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Integrated Remote Sensing and GIS for Decision-oriented Climate-resilient Management of Groundwater-irrigated Cropping Systems: A Review

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Review Article

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Abstract

Groundwater irrigation remains a critical component of agricultural production, particularly in regions experiencing climatic variability. However, increasing pressures from temperature extremes, erratic precipitation, and unsustainable extraction threaten aquifer sustainability and long-term food security. This review synthesizes recent advances in the integration of Remote Sensing (RS) and Geographic Information Systems (GIS) for climate-resilient groundwater management in irrigated cropping systems. It examines how satellite-derived indicators, including evapotranspiration, vegetation indices, soil moisture, and groundwater

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storage anomalies, enable improved spatial and temporal assessment of water resources. The review further evaluates GIS-based frameworks for integrating multi-source datasets to support groundwater potential mapping, irrigation planning, and adaptive decision-making. Emerging approaches such as machine learning, hydrological modeling, and multi-criteria decision analysis are also discussed for their role in predictive irrigation management and recharge zone identification. The synthesis highlights a shift from conventional monitoring toward integrated, decision-oriented systems that enhance water-use efficiency and resilience under climate uncertainty. Despite these advancements, challenges persist, including data limitations, model uncertainty, and institutional constraints. This review adopts a structured literature synthesis approach to identify key advancements, categorize applications, and highlight research gaps. Overall, integrating RS–GIS technologies into decision-support frameworks is essential for sustainable groundwater governance and resilient agricultural systems.

Keywords: Remote sensing; geographic information systems (GIS); groundwater management; climate resilience; irrigated agriculture; decision support systems.

1. Introduction

Many regions of the world still rely heavily on groundwater-supported irrigation for food production, especially in arid and semi-arid regions where surface water supplies are either limited or extremely seasonal. Groundwater is a vital resource for maintaining agricultural yields and bolstering rural economies, as a significant portion of irrigated farming worldwide depends on subterranean water supplies (Siebert et al., 2010). As the largest distributed store of freshwater on Earth, groundwater plays a vital role in sustaining agricultural productivity; however, it is increasingly being depleted due to climatic stress and unsustainable extraction practices (Famiglietti, 2014). Conventional methods of groundwater monitoring are spatially restricted and inadequate for large-scale assessment. In contrast, advancements in Remote Sensing (RS) and Geographic Information Systems (GIS) now allow spatially distributed evaluation of land, water, and crop processes. Satellite-based remote sensing has evolved from a research tool to a practical system for irrigation management and water resource planning (Bastiaanssen et al., 2000). The ongoing challenges of climate variability, erratic rainfall, and excessive groundwater abstraction have intensified the vulnerability of irrigated agriculture worldwide. Groundwater-dependent farming systems, particularly those in arid and semi-arid landscapes, are facing risks of aquifer depletion and quality degradation due to poor management. The integration of RS and GIS provides an innovative, data-driven framework for decision-oriented and climate-resilient groundwater management (Zacharia et al., 2025). RS and GIS technologies enable dynamic monitoring of groundwater conditions, evapotranspiration, soil moisture, and crop stress all critical parameters for adaptive and informed decision-making under uncertain climatic conditions. These spatial tools have become essential for precision agriculture, spatially explicit resource allocation, and irrigation optimization (Reddy et al., 2018). Furthermore, groundwater-fed farming systems are increasingly threatened by climate-induced shifts in rainfall patterns, evapotranspiration rates, and groundwater recharge processes. Addressing these challenges requires advanced monitoring and adaptive management that integrate RS, GIS, and emerging data analytics such as machine learning (Rabie et al., 2025). The compounded impacts of climate change on groundwater-dependent agriculture highlight the need for RS-GIS-based frameworks that support precise spatial analysis and real-time decision-making for sustainable cropping systems (Shaikh and Birajdar, 2024). By merging spatial datasets, satellite imagery, and hydrological modeling, RS-GIS integration provides transformative opportunities for monitoring aquifer behavior, evaluating irrigation efficiency, and strengthening climate adaptation strategies (Haque et al., 2025). Such frameworks function as decision-support systems, fostering data-driven, climate-resilient management of groundwater and cropping systems (Bwambale et al., 2022). The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) transforms climate resilience by enhancing monitoring, prediction, and sustainable management of groundwater and agricultural water resources (Haque et al., 2025). At a governance level, embedding RS-GIS within national and local water management frameworks enhances decision-making from basin to farm scales. Encouraging open-access geospatial datasets, stakeholder training, and RS-GIS-based policy tools can ensure sustainable and climate-resilient management of groundwater-irrigated agriculture (Kumar and Yasmin, 2025).

This review aims to demonstrate how integrating Remote Sensing (RS) and Geographic Information Systems (GIS) supports climate-resilient management of groundwater-irrigated cropping systems. It emphasizes using spatial data, hydrological modeling, and decision-support tools to enhance irrigation efficiency, recharge planning, and adaptive, data-driven strategies for sustainable agricultural water governance.

2. Methodology

To enhance transparency and scientific rigor, this review adopts a structured literature assessment approach. Relevant studies were identified using major academic databases, including Google Scholar, Scopus, and Web of Science, covering publications from 2015 to 2026, with particular emphasis on recent advancements (2023-2026).

The literature search was conducted using combinations of the following keywords: “remote sensing,” “geographic information systems (GIS),” “groundwater management,” “climate resilience,” “irrigation,” and “decision support systems.”

2.1 Selection Criteria

The inclusion criteria for selecting relevant studies were as follows:

- Peer-reviewed journal articles, book chapters, and high-quality reports
- Studies focusing on groundwater, irrigation, and climate adaptation
- Research integrating Remote Sensing (RS), Geographic Information Systems (GIS), and advanced analytical approaches such as artificial intelligence and machine learning

2.2 Exclusion Criteria

The following criteria were used to exclude studies:

- Studies lacking a clear methodological description
- Non-scientific or non-peer-reviewed sources
- Duplicate or redundant publications
- Studies not directly related to groundwater or irrigated agricultural systems

2.3 Data Analysis and Synthesis

The selected studies were analyzed using a thematic classification approach, focusing on key domains such as technological applications, methodological frameworks, decision-support systems, and research gaps. A comparative synthesis was also performed to evaluate differences in approaches, identify common trends, and highlight limitations across studies. This structured methodology enhances the reliability and reproducibility of the review.

3. Critical Analysis of Existing Approaches

While Remote Sensing (RS) and GIS-based approaches have significantly advanced groundwater monitoring and irrigation management, notable variations exist in their effectiveness across different contexts. RS-based methods provide strong spatial coverage and temporal monitoring capabilities; however, they often suffer from limitations related to spatial resolution and cloud interference. In contrast, GIS-based models enable multi-criteria spatial analysis but depend heavily on input data quality and expert-driven weighting schemes.

Recent studies integrating artificial intelligence and machine learning demonstrate improved predictive accuracy and automation in groundwater assessment and irrigation scheduling. However, these approaches introduce challenges related to model interpretability, data requirements, and uncertainty propagation. Furthermore, inconsistencies across studies in terms of validation techniques and data integration frameworks limit comparability and generalization of findings.

Overall, while integrated RS–GIS–AI frameworks represent a significant advancement, there remains a need for standardized methodologies, improved ground validation, and transparent uncertainty assessment to enhance their reliability and scalability across diverse agro-ecological regions.

4. Role of Remote Sensing and GIS in Agricultural Groundwater Systems

Remote sensing, when integrated with Geographic Information Systems (GIS), strengthens spatial analysis and monitoring of agricultural groundwater systems. The use of multispectral satellite data such as Landsat 8, Sentinel-2, and the Moderate Resolution Imaging Spectroradiometer (MODIS) enhances the quantification of evapotranspiration, soil moisture, and groundwater–irrigation interactions (Taghvaeian et al., 2018). The estimation of crop evapotranspiration using satellite data has substantially improved the accuracy of groundwater abstraction assessments, thereby supporting climate-resilient irrigation practices (Nhamo et al., 2020). GIS-based spatial analysis, combined with RS-derived datasets like Digital Elevation Models (DEMs), Land Use/Land Cover (LULC) maps, and precipitation indices, facilitates the delineation of groundwater potential zones and enhances irrigation planning (Sarwar et al., 2021). Land use and land cover changes due to agricultural expansion and urbanization influence recharge processes, while RS–GIS-based modeling supports adaptive aquifer management in response to climate variability (Ali and Bilal, 2025). Advanced platforms such as Google Earth Engine (GEE) have also been used for assessing groundwater drought resilience. The application of satellite-derived indices in GEE enables spatio-temporal mapping of groundwater drought conditions, assisting policy formulation and regional water governance (Farhat, 2024). Furthermore, the integration of Phased Array Type L-band Synthetic Aperture Radar (PALSAR), Sentinel-1, and Planet imagery facilitates high-resolution mapping of crop distribution and groundwater-dependent irrigation systems, advancing sustainable water resource management (Anconitano et al., 2024). Coupling remote sensing-based evapotranspiration (ET) data with GIS-grounded groundwater modeling allows for a holistic understanding of irrigation water supply and demand relationships, thereby improving sustainable management of agricultural water resources (Alexandridis et al., 2014). Likewise, the integration of lithology, slope, rainfall, lineament density, and LULC data within GIS frameworks increases the accuracy of groundwater potential zoning and minimizes exploration costs in semi-arid environments (Mostafa et al., 2025).

5. Integrated Remote Sensing and Gis Framework for Climate-Resilient Groundwater-Irrigated Cropping Systems

5.1 Remote Sensing in Groundwater and Irrigation Assessment

Remote sensing provides continuous, synoptic observations that aid in identifying groundwater potential zones, evapotranspiration rates, and vegetation health. For instance, normalized difference vegetation index (NDVI) and land surface temperature (LST) derived from MODIS and Landsat satellites allow researchers to detect water stress in crops (Akpoti et al., 2023). Aquifer depletion, observable through satellite gravimetry and thermal infrared remote sensing data, exacerbates drought-induced crop losses, underscoring the critical role of remote sensing in groundwater sustainability and drought resilience analysis (Mieno et al., 2024). Applied multi-spectral and Analytic Hierarchy Process (AHP)-based remote sensing models have been utilized to map groundwater potential zones in semi-arid Tanzania, enhancing irrigation planning and supporting climate-resilient water allocation strategies for sustainable agricultural management (Zacharia et al., 2025).

5.2 GIS for Spatial Integration and Decision Support

By combining multi-layered spatial datasets, such as soil, aquifer maps, and agricultural zones, Geographic Information Systems (GIS) enhance Remote Sensing (RS) by producing thorough decision-support frameworks. The use of GIS for evaluating water resource management in arid landscapes highlights the significance of groundwater–surface water interactions as a foundation for sustainable irrigation and resource planning (Machiwal et al., 2023). GIS-integrated hydrological models effectively simulate river flow variations and land-use dynamics, providing crucial insights for sustainable water management and climate adaptation planning under changing environmental conditions (Ullah et al., 2024). When combined with Machine Learning (ML) and Artificial Intelligence (AI) models, GIS enhances predictive modeling for groundwater recharge and irrigation scheduling (Rabie et al., 2025). Integration provides real-time visualizations and predictive modeling capabilities. Studies have illustrated how integrated RS–GIS models helped simulate groundwater level dynamics in India’s Mahanadi Basin under varied climate scenarios (Singha et al., 2024).

5.3 Decision-Oriented Frameworks for Climate-Resilient Management

Decision-oriented systems rely on the integration of hydrological, climatic, and agronomic data within GIS platforms to inform adaptive and sustainable groundwater management. These systems often employ multi-criteria decision analysis (MCDA) and Bayesian network models to optimize resource allocation for maximum resilience (Mălinaş et al., 2025). Decision-oriented frameworks emphasize data-driven adaptation planning by integrating biophysical monitoring with socio-economic decision tools. A system dynamics model links climate and urbanization impact on groundwater, supporting sustainable withdrawal and policy decisions (Asadollahi et al., 2024). An integrated framework utilizes green water as a strategic lever for enhancing food security under climate stress by merging hydrological datasets with advanced decision-support tools for sustainable resource management (Chahed, 2025).

5.4 Decision-Oriented System Design and Implementation

Decision support systems (DSS) integrate hydrological model outputs with socio-economic datasets to guide irrigation scheduling, equitable water allocation, and crop diversification. A GIS–remote sensing–GPS integrated approach supports agricultural land-use planning, forming a prototype for spatial decision support in cropping pattern management (Reddy et al., 2018). A decision-oriented system integrates remote sensing, GIS, and predictive analytics into an operational framework for agricultural and groundwater management (Jain et al., 2024). Advocated hybrid models combine traditional water-harvesting techniques with modern geospatial tools for resilient irrigation planning. AI-driven DSS significantly improves the adaptability and resilience of irrigation management under fluctuating climatic and hydrological conditions (Rajaput et al., 2025).

6. Applications in Groundwater-Irrigated Cropping Systems

Integrated applications of Remote Sensing (RS) and Geographic Information Systems (GIS) have transformed groundwater-irrigated farming by improving aquifer mapping, identifying recharge zones, detecting crop water stress, and predicting irrigation needs through artificial intelligence (AI), particularly vital in regions experiencing groundwater depletion and climate-driven agricultural instability (Rabie et al., 2025).

6.1 Groundwater Mapping and Recharge Zone Identification

Integrated Remote Sensing (RS) and Geographic Information System (GIS) techniques facilitate the mapping of aquifer zones and groundwater recharge areas by combining satellite-derived parameters with field hydrogeological data. This integration supports climate-resilient groundwater assessment and sustainable water resource management (Srivastav et al., 2021). Groundwater potential and recharge zone mapping help assess spatial aquifer variability. GIS-based multi-criteria decision analysis (MCDA) integrates lithology, slope, land use, rainfall, and drainage density. Remote sensing parameters such as the Normalized Difference Vegetation Index (NDVI) and drainage texture enhance recharge zone delineation accuracy in semi-arid areas (Gururani et al., 2023). Robust machine learning algorithms, including Random Forests and Support Vector Machines (SVM), substantially improve the accuracy of groundwater potential zone mapping. Their integration with remote sensing and GIS data enhances predictive precision in Bangladesh's agriculture-dominated regions facing severe groundwater stress (Rana et al., 2025). Integrated RS–GIS and machine learning approaches applied in Mediterranean landscapes have effectively identified optimal groundwater recharge sites. The resulting maps offer crucial insights that support sustainable irrigation planning and aquifer restoration efforts amid increasing water scarcity and climatic stress conditions (Moumane et al., 2025).

6.2 Crop Water Stress Detection and Irrigation Optimization

Machine learning integrated with remote sensing enables detection of subtle variations in plant canopy temperature and spectral reflectance, providing real-time assessment of crop water stress, irrigation needs, and overall plant health across diverse agroecosystems under changing climatic conditions (Virnodkar et al., 2020). GIS applications in groundwater potential mapping have been effectively integrated with plant-based and meteorological sensors to monitor water stress, optimize irrigation efficiency, and enhance decision-making for sustainable agricultural water management under varying environmental and climatic conditions (Bwambale et al., 2022). Crop water stress detection and irrigation optimization use remote sensing and GIS to monitor evapotranspiration, soil moisture, and vegetation indices, enabling precise water allocation for sustainable, climate-resilient agriculture (Chouhan et al., 2023).

6.3 Integration with AI for Predictive Irrigation

Combining Remote Sensing (RS) and Geographic Information Systems (GIS) with machine learning significantly improves irrigation performance assessment and supports sustainable water allocation in arid agricultural regions (Rabie et al., 2025). Modern AI algorithms, including genetic and ensemble learning models, effectively predict crop water requirements by analyzing climatic, soil, and vegetation parameters. When integrated with RS-GIS data, these approaches deliver precise, site-specific irrigation recommendations that enhance agricultural productivity and climate resilience (Mălinaș et al., 2025). AI-enhanced GIS modeling frameworks effectively identify vulnerable aquifer zones and predict irrigation demand across diverse land-use and climatic scenarios, establishing an essential decision-support mechanism that strengthens sustainable groundwater governance and adaptive agricultural resource management (Ali and Bilal, 2025).

6.4 Irrigation Water Productivity Assessment

Crop Water Productivity (CWP) was analyzed for key crops by combining yield records with Landsat-derived actual evapotranspiration (ET) within the canal command region. Using a Geographic Information System (GIS), ET data were processed to generate spatial CWP layers, which helped locate zones of low irrigation efficiency and informed strategies for precision water allocation (Talpur et al., 2023). Furthermore, Remote Sensing (RS) observations supported irrigation performance analysis across the Indus Basin by merging Landsat and MODIS-based ET retrievals with GIS-driven spatial classification. These multi-season datasets revealed distinct relationships between irrigation schedules and temporal variability in crop water productivity (Peña-Arancibia et al., 2025). In addition, irrigation efficiency was appraised using RS-based evapotranspiration and crop water stress indicators integrated within a GIS framework, providing a spatially explicit evaluation of water delivery relative to crop demand. The approach identified inefficiencies and informed region-specific strategies for enhancing overall water productivity (Mishra et al., 2022).

6.5 Conjunctive Water Use Planning

Conjunctive water management promotes the coordinated use of surface and groundwater resources through GIS-based spatial decision frameworks, which help delineate water potential zones and balance allocation strategies for sustainable use in drought-prone or resource-stressed basins (Sekar et al., 2024).

Advanced geospatial tools such as the Fuzzy Analytic Hierarchy Process (Fuzzy-AHP) within a GIS environment facilitate the mapping of groundwater potential areas, allowing resource planners to pinpoint locations where groundwater can effectively complement surface supplies under diverse climatic and hydrological conditions (Kumar et al., 2025). Furthermore, the integration of Remote Sensing (RS) with GIS in irrigation mapping enhances the spatial understanding of irrigated extents and water-use variability. This combined approach strengthens conjunctive planning by highlighting zones predominantly reliant on groundwater versus those primarily supported by surface irrigation networks, fostering adaptive and resilient water governance systems (Mishra et al., 2025).

6.6 Adaptive Cropping and Diversification Strategies

Soil moisture variability critically influences crop productivity; therefore, implementing site-specific soil water management through GIS-based monitoring systems is essential to sustain agricultural yields under increasing climatic variability (Vwavware et al., 2024). To address fluctuating water availability, double or multiple cropping practices and the selection of drought-tolerant crop varieties have proven highly effective. These adaptive approaches can be strategically planned and optimized using remote sensing data integrated with GIS-based soil-water interaction mapping (Myint et al., 2021). In addition, multivariate adaptive regression spline models have demonstrated efficiency in mapping groundwater potential zones. Such predictive models enable alignment of high-yield crop areas with groundwater recharge-prone regions, thereby preventing overexploitation of aquifers and promoting sustainable irrigation management (Park et al., 2017). Furthermore, crop diversification and improved irrigation management, facilitated through GIS-supported advisory systems, play a pivotal role in enhancing resilience, optimizing water utilization, and sustaining productivity within Indian agriculture amidst rising climate variability and resource limitations (Rajesh et al., 2024).

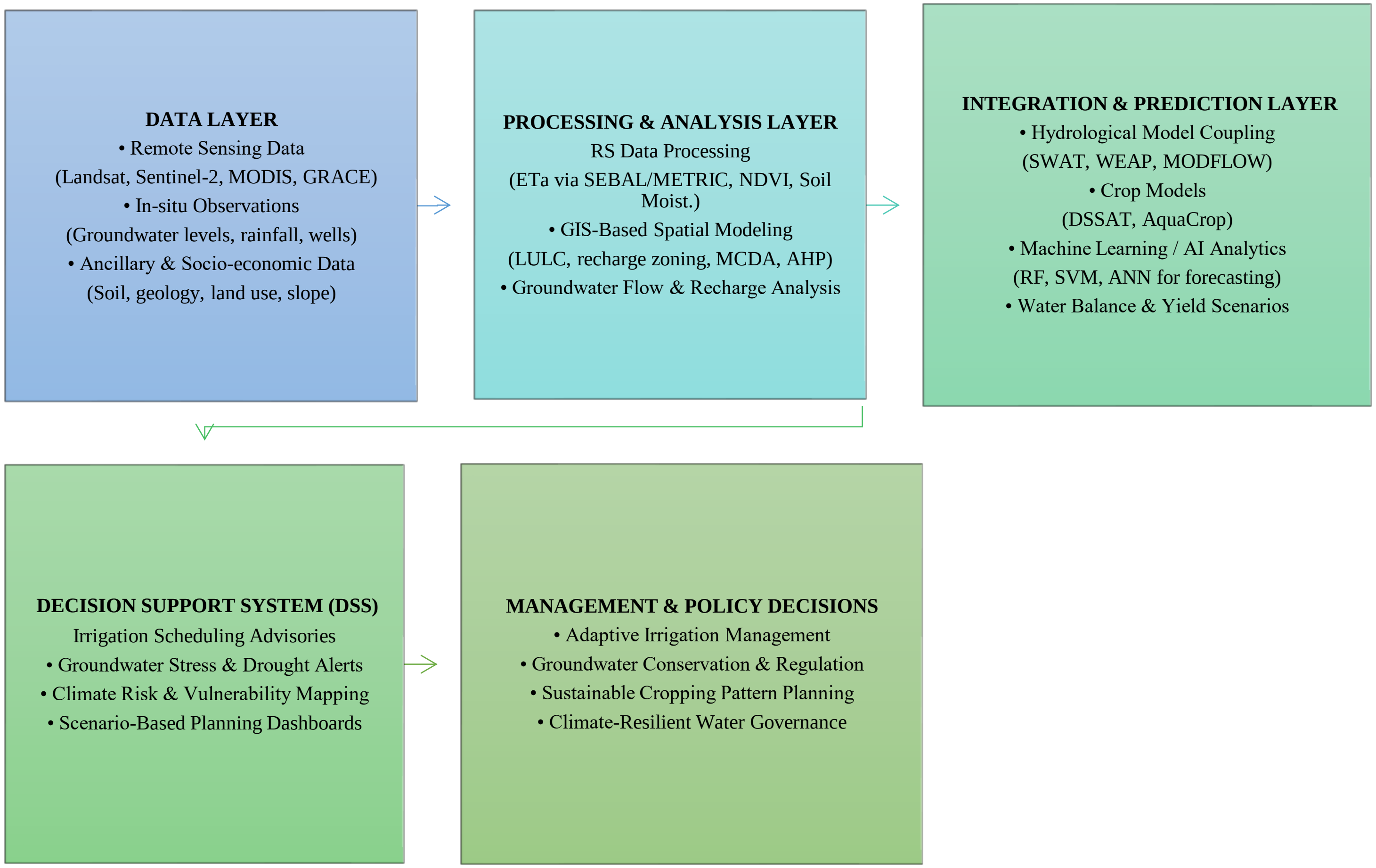

Fig. 1. Conceptual framework for integrated RS–GIS–AI decision-oriented groundwater management

Table 1. Applications of integrated RS–GIS approaches for climate-resilient groundwater and irrigation management

Sl. No.	Region	Tools / Approach	Major Focus	Key Implications	Reference
1	Eastern Nile River Basin, Ethiopia	Combining hydrology, GIS data, and economics, the hybrid partial + general equilibrium hydro-economic model	Large-dam impacts and basin-scale water allocation	Determined that evaluating trade-offs between the advantages of irrigation and the control of downstream flow is made possible by combining hydrological and economic modeling.	(Kahsay et al., 2019).
2	India	RS–GIS–GPS integrated mapping	Groundwater resource assessment and management for irrigated agriculture	Applied multi-parameter GIS overlays (slope, rainfall, lithology, and soil) to guide irrigation zoning and identify groundwater-potential zones.	(Saha et al., 2020).
3	Sub-Saharan Africa	RS–GIS review and meta-analysis of precision-irrigation studies	Precision irrigation and spatial water-use optimization	Improved on-farm water-use efficiency and yield stability by using the use of synthesized RS-GIS techniques (NDVI, ET mapping, and land-suitability analysis).	(Bwambale et al., 2022).
4	China	RS-supported physiological and agronomic modeling	Crop trait selection under limited water supply	RS-based crop-growth calibration is supported by identified wheat features (leaf area, root depth, and stomatal conductance) that increase yield and WUE.	(Lu et al., 2020).
5	Australia	RS–GIS–MAR Cost Model (Managed Aquifer Recharge)	Groundwater recharge economics for agriculture	The most economical solutions for improving irrigation water security were determined to be infiltration-basin systems once MAR infrastructure costs were quantified.	(Vanderzalm et al., 2022).

6.7 Crop Monitoring and Yield Prediction

Integrated Remote Sensing (RS)–Geographic Information System (GIS)–Global Positioning System (GPS) frameworks enable accurate yield forecasting, crop acreage estimation, and efficient irrigation scheduling, collectively forming the foundation for precision agricultural land-use planning (Reddy et al., 2018). Unmanned Aerial Vehicle (UAV)-based remote sensing integrated with machine-learning algorithms enables precise prediction of crop growth stages, optimizes irrigation scheduling, and enhances yield forecasting accuracy for sustainable groundwater-irrigated agriculture (Zheng et al., 2021). Real-time monitoring of crop health and water status through remote sensing feeds back into irrigation scheduling and drought risk assessment, offering decision support to reduce yield losses under climate extremes (Joshika et al., 2025).

7. Climate Resilience and Groundwater-Irrigated Agriculture

Adaptive irrigation planning promotes the use of solar-powered micro-irrigation technology, rainwater collection systems, and groundwater recharge structures in India. These measures contribute to improved groundwater recharge, reduced surface runoff, and increased agricultural systems' overall resilience (Sikka et al., 2018). The conjunctive use of surface and groundwater resources enhances irrigation system flexibility. Such integrated water management reduces irrigation demand or increases irrigation efficiency, thereby strengthening adaptive capacity under variable and changing climatic conditions (Zhao and Boll, 2022). As canal irrigation declined, farmers increasingly relied on groundwater, resulting in severe overextraction and resource stress. This shift underscores the urgent need for integrated adaptation strategies to improve water efficiency and strengthen climate resilience (Sikka et al., 2022). Machine learning integrated with GIS has been applied to map groundwater recharge potential zones across Mediterranean landscapes, enhancing sustainable water management and promoting water use efficiency under arid conditions (Moumane et al., 2025). Climate-smart irrigation focuses on technologies that enhance water productivity such as drip irrigation, sensor-based scheduling, and soil-moisture monitoring. These climate-resilient water management practices enable farmers to make informed, adaptive decisions for sustainable irrigation planning (Chouhan et al., 2023). Policy reform remains vital for balancing groundwater use with climate resilience by exploring alternative water resources for sustainable irrigated agriculture, such as treated wastewater and desalinated water, to reduce overdependence on aquifers (Elmahdi, 2024). Resilience to climate change in water-scarce regions demands institutional innovation through decentralized groundwater governance, active stakeholder participation, and incentive-based water pricing to promote sustainable water use at the farm level (Ahmadi et al., 2025). Climate resilience in groundwater-irrigated systems spans social, economic, and hydrological dimensions, requiring cooperation among farmers, policymakers, and researchers, alongside investments in climate services, early-warning systems, and adaptive credit schemes (Rosa, 2022).

8. Decision-Oriented Climate-Resilient Framework

8.1 Climate Risk Assessment Using RS and GIS

Digital Elevation Models (DEMs) and remote sensing-derived hydrological indices are vital for basin-level groundwater recharge modeling, enabling precise spatial analysis and improved prediction of recharge variability under changing rainfall and climate conditions (Sharma, 2019). GIS-based multi-criteria analysis integrating groundwater levels, rainfall, and land-use data effectively delineates climate-sensitive irrigation zones, enabling sustainable groundwater allocation (Saha et al., 2020). Integrating downscaled CMIP6 climate projections with RS–GIS enables spatially explicit vulnerability mapping, identifying climate-exposure hotspots and groundwater stress zones to prioritize adaptive, climate-resilient water management interventions (Rajaput et al., 2025). Integrating remote sensing (RS) climate indicators such as temperature and precipitation anomalies with socioeconomic datasets enables comprehensive assessment of the combined impacts of climate change and urbanization on groundwater storage in irrigated basins (Asadollahi et al., 2024). Machine learning-driven GIS analysis effectively mapped heatwave, health, and agricultural risk zones in Mediterranean regions, demonstrating RS-based models' strong potential for identifying localized climate threats (Zitouni et al., 2025). The integration of Decision Support Systems (DSS) within multi-stakeholder water governance enhances collaboration, as these systems facilitate not only scientific analysis but also policy dialogue and cooperative resource allocation among water users (Hoogesteger et al., 2025).

8.2 Decision Support Systems (DSS)

Integrated GIS with remote sensing effectively assesses groundwater recharge in agricultural landscapes, demonstrating how RS–GIS modeling links groundwater storage with land-use and rainfall variability (Shit et al., 2024). The Watershed Analysis Risk Management Framework (WARMF) is a Decision Support System (DSS) developed for regional-scale salinity and irrigation water quality management. It integrates satellite-derived evapotranspiration and climate forecasts to optimize irrigation practices and reduce non-point source pollution in groundwater-irrigated regions (Dinar and Quinn, 2022). Decision-oriented systems use AI-enabled models for predictive irrigation scheduling and water balance optimization. Integration of IoT sensors with RS–GIS platforms provide real-time data on soil moisture, groundwater levels, and weather forecasts to inform adaptive irrigation strategies (Haque et al., 2025). The Artificial Intelligence–Geographic Information System–Internet of Things (AI–GIS–IoT) framework delivers real-time, data-driven dashboards for monitoring climate resilience indicators, significantly enhancing watershed-level governance and adaptive water resource management effectiveness (Shaikh and Birajdar, 2024). AI-augmented GIS systems for sustainable urban water governance rank and prioritize interventions using spatial and socio-technical data, showcasing their potential for optimizing irrigation, groundwater recharge, and drought planning (Mkhitaryan et al., 2025). Next-generation DSS utilize AI-driven hydrological forecasting models that integrate satellite data, in-situ observations, and machine learning to deliver early groundwater and water-stress alerts, enabling proactive local action (Robles et al., 2026).

9. Challenges and Future Perspectives

9.1 Challenges

9.1.1 Data Resolution and Accessibility

The absence of high-resolution, temporally consistent datasets hinders groundwater monitoring in developing regions. Limited satellite data continuity, cloud cover, and acquisition gaps restrict accurate irrigation assessments during crucial growing periods (Saha et al., 2020).

9.1.2 Socio-Economic and Technological Gaps

Adoption among smallholder farmers is constrained by financial and technical limitations. Hence, capacity-building initiatives and participatory approaches are vital to democratize and enhance the accessibility of GIS-based decision support (Reddy et al., 2018).

9.1.3 Ground Validation and Calibration Constraints

Model outputs from RS–GIS systems frequently suffer from inadequate ground truthing, as limited field calibration data can cause major discrepancies in groundwater targeting accuracy and aquifer mapping reliability (Seelan, 2024).

9.1.4 Spatial Resolution Limitations for Smallholder-Dominated Landscapes

The mismatch between satellite sensor resolution and the fine-scale heterogeneity of smallholder agricultural plots continues to pose a major technical limitation for precise monitoring and analysis (Haque et al., 2025).

9.1.5 Data Gaps in Groundwater Observation Networks

The complexity of subsurface hydrological processes, coupled with fragmented and inconsistent datasets, creates significant knowledge gaps and uncertainty in groundwater modeling and management systems (Bhunia, 2026). Groundwater monitoring infrastructure remains sparse, inconsistent, and spatially fragmented, which critically hampers the integration of Remote Sensing and GIS datasets into effective real-time decision-support systems (Rabie et al., 2025).

9.1.6 Uncertainty Propagation in Multi-Source Model Integration

Integrating datasets from multiple sensors, models, and hydrological frameworks leads to uncertainty propagation that undermines decision reliability. Variations in spatial scale, temporal resolution, and sensor calibration further amplify compounded model uncertainties (Rajaput et al., 2025). Artificial intelligence (AI) and machine learning-based fusion of Remote Sensing and GIS data necessitates transparent uncertainty quantification frameworks to improve model interpretability, reliability, and stakeholder trust (Abdulameer et al., 2025).

9.1.7 Institutional and Capacity Barriers in Decision-Making Adoption

Institutional fragmentation, poor coordination, and weak regulatory frameworks hinder large-scale adoption of remote sensing in irrigation, causing data underutilization and limiting evidence-based decision-making efficiency (Benli et al., 2025). Governance challenges, coupled with limited technical training and inadequate resource allocation, significantly hinder the mainstreaming and effective utilization of GIS tools within local water management departments (Roy et al., 2025).

9.1.8 Climate Variability and Uncertainty in Predictions

The dynamic and unpredictable nature of climate change increases uncertainty in model predictions. Rising greenhouse gas emissions from groundwater-irrigated agriculture further intensify water resource management challenges (Jagadeesha and Manavalan, 2025).

9.2 Future Perspectives

9.2.1 Artificial Intelligence and Machine Learning Integration

AI-driven models significantly improve groundwater prediction and irrigation efficiency. Simulation-based learning and satellite data pattern recognition enhance accuracy and predictive assessments for sustainable, climate-resilient irrigated agriculture (Chen et al., 2018).

9.2.2 Integration of IoT and Ground Sensors

Deploying IoT-based soil moisture and groundwater sensors bridges the gap between RS-derived estimates and field data, creating a smart feedback loop that enables sustainable, data-driven irrigation decisions (Borgohain et al., 2025).

9.2.3 AI-Driven Fusion Models for Integrating Heterogeneous Datasets

AI-driven fusion models are increasingly being developed to integrate heterogeneous datasets from multiple remote sensing and GIS sources, enhancing predictive accuracy and supporting climate-resilient water management (Abdulameer et al., 2025).

9.2.4 High-Resolution Satellites and UAVs

High-resolution satellite constellations and UAV systems enable precise monitoring of smallholder farms, capturing sub-field variations essential for improved irrigation efficiency and climate-resilient agricultural management (Haque et al., 2025).

9.2.5 Participatory GIS Frameworks

Participatory GIS frameworks engage local communities and policy institutions in data-driven governance, fostering collaborative decision-making and enhancing the sustainability of groundwater and irrigation management systems (Khatana et al., 2025).

9.2.6 Sustainability-Oriented Capacity Building

Future research must emphasize inclusive education and skill development. Strengthening local analytical capabilities is essential for effectively mainstreaming RS–GIS technologies into climate-resilient agricultural planning (Ullah et al., 2024).

9.2.7 Policy and Governance Innovations

Strengthened water governance and transparent data-sharing systems are vital. National frameworks should integrate RS–GIS-derived evidence into adaptive water policies to enhance long-term climate resilience (Reddy et al., 2018).

10. Limitations

This review is subject to certain limitations. First, the analysis relies on available published literature, which may lead to evidence imbalance and uneven regional representation, particularly in data-limited regions. Second, variations in spatial and temporal scales, data resolution, and methodological approaches across studies restrict direct comparability of results. Third, the absence of uniform validation protocols and limited ground-based verification in many RS–GIS applications introduce uncertainty in the synthesis of findings. Furthermore, differences in data sources and modeling frameworks may affect the generalizability of conclusions. Therefore, future research should emphasize the development of standardized evaluation methods, improved data integration practices, and more comprehensive validation approaches to enhance the reliability and applicability of geospatial decision-support systems.

11. Conclusion

The integration of Remote Sensing (RS) and Geographic Information Systems (GIS) provides a robust and scalable framework for improving groundwater management in irrigated agricultural systems under increasing climatic stress. This review demonstrates how geospatial technologies enable precise monitoring of key hydrological variables, support efficient irrigation planning, and enhance understanding of aquifer dynamics across multiple spatial and temporal scales. The incorporation of advanced analytical approaches, including machine learning and multi-criteria decision models, further strengthens predictive capacity and facilitates adaptive, data-driven decision-making. A key insight from this synthesis is the ongoing transition from conventional, data-limited approaches toward integrated, decision-oriented systems that enhance water-use efficiency and climate resilience. However, challenges related to data resolution, model uncertainty, limited ground validation, and institutional constraints continue to hinder large-scale implementation and operational adoption. Addressing these limitations requires improved data integration, standardized validation frameworks, capacity building, and stronger alignment between scientific outputs and policy mechanisms. Overall, embedding RS–GIS technologies within user-oriented decision-support systems represents a critical pathway for achieving sustainable groundwater governance, optimizing irrigation strategies, and ensuring long-term resilience of agricultural production systems under climate change.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of this manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

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