2–12.3 in paddy, 5.4–6.0 in rubber; Dual Polarimetric Radar Vegetation Index peaking at 0.75 in paddy) and optical moisture indices (NDMI dropping from 0.26 to 0.06 during drought in sugarcane; NDWI and RDI providing complementary stress signals). The framework captures distinct phenological signatures and water stress responses specific to each crop type—synchronized VV/VH and drought index peaks during paddy inundation versus lagged NDMI–VV/VH responses capturing stress-induced defoliation in rubber. By leveraging cloud-based geospatial platforms, the authors overcome a major barrier in tropical regions: persistent cloud cover that limits optical-only monitoring. The multi-sensor integration provides spatially explicit, temporally continuous, and cost-effective monitoring to support irrigation scheduling, drought early warning, and agricultural planning, thus directly addressing a gap between technological potential and operational accessibility, and demonstrating how modern geospatial platforms can democratize water stress monitoring even in data-scarce, climatically challenging regions where traditional monitoring networks are absent.

4. Integrated Framework Evolution: Bridging Mapping, Monitoring, and Adaptive Management

The five articles collectively illustrate an emerging GIS-based integrated framework advancing water resource management across three frontiers: from static snapshot mapping to continuous temporal monitoring enabled by Sentinel platforms' daily–weekly revisit frequencies, exemplified by algal bloom detection, combined drought indices, and real-time stress monitoring supporting monthly–weekly operational decisions via

probabilistic forecasting [2–7,13–16,24–30,32,34,41,45]. They progress from single-variable indices (precipitation, NDVI, discharge), which are inadequate for multifaceted climatic, hydrological, and societal challenges, to multivariable integration—merging hydrological modeling with ecosystem services, radar–optical indices, and PCA-synthesized drought indicators—aligning with evidence that machine learning ensembles outperform single models [34–37,39–42]. Finally, they evolve from biophysical optimization to socio-hydrological integration, as seen in heritage-focused governance, emphasizing GIS tools bridging water provisioning with cultural values, equity, and adaptive frameworks essential amid intensifying scarcity [33,48–53].

5. Future Research Directions and Emerging Opportunities

While this Special Issue advances GIS applications in agricultural water management, several critical research frontiers warrant concerted attention.

5.1. Machine Learning and Predictive Modeling for Seasonal-to-Interannual Forecasting

Recent advances demonstrate that ensemble machine learning methods—random forests, gradient boosting, and extreme gradient boosting—combined with remote sensing data consistently outperform traditional statistical approaches for water quality and hydrological prediction [36,37]. Deep learning architectures including convolutional neural networks (CNNs), long short-term memory (LSTM) networks, and recurrent neural networks (RNNs) show particular promise for capturing spatio-temporal patterns in water dynamics [37,56]. Future research should integrate these advanced machine learning approaches with remote sensing and GIS frameworks to develop predictive drought and water stress forecasting systems operating at seasonal-to-interannual timescales [36,37]. Such systems could extend prediction windows from current operational timeframes (weeks to months) toward climate-scale forecasting, provided that they adequately address the challenge of model interpretability, ensuring that predictions remain explainable to water managers and decision-makers [57].

5.2. Uncertainty Quantification, Propagation, and Probabilistic Decision Support

Remote sensing estimates inevitably contain uncertainty from atmospheric correction, spatial heterogeneity, sensor limitations, and model parameterization [58]. Advanced approaches including Bayesian neural networks with Monte Carlo dropout, mixture density networks, and probabilistic ensemble methods can quantify prediction uncertainty [58]. Future GIS frameworks should explicitly quantify and propagate uncertainty through to management decisions, moving from point estimates toward probabilistic forecasts and decision-support systems that communicate confidence levels and risk metrics to water managers [43,59]. The probabilistic framing aligns with recent advances in climate-informed water resource planning under uncertainty [43].

5.3. Transdisciplinary Integration and Stakeholder-Centered Design

Water resource challenges increasingly require integration of hydrological science with economics, sociology, political ecology, ethics, and cultural studies. Future GIS platforms should facilitate this integration—for example, by linking water stress maps to livelihood vulnerability assessments, water-use valuation frameworks, or social–ecological resilience indicators [48–53]. This requires the development of GIS interfaces that are accessible to non-technical stakeholders and embedding participatory mapping approaches that engage farmers, water users, and local communities in data collection and decision-making [59]. Co-production of decision-relevant metrics between scientists and decision-makers, as demonstrated in climate adaptation literature, can enhance the relevance and usability of GIS-based tools [45].

5.4. Climate Adaptation and Adaptive Management of Vulnerabilities

As climate change intensifies water variability and supply source vulnerabilities, GIS tools must evolve from describing current conditions toward supporting adaptive management, including multi-indicator vulnerability and sustainability assessments of critical water supply infrastructure [43,60,61]. Future frameworks should help water managers explore trade-offs between competing objectives (e.g., irrigation maintenance vs. environmental flows vs. hydroelectric generation), simulate outcomes of alternative management strategies under climate scenarios, and identify adaptation pathways that balance multiple sustainability dimensions. This requires integrating climate projections and their associated uncertainties with water resource modeling in accessible decision-support frameworks.

5.5. Data Harmonization, Interoperability, and Capacity for Developing Regions

Despite proliferation of remote sensing platforms and GIS tools, interoperability remains limited. Future research should invest in standardized data formats (NetCDF, GeoJSON, HDF5), metadata conventions like ISO 19115, Dublin Core [62,63], and web service architectures (Open Geospatial Consortium standards including WMS, WFS, WCS) that enable seamless integration of diverse data sources [64]. Open-source platforms (QGIS, GDAL, PostGIS) combined with cloud infrastructure (Google Earth Engine, AWS, Azure) should be leveraged to support open-access platforms in developing regions where access to proprietary GIS licenses is limited [30,64].

5.6. Ecosystem Service Valuation and Water Ethics Frameworks

Future work should extend ecosystem service assessment—as exemplified in the Honghe study—toward explicit integration with water ethics frameworks [33]. This includes quantifying not only water provisioning but also water quality, aquatic biodiversity, and cultural values; transparently assessing trade-offs in water allocation across competing uses; and developing governance mechanisms that ensure equitable access to water while safeguarding ecosystem health [48,49,53] GIS-based approaches to visualizing and evaluating these trade-offs can support more inclusive water governance.

6. Conclusions

The five articles in this Special Issue demonstrate that GIS and remote sensing have matured from visualization and analysis tools into operational systems capable of addressing critical water resource challenges in agriculture. By mapping hydrologic dynamics at fine resolution using the InVEST model, integrating multi-sensor remote sensing data through systematic index selection and machine learning, coupling biophysical models with socio-ecological considerations, and leveraging cloud-based platforms for near-real-time monitoring, modern GIS frameworks provide unprecedented capacity to optimize irrigation, prevent water pollution, predict extreme events, and support adaptive water governance [33,34,39,41,55].

Yet this moment of technological opportunity coincides with intensifying water scarcity and climate uncertainty [31,42]. The practical impact of advancing GIS science depends not solely on methodological innovation but on translating research into accessible, locally relevant, culturally appropriate tools that empower communities to manage water resources sustainably. The papers in this Special Issue, through their diverse methodological approaches and geographical contexts, provide essential foundations for this translation.

As the global community confronts the defining water challenges of the 21st century—ensuring food security, drinking water access, and ecosystem integrity amidst climate variability and competing demands [31,53]—GIS and remote sensing offer powerful tools for mapping pathways toward sustainable agricultural water futures.

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Future success requires sustained investment in machine learning and predictive forecasting, explicit uncertainty quantification and probabilistic decision support, transdisciplinary integration bridging natural and social sciences, operational implementation and capacity building in resource-constrained settings, and open data standards enabling seamless global collaboration. Most critically, it requires centering the voices and knowledge of water users, farmers, and local communities in the design and implementation of GIS-based water management systems.

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