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REVIEW ARTICLE

A review of integrated groundwater and surface water management for environmental sustainability

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Abstract This review critically examines strategies for sustainable groundwater and surface water management, emphasizing their integration to achieve environmental sustainability. The study synthesizes findings from a wide range of research articles, identifying key trends, gaps, and controversies within the field. It highlights the importance of cohesive management approaches that take into account climate change, policy impacts, and methodological advancements. The review aims to provide a structured, analytical discussion that aligns with the thematic focus of integrated water management. By offering original insights and practical recommendations, this review seeks to contribute to the development of more effective and sustainable water management practices. The analysis underscores the necessity of interdisciplinary approaches that integrate hydrological, ecological, and socio-economic factors. Furthermore, the review discusses the role of adaptive management and technological innovations in enhancing the resilience and efficiency of water management systems. The findings suggest that a comprehensive understanding of the interactions between groundwater and surface water is crucial for developing strategies that ensure long-term environmental sustainability. This review concludes with recommendations for future research and policy development, emphasizing the need for adaptive, resilient, and integrated water management strategies that can address the challenges posed by climate change and other environmental pressures.

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1 Introduction

The sustainable management of groundwater and surface water resources is crucial for maintaining environmental sustainability. Water resources are increasingly under pressure due to climate change, population growth, and industrial expansion (Evans et al. 2014). These pressures necessitate the development of integrated water management strategies that consider the complex interactions between groundwater and surface water systems. Integrated management approaches are essential for ensuring the long-term availability and quality of water resources, which are vital for both human and ecological health (Foster et al. 2003.). This review aims to provide a comprehensive analysis of integrated water management strategies, focusing on the interplay between groundwater and surface water systems. By synthesizing existing research, the review seeks to identify effective approaches, highlight methodological advancements, and address gaps in current knowledge. The review emphasizes the importance of cohesive management strategies that incorporate climate resilience, policy impacts, and technological innovations (Gleeson et al. 2012).

One of the key challenges in water management is the need to balance the demands of various stakeholders, including agricultural, industrial, and domestic users, while ensuring the sustainability of water resources. Effective integrated water management requires a multidisciplinary approach that combines hydrological, ecological, and socio-economic perspectives. This review explores various strategies, such as conjunctive use of surface and groundwater, managed aquifer recharge, and watershed management, to provide a holistic understanding of sustainable water management practices. Furthermore, the review critically evaluates the methodologies used in water management studies, comparing their effectiveness and identifying limitations. It highlights the need for robust, interdisciplinary approaches that integrate scientific research with practical policy and management frameworks. By offering original insights and practical recommendations, this review aims to contribute to the development of more effective and sustainable water management practices.

This review aims to provide a comprehensive analysis of integrated groundwater and surface water management strategies, focusing on their effectiveness in achieving environmental sustainability. It seeks to evaluate the impact of climate change on water resources, recognizing the significant alterations in precipitation patterns, frequency of extreme weather events, and overall water availability. Additionally, the review assesses the role of policy and governance in promoting sustainable water management practices, emphasizing the importance of stakeholder participation and equitable water distribution. A critical examination of the methodologies used in water management studies is also conducted, comparing their effectiveness and identifying limitations. By synthesizing these findings, the review aims to offer practical recommendations for future research and policy development, contributing to the advancement of sustainable water management practices that are resilient to environmental pressures and adaptable to changing conditions.

2 Integrated water management strategies

Integrated Water Management (IWM) is a holistic approach that balances human water needs with ecological sustainability by integrating surface water, groundwater, and land-use practices. It aims to maximize economic and social benefits while preserving vital ecosystems. By addressing water scarcity, enhancing climate resilience, and promoting ecosystem health, IWM ensures sustainable water resource management (Dillon et al. 2018). Three key strategies underpin this approach: conjunctive use of surface and groundwater, managed aquifer recharge (MAR), and watershed management. These strategies work together to optimize water availability, improve storage, and maintain the long-term health of water systems in the face of growing environmental challenges.

2.1 Conjunctive use of surface and groundwater

Water scarcity and rising demand are driving the need for innovative strategies to ensure a sustainable water supply (Foster et al. 2010). One such approach is conjunctive use, which refers to the coordinated management of surface water (e.g., rivers, lakes, reservoirs) and groundwater (e.g., aquifers) to optimize overall water availability and reliability (Sophocleous 2002). By balancing the strengths and limitations of each source, conjunctive use enhances resilience and supports more efficient and sustainable water resource management (Dillon et al. 2019). The strategy mitigates the risks associated with the exclusive dependence on either resource by balancing their use based on availability and demand (Szabó et al. 2023) Studies have shown that conjunctive use can enhance water security, particularly in regions with variable precipitation (Shukla 2015). The fundamental concept of conjunctive use is to exploit the strengths of each water source while mitigating their weaknesses (Bredehoeft 2002) (Table 1).

Conjunctive use of surface and groundwater is a strategy that harmonizes the utilization of both water sources to enhance reliability and reduce the risks associated with over-reliance on a single source. This approach offers several key benefits. It improves water security by allowing farmers, such as those in Pakistan's irrigation systems, to supplement canal water with groundwater during shortages, ensuring crop viability (Foster and van Steenbergen 2011). Additionally, it reduces environmental impact by preventing waterlogging and salinization through balanced extraction and recharge (Sekar et al. 2024). Moreover, it enhances climate adaptability, as groundwater serves as a buffer against surface water variability caused by shifting rainfall patterns, a factor highlighted in studies on hydrological resilience (Zhang 2015). Zhang and Sato (2024) demonstrated that conjunctive use in the Cao'e River basin in China stabilized water supply and reduced the impact of surface water fluctuations. Effective conjunctive use of surface and groundwater depends on a range of hydrological, infrastructural,

Table 1 Comparative characteristics of surface water and groundwater (Scanlon et al. 2012)

Feature	Surface water	Groundwater
Availability	Highly variable (seasonal)	Relatively stable (long-term storage)
Storage capacity	Limited (reservoir-dependent)	Large (aquifer pore space)
Evaporation loss	High	Negligible
Quality	Susceptible to pollution	Naturally filtered
Extraction cost	High (canals, pipelines)	Moderate (wells, pumping)
Environmental impact	Alters ecosystems	Localized (subsidence, energy)

socio-economic, and institutional drivers. Based on the literature from recent peer-reviewed sources the Table 2 summarizing drivers of groundwater and surface water use in conjunctive water management.

2.2 Managed aquifer recharge (MAR)/marine protected areas (MPAs)

Managed Aquifer Recharge (MAR) and Marine Protected Areas (MPAs) are increasingly recognized as essential strategies for addressing water scarcity and marine ecosystem degradation, respectively. MAR enhances groundwater storage and quality by intentionally recharging aquifers with treated wastewater or surplus surface water, while MPAs aim to conserve marine biodiversity by limiting human activities in ecologically sensitive zones.

Both approaches offer substantial ecological and resource management benefits. MAR, for instance, has been shown to increase aquifer storage capacity significantly. Australia's National Water Grid Fund identified 17 agricultural regions with MAR potential, with individual sites capable of storing between 50 and 280 gigalitres of water (NWDAG 2025). Similarly, Denmark's Enghaveparken Climate Park illustrates how MAR can support climate adaptation by stabilizing groundwater levels and reducing vulnerability to droughts. MAR also contributes to water quality improvement by diluting contaminants in overexploited aquifers, particularly in mining-intensive regions (Allied Pumps 2024) (Tables 3, 4).

Technically, MAR involves the deliberate recharge of water into aquifers for subsequent recovery or environmental benefit (Batey and Kim 2021). It plays a critical role in mitigating the effects of groundwater over-extraction and

Table 2 Drivers influencing the use of groundwater and surface water resources

Driver	Groundwater use favored when…	Surface water use favored when…
Variable climate	Groundwater offers more reliable supply during periods of rainfall variability (Zhang and Sato 2024)	Surface water may be less dependable in highly variable climates
Surface water quality	Poor surface water quality (e.g., due to irrigation return flows) encourages groundwater use (Akbarifard et al. 2024)	–
Groundwater quality	–	Poor groundwater quality (e.g., salinity) makes surface water the preferred source (Akbarifard et al. 2024)
Infrastructure gaps	Inadequate or poorly maintained surface water infrastructure leads users to rely on groundwater (Zhang and Sato 2024)	–
Depth of groundwater table	Shallow aquifers are more accessible; deep aquifers incur high pumping costs, reducing use (Sepahvand et al. 2019)	Surface water is preferred when groundwater is deep and costly to extract (Sepahvand et al. 2019)
Traditional farming practices	Farmers with long-standing reliance on one source may resist switching to conjunctive use (Akbarifard et al. 2024)	Same resistance applies when surface water is the traditional source (Akbarifard et al. 2024)
New groundwater discovery	Newly discovered aquifers, especially in capped surface water systems, drive groundwater use. (Zhang and Sato 2024)	–
Economic value of production	High-value crops justify investment in groundwater extraction (Sepahvand et al. 2019)	If surface water is subsidized or cheaper, it remains the preferred source (Sepahvand et al. 2019)
Energy pricing	Subsidized or low-cost energy for pumping encourages groundwater use (Akbarifard et al. 2024)	–
Technological advances	Innovations like managed aquifer recharge and efficient pumps increase groundwater feasibility (Sepahvand et al. 2019)	–
Irrigation education	Lack of awareness about conjunctive use benefits can lead to over-reliance on groundwater (Akbarifard et al. 2024)	Similarly, lack of education can cause over-reliance on surface water (Akbarifard et al. 2024)
Institutional structures	Weak policy support for conjunctive use sustains groundwater dominance (Zhang and Sato 2024)	Strong surface water institutions may inhibit transition to conjunctive use (Zhang and Sato 2024)
Shallow water mitigation	Government incentives to lower high water tables can promote groundwater extraction (Sepahvand et al. 2019)	–

Table 3 Comparative table of managed aquifer recharge (MAR) and marine protected areas (MPAs)

Aspect	Managed aquifer recharge (MAR)	Marine protected areas (MPAs)
Main goal	Enhance groundwater storage and quality (Dillon et al. 2019; Sheik et al. 2024)	Conserve marine biodiversity and habitats (Gonçalves 2023; Xuereb et al. 2019)
Techniques/methods	Artificial recharge, infiltration, wells, etc. (Dillon et al. 2019)	No-take zones, regulated fishing, zoning (Wilson 1995; Xuereb et al. 2019)
key benefits	Water security, drought resilience, quality gains (Sheik et al. 2024; Stefan and Nienke 2018)	Biodiversity, fish stock recovery, resilience (Gonçalves 2023; Xuereb et al. 2019)
Major challenges	Clogging, water quality, regulation, cost	Enforcement, stakeholder conflict (Gonçalves 2023; Xuereb et al. 2019)
Recent trends	Climate adaptation, integrated assessment. (Dillon et al. 2019)	Network expansion, adaptive management (Gonçalves 2023)

Table 4 Comparative analysis of MAR and MPA

Aspect	Managed aquifer recharge (MAR) challenges	Marine protected areas (MPA) challenges
Technical	Clogging, sedimentation, design failures (Palma Nava et al.2022; Stefan et al. 2019; Zhang et al. 2020)	Variable protection levels, connectivity measurement challenges (Kriegl et al. 2021; Lagabrielle et al. 2014)
Regulatory	Complex legal frameworks, lack of strategic guidelines in most countries (Palma Nava et al.2022)	Weak enforcement mechanisms, jurisdictional mismatches (Hanri et al. 2022; Kriegl et al. 2021)
Economics	High operational/maintenance costs ($16 M construction cited) (Palma Nava et al. 2022; Zhang et al. 2020)	Short-term economic trade-offs, opportunity costs for communities (Hanri et al. 2022; Kriegl et al. 2021)
Social	Community resistance due to perceived health risks (Sufyan et al. 2024)	Displacement of traditional users, cultural impacts (Hanri et al. 2022; Kriegl et al. 2021)
Environmental	Contamination risks (pathogens, metals), aquifer dissolution (Stefan et al. 2019; Zhang et al. 2020)	Climate change vulnerability (ecosystem transformation by 2050), habitat fragmentation (Kriegl et al. 2021; Lagabrielle et al. 2014)

improving water quality (Achieng'David et al. 2015). Dillon et al. (2019) emphasized the global progress of MAR, highlighting its effectiveness in sustaining groundwater levels. Techniques such as infiltration basins and recharge wells have been successfully implemented across various regions, demonstrating MAR's practical benefits for integrated water management (Sekar et al. 2024).

Marine Protected Areas (MPAs) are established to conserve marine biodiversity by restricting human activities in ecologically sensitive zones. Strongly protected MPAs significantly increase fish biomass and biodiversity (Pinillos and Riera 2022) and often generate spillover benefits that enhance adjacent fisheries (Hilborn et al. 2025). However, the extent of spillover depends on habitat continuity and species mobility (Pinillos and Riera 2022). MPAs are most effective in areas with intense prior fishing pressure, where recovery potential is high and enforcement is strong (Hilborn et al. 2025).

2.3 Watershed management

Watershed management is a holistic and integrated approach that coordinates land and water use to sustain the health of hydrological systems. Its primary objective is to enhance both the quality and quantity of water resources within a watershed, while addressing key challenges such as soil erosion, water pollution, and habitat degradation. By implementing a combination of conservation practices and technological interventions, watershed management contributes significantly to water security, ecological integrity, and the sustainable use of natural resources (Kumar et al. 2025). This approach not only protects vital water sources but also promotes long-term environmental and socio-economic resilience.

One of the key benefits of watershed management is its ability to reduce pollution. Through frameworks like Integrated Water Resources Management (IWRM), it regulates agricultural runoff and industrial discharges, helping to maintain healthy rivers (GPW 2017). These efforts also contribute to the preservation of ecosystems by ensuring that environmental flows are maintained in rivers, which are vital for sustaining fisheries and biodiversity. An example of this is seen in the initiatives by the United Nations Environment Programme (UNEP) in Sudan, where watershed management has supported environmental conservation (Table 5).

In addition to pollution reduction and ecosystem preservation, watershed management strengthens agricultural resilience. Techniques like soil conservation and the

Table 5 Key aspects and benefits of watershed management with supporting references

Aspect/approach	Description	Key Benefits	References
Pollution reduction	Regulation of agricultural runoff and industrial discharges using IWRM	Improved water quality, healthier river systems	(Ashofteh et al. 2024)
Ecosystem preservation	Maintenance of environmental flows and protection of aquatic habitats	Sustained fisheries, biodiversity conservation	(Mekonen et al. 2025)
Agricultural resilience	Soil conservation, afforestation, and green infrastructure (e.g., wetlands)	Enhanced water retention, reduced erosion and soil loss	(Faiz et al. 2025)
Technological integration	Use of remote sensing, GIS, and adaptive management strategies	Improved monitoring, data-driven decision-making	(Chaminé et al. 2021)

creation of green infrastructure—such as wetlands—are effective in reducing erosion and improving water retention in catchment areas. These practices not only safeguard water resources but also enhance the overall health of the landscape, making it more resilient to environmental challenges (Wavin 2024). Watershed management is comprehensive approach that promotes the sustainable use of land and water resources, ensuring the long-term health of both ecosystems and human communities. (Wang et al. 2016) emphasized the importance of adaptive management and the incorporation of technological advancements, such as remote sensing and GIS, in watershed management. Effective watershed management can lead to improved water quality, increased agricultural productivity, and enhanced ecosystem services (Table 6).

The key water management strategies and their associated benefits include the conjunctive use of surface and groundwater, which enhances water security by stabilizing supply and mitigating the risks associated with over-reliance on a single source, while also addressing issues such as land degradation. Managed Aquifer Recharge (MAR) improves groundwater storage and quality, helping to mitigate over-extraction and reduce the impacts of drought by replenishing aquifers during surplus periods. Watershed management emphasizes integrated land and water practices to enhance water quality, increase agricultural productivity, and support ecosystem services. Collectively, these strategies contribute to more resilient, efficient, and sustainable water resource management.

3 Climate change impact on water resources

Climate change is increasingly undermining the effectiveness of traditional water management approaches. As climatic conditions grow more variable and extreme, the adoption of adaptive water management becomes critical to ensure the long-term reliability and sustainability of water systems (Mehta 2024). Climate change influences hydrological cycles by altering precipitation patterns, increasing the frequency and intensity of extreme weather events, and reducing overall water availability (Dixit et al. 2022). These shifts present significant challenges to water resource management and highlight the urgent need for climate-resilient strategies (Bartlett and Dedekorkut-Howes 2023).

Among the key hydrological impacts are shifting precipitation regimes, declining snowpack levels, and heightened evaporation rates, all of which jeopardize both water quantity and quality. In mountainous regions, rising temperatures are increasingly causing precipitation to fall as rain rather than snow. This trend reduces snowpack accumulation, a vital freshwater reservoir that supports water supply for millions of people downstream (Dillon et al. 2019, US EPA 2022).

Addressing these challenges requires an integrated and forward-looking approach that incorporates flexibility, continuous learning, and the capacity to respond dynamically to changing climatic and hydrological conditions. For example, the Colorado River Basin—a vital water source for 33 million people has seen reservoir levels decline due to reduced

Table 6 Water management strategies

Strategy	Key benefits	References
Conjunctive use	Enhanced water security, reduced supply variability Stabilizes supply, reduces land degradation	(Dillon et al. 2019; Foster et al. 2010; Fosterand van Steenbergen 2011; Shukla 2015; Sekar et al. 2024; Zhang and Sato 2024; Zhang 2015)
Managed aquifer recharge (MAR)	Improved groundwater storage, enhanced water quality, mitigation of over-extraction, mitigates drought impacts	(Sekar et al. 2024; Zhang and Sato 2024)
Watershed management	Improved water quality, increased agricultural productivity, enhanced ecosystem services	(GPW 2017; Wavin 2024; Wang et al. 2016)

snowmelt runoff and prolonged droughts (US EPA 2010). Concurrently, over-extraction of groundwater in water-stressed regions exacerbates aquifer depletion, particularly where climate change intensifies drought frequency (Fecht 2019, US EPA 2022).

3.1 Developing climate-resilient infrastructure

Climate-resilient infrastructure is essential for mitigating the adverse effects of climate change on water resources. This includes the construction of robust water storage systems, flood defenses, and drought-resistant water supply networks (Asif et al 2023). To address these challenges, climate-resilient water infrastructure is essential. Strategies include:

- **Enhanced storage systems**: Constructing reservoirs, rainwater harvesting structures, and managed aquifer recharge projects to buffer against water scarcity (State of Green 2017), WaterAid. (n.d.).
- **Green infrastructure**: Implementing wetlands, permeable pavements, and green roofs to improve water infiltration and reduce urban flooding (State of Green 2017)
- **Infrastructure upgrades**: Modernizing aging pipelines to reduce leaks and deploying flood barriers to protect against extreme weather (Fritts 2023) (gwd)

The Jamaica Water Resilience Model demonstrates how adaptive measures like leak repairs and cyclone-resistant infrastructure can halve climate-related water disruptions by 2100 under moderate emissions scenarios (Fritts 2023). Similarly, Denmark's Enghaveparken Climate Park combines flood management with public recreation spaces, showcasing multifunctional resilience solutions (State of Green 2017). The implementation of green infrastructure, such as wetlands and green roofs, can enhance water infiltration and reduce runoff, thereby mitigating flood risks (Batey and Kim 2021). Sinha et al. (2023) emphasizes the importance of integrating social, ecological, and technical systems to enhance the resilience of water infrastructure.

3.2 Incorporating predictive modeling for water resource planning

Predictive modeling is a critical tool for water resource planning in the context of climate change. Advanced models, including machine learning algorithms and climate models, can predict changes in water availability and quality, enabling precise forecasts of water availability shifts. It helps utilities optimize allocations during droughts and floods while informing adaptive management strategies. For instance, seasonal weather forecasting integrated with utility operations in the Caribbean has improved drought contingency planning and disaster response coordination (gwd). These models also inform infrastructure design such as sizing reservoirs to accommodate projected rainfall variability and prioritize investments in high-risk areas (Fecht 2019, gwd). Applications include (Mehta 2024).

- **Seasonal forecasting:** Integrated into utility operations in the Caribbean to improve drought contingency planning.
- **Infrastructure design:** Informing reservoir sizing and investment prioritization in high-risk areas.
- **Machine learning:** Enhances hydrological prediction accuracy and optimizes water allocation.

Liu et al. (2024) highlights the effectiveness of machine learning in improving the accuracy of hydrological predictions and optimizing water resource allocation. Additionally, Granata and Di Nunno (2025) discuss the role of nature-based solutions and hydrological modeling in enhancing hydrological resilience. Proactive integration of these approaches can reduce water stress for vulnerable populations while safeguarding ecosystems. As emphasized by UN-Water, addressing the water-climate nexus requires interdisciplinary collaboration, equitable governance, and sustained investment in innovation (UN-Water 2023). Granata and Di Nunno (2025). Without such measures, up to 40% of U.S. freshwater basins may fail to meet demand by 2071 due to climate pressures and population growth (Fecht 2019).

3.3 Climate adaptation and governance in integrated water management

As climate change accelerates, the resilience of water systems—both surface and groundwater is increasingly threatened by rising temperatures, altered precipitation patterns, and more frequent extreme weather events (Tsakiris and Loucks 2023). These changes demand a shift from traditional water management approaches toward more integrated, adaptive, and inclusive governance frameworks.

Integrated Water Management (IWM) offers a comprehensive approach to managing water resources across sectors and scales. However, its effectiveness is contingent upon governance systems that are capable of responding to uncertainty, incorporating stakeholder input, and fostering innovation. Adaptive governance, in particular, has emerged as a critical strategy, enabling institutions to adjust policies and practices in response to evolving climate data and socio-environmental feedback (Tsakiris and Loucks 2023).

Recent literature emphasizes the importance of mainstreaming climate adaptation into water governance. This includes aligning water policies with climate resilience goals, enhancing institutional coordination, and investing in nature-based and technological solutions (Lindner and Stamm 2025). Moreover, inclusive governance assuring the participation of marginalized communities and decentralized decision-making are increasingly recognized as essential for building local adaptive capacity (Bartlett and Dedekorkut-Howes 2023).

The following table synthesizes key findings from recent academic studies, highlighting how governance structures and climate adaptation strategies intersect to shape the future of sustainable groundwater and surface water management (Table 7).

Adaptive water management, as discussed by Tsakiris and Loucks (2023), emphasizes flexibility and learning-based approaches that respond to evolving climate conditions. The adaptability crucial for IWM, which requires coordination across sectors and scales. When governance structures are inclusive and responsive, they enable the integration of surface and groundwater systems, as seen in conjunctive management strategies (Table 8).

However, several papers, including those by Zhang (2015), and Ciampittiello et al. (2024), point out that fragmented governance and institutional silos often hinder IWM. Inadequate coordination between agencies, lack of data sharing, and rigid policy frameworks limit the ability to implement adaptive strategies. Moreover, in regions like North America, as noted by Asif et al. (2023), policy reform and regional planning are essential to align climate adaptation goals with water management practices.

Effective governance also supports the implementation of nature-based solutions and technological innovations, which are key recommendations across multiple studies. Conversely, where governance fails to incorporate climate risks or lacks stakeholder engagement, adaptation efforts remain piecemeal and reactive, undermining the holistic vision of IWM. The adaptive governance acts as both an enabler and a gatekeeper for integrated water management. Its success depends on institutional capacity, cross-sector collaboration, and the political will to embed climate resilience into water policy and practice.

4 Policy and governance in sustainable water management

The sustainable management of water resources is heavily reliant on effective policy and governance frameworks. These frameworks play a pivotal role in ensuring the efficient allocation of water, safeguarding water quality, and protecting aquatic ecosystems (Salman and Bradlow 2008). This section examines three critical dimensions of governance essential for achieving sustainable water management: regulatory frameworks, stakeholder participation, and market-based mechanisms.

Table 7 Key Studies on climate adaptation and governance in IWM

Author(s)	Key finding	Impact on climate	Recommendation
Davamani et al. (2024)	Climate change affects groundwater recharge, discharge, and quality; coastal aquifers are vulnerable	Reduced recharge in arid/semi-arid regions; increased evapotranspiration	Sustainable groundwater management and climate-resilient infrastructure
Zhang (2015)	Coordinated use of surface water and groundwater enhances water security	More frequent droughts and floods; reduced surface water availability	Integrated planning and adaptive management strategies
Ciampittiello et al. (2024)	Climate change reduces freshwater availability and increases water demand	Ecosystem degradation and heightened socio-economic vulnerabilities	Integrated Water Resources Management (IWRM) and nature-based solutions
Tsakiris and Loucks (2023)	Adaptive management adjusts policies based on new information and changing conditions	More frequent floods, droughts, and unpredictable water flows	Adopt adaptive frameworks and encourage global cooperation
Asif et al. (2023)	Altered precipitation patterns and increased extreme events affect water resources	Southwestern U.S., Canadian prairies, and parts of Mexico face water supply deficiencies	Regional planning, policy reform, and investment in adaptive capacity
Minea et al. (2025)	Groundwater is vital for communities; new areas of concern include the Arctic and Antarctic	Temperature rise and changing precipitation patterns affect groundwater recharge	Sustainable and adaptive management to mitigate future risks

Table 8 Climate change impact

Adaptation strategy	Key benefits	References
Climate-resilient infrastructure	Enhanced water storage, flood mitigation, drought resistance	(Asif et al. 2023; Batey and Kim 2021; Sinha et al. 2023)
Predictive modeling	Improved accuracy of hydrological predictions, optimized water resource allocation, reduces risks	(Liu et al 2024; Preetha et al. 2025)
Climate adaptation and governance in IWM	Promotes inclusive, adaptive, and coordinated water governance; enhances institutional capacity and resilience; supports integration of surface and groundwater systems	(Asif et al. 2023; Bartlett and Dedekorkut-Howes 2023; Davamani et al. 2024; Lindner and Stamm 2025; Minea et al. 2025; Tsakiris and Loucks 2023; Sekar et al. 2024)

4.1 Regulatory frameworks for water allocation and quality control

Regulatory frameworks set the rules and standards for water use, pollution control, and conservation efforts. These regulations are vital for guiding the responsible use of water and ensuring that resources are managed sustainably (UN-Water 2015). These frameworks vary across jurisdictions but generally include laws and regulations that govern water rights, usage, and quality standards (CPR 2019). For example, the European Union's Water Framework Directive sets comprehensive standards for water quality and management across member states (Kaika 2003). Similarly, the Clean Water Act in the United States provides a regulatory framework for maintaining water quality (Cooter 2004). Effective regulatory frameworks are crucial for preventing over-extraction, pollution, and ensuring equitable water distribution (Salman and Bradlow 2008). After reviewing the research publication, it observed that: -

- **European Union's Water Framework Directive**: Sets comprehensive standards for water quality and management across member states
- **United States Clean Water Act**: Provides a robust regulatory framework to maintain water quality and prevent pollution

Such frameworks prevent over-extraction, ensure equitable distribution, and protect water bodies from contamination. They also promote transparency and accountability in water governance, which is critical for public trust.

4.2 Stakeholder participation in decision-making processes

Stakeholder participation is equally important, as it allows communities, industries, and other relevant groups to have a voice in decision-making processes, ensuring that policies reflect diverse needs and priorities. It is critical for inclusive and effective water management (Patel 2023). Engaging stakeholders, including local communities, industries, and government agencies, in decision-making processes ensures that diverse perspectives and needs are considered (Megdal et al. 2017). This participatory approach can lead to more equitable and sustainable water management outcomes (Langsdale et al. 2022). The benefits of stakeholder engagement in water governance are significant. As it improves legitimacy by enhancing the acceptance of policies and decisions, as stakeholders are more likely to support initiatives when they have been involved in the decision-making process (Australian Government Initiative, Moreira et al. 2024). Additionally, it leads to more equitable outcomes. By ensuring that marginalized voices are heard, participation fosters fairness in the distribution of resources, helping to address disparities and promote social justice within water management practices (Moreira et al 2024; Adom and Simatele 2022). For instance, the Integrated Water Resources Management (IWRM) framework emphasizes stakeholder engagement as a key component of sustainable water governance. Studies have shown that stakeholder participation can improve the legitimacy and acceptance of water management decisions. Adom and Simatele (2022) highlights the importance of stakeholder engagement for sustainable water management in South Africa. While public engagement is vital for post-independence transformation, many communities remain uninformed and unequipped, leading to ineffective participation and failed engagement programs.

4.3 Market-based mechanisms

Market-based mechanisms, such as water pricing and trading, introduce economic incentives that encourage the efficient use and allocation of water resources. By treating water as an economic good, these tools can promote conservation and improve overall resource management. Water pricing aims to reflect the true costs associated with water supply, treatment, and infrastructure maintenance. By doing so, it discourages wasteful use and supports financial sustainability. Water trading, on the other hand, enables the voluntary transfer of water rights among users, allowing water to flow toward higher-value or more efficient uses. A notable example is Australia's water trading system, which has successfully facilitated the reallocation of water to more productive sectors, thereby enhancing water use efficiency (Zaman et al. 2009).

Moreover, analogous systems such as emissions trading schemes offer insights into how market-based tools can drive environmentally and economically effective resource management by incentivizing pollution reduction at the lowest possible cost.

4.4 Policy tools and governance frameworks for integrated water management

Integrated water management is widely recognized as essential, but institutional barriers especially the fragmentation of legal and governance frameworks complicate its implementation. These challenges are particularly acute in low- and middle-income regions, where informal economies, limited capacity, and chronic underfunding exacerbate the difficulties. Successful integration requires harmonized legal frameworks, strengthened institutional coordination, robust data systems, and inclusive stakeholder engagement tailored to local contexts (Table 9).

4.5 Institutional barriers to integrated water management

Institutional barriers to integrated water management arise from fragmented legal and organizational frameworks that separate surface water, groundwater, and wastewater systems. Poor coordination among government levels and unclear mandates create inefficiencies. Many local authorities also lack the technical and financial resources needed for integrated approaches. Limited data sharing and weak monitoring systems hinder informed decision-making. Additionally, political resistance, lack of stakeholder engagement, and informal water use practices obstruct effective reform and integration.

a. Siloed institutions and legal frameworks

- Separate agencies and laws for surface water, groundwater, and wastewater create fragmented management and hinder integration (Winter 2000; Mukheibir et al. 2015)
- Regulations often do not recognize the hydrological connections between water sources, leading to inefficiencies and missed opportunities for reuse or recharge (Winter 2000).

b. Coordination and capacity challenges

- Overlapping mandates and unclear roles among national, regional, and local authorities cause confusion and inefficiency (Özerol et al.2018).

Table 9 Tools and governance frameworks comparison

Framework/tool	Key features	Strengths	Limitations/barriers	Example/Context
IWRM (integrated water resources management)	Holistic, cross-sectoral, stakeholder participation, basin-level management	Promotes integration and negotiation among stakeholders; adaptable to change	Difficult to implement fully; requires strong institutions and stakeholder buy-in; integration is context-dependent (CWP 2009; Rahaman et al. 2004)	Danube River Basin, India (Nagata et al. 2022; Rahaman et al. 2004)
EU water framework directive (WFD)	Legal framework for water quality and ecological status, transboundary cooperation	Strong regulatory basis; fosters cross-border collaboration	Complexity in aligning national laws; resource-intensive; may not fit all local contexts (Rahaman et al. 2004)	European Union, Danube Basin (Rahaman et al. 2004)
Traditional command-and-control regulation	Top-down standards and enforcement	Clear rules and accountability	Often siloed; inflexible; may ignore local needs and hydrological realities (CWP 2009; Mukheibir et al. 2015)	US Clean Water Act
Decentralized/Community-based management	Local participation, customary law, informal systems	Culturally relevant, increases local ownership	Limited scalability; weak enforcement; often marginalized in formal policy (Nagata et al. 2022)	Water user associations in Africa (Nagata et al. 2022)

- Insufficient technical and financial capacity, especially at the local level, limits the ability to implement integrated approaches (Mukheibir et al. 2015; Özerol et al.2018)

c. Data and information gaps

- Lack of harmonized data systems and limited monitoring impede evidence-based decision-making and adaptive management (Mukheibir et al. 2015; Nagata et al. 2022)

d. Financial constraints

- Chronic under-financing of water infrastructure and management, especially in low- and middle-income regions, restricts the adoption of integrated solutions (Nagata et al. 2022).
- Poorly functioning water markets and lack of economic incentives discourage efficient water use and investment (UNDP 2004; Nagata et al. 2022).

e. Political and social barriers

- Weak political will, resistance from vested interests, and limited stakeholder engagement—particularly for marginalized groups—undermine reforms (UNDP 2004; Nagata et al. 2022).
- Informal water economies in developing countries often operate outside formal institutional frameworks, making regulation and integration difficult (Nagata et al. 2022).

4.6 Governance challenges in low- and middle-income regions

Low- and middle-income regions often face significant governance challenges in managing water resources effectively. Weak institutional capacity and fragmented governance structures lead to poor coordination between agencies and sectors. Limited financial resources and underinvestment in infrastructure hinder the implementation of integrated water management practices. Additionally, a lack of transparency, accountability, and stakeholder engagement especially among marginalized communities reduces the effectiveness and equity of water governance. Informal water use, political interference, and corruption further complicate efforts to establish sustainable and inclusive water management systems (Table 10).

- **Informal water use:** Large portions of water use are outside formal regulation, making enforcement and integration challenging (Nagata et al. 2022).
- **Limited institutional capacity:** Many countries lack the financial, technical, and human resources needed for effective governance (UNDP 2004). (Nagata et al. 2022).
- **Equity and access:** Water governance often favors the powerful, leaving poor and marginalized communities with inadequate access (UNDP 2004).
- **Donor dependence and fragmentation:** Multiple externally funded projects can create parallel systems, undermining national strategies (UNDP 2004).
- **Implementation gaps:** While drafting new policies and laws is relatively easy, enforcing them and achieving real integration is much harder in practice (Nagata et al. 2022) (Table 11).

5 Methodological analysis

Sustainable water resource management relies heavily on the application of robust analytical methodologies that support informed planning and decision-making. Among the most widely adopted approaches are hydrological modeling, remote sensing and GIS, and socio-economic analysis. These tools collectively enable a comprehensive understanding of water systems, from physical processes to human impacts (Loucks and Van Beek 2017; Shaw 2005). This section focuses on hydrological modeling, a critical technique for simulating the movement, distribution, and quality of water within natural and engineered systems. Hydrological models are essential for evaluating water availability, forecasting floods and droughts, and designing adaptive management strategies under changing climatic conditions. They also support integrated planning by linking surface and groundwater dynamics, enabling more accurate assessments of water resource sustainability (Beven 2012).

Complementing hydrological models, remote sensing and GIS technologies have revolutionized water monitoring

Table 10 Institutional barriers and regional challenges

Barrier/challenge	High-income regions	Low-/middle-income regions
Siloed institutions	Common, but often with more resources to address	Widespread, compounded by weak institutions
Data and monitoring	Advanced but sometimes fragmented	Limited, often outdated or unavailable
Financial resources	Generally sufficient, but aging infrastructure	Chronic underfunding, donor dependence
Stakeholder engagement	Stronger frameworks, but gaps remain	Often limited, especially for the poor
Policy implementation	Better enforcement, but still complex	Major gap between policy and practice

Table 11 Policy and governance

Aspect	Key benefits	References
Regulatory frameworks	Ensures sustainable allocation, prevents over-extraction, maintains water quality	(Cooter 2004; Kaika 2003; Water Governance OECD; Salman and Bradlow 2008, CPR 2019; UN-Water 2015)
Stakeholder participation	Inclusive decision-making, improved legitimacy, equitable outcomes	(Adom and Simatele 2022; Austialian Government Initiative, Langsdale et al. 2022; Megdal et al. 2017; Moreira et al. 2024; Patel 2023)
Market-based mechanisms	Encourages conservation, efficient use, reallocation to higher-value uses	Zaman et al. (2009)

by providing spatially explicit data for watershed analysis, flood mapping, and groundwater assessment and groundwater dynamics, enabling more accurate assessments of water resource sustainability. These tools enhance the accuracy of hydrological simulations and facilitate real-time decision-making across various spatial and temporal scales and groundwater dynamics, enabling more accurate assessments of water resource sustainability (Schultz 2012). Furthermore, socio-economic analysis plays a vital role in evaluating the impacts of water management decisions on communities, particularly in terms of equity, access, and resilience. Integrating these methodologies ensures that water resource strategies are not only technically sound but also socially inclusive and environmentally sustainable and groundwater dynamics, enabling more accurate assessments of water resource sustainability (Pltonykova et. al 2020).

5.1 Hydrological modeling for resource assessment

Hydrological modeling is a cornerstone of modern water resource management, enabling the simulation of water flow, quality, and distribution across diverse hydrological systems. These models are essential for assessing water availability, predicting hydrological responses to climate and land use changes, and supporting strategic planning (Baran-Gurgul and Rutkowska 2024). Prominent models include:

SWAT (Soil and water assessment tool): Ideal for long-term, watershed-scale simulations, SWAT evaluates the impacts of land use and climate change on water quantity and quality. For example, its application in the Yellow River Basin effectively predicted streamflow and sediment yield under various land use scenarios (Sabale et al. 2023; Sahuet al.2023).

HEC-HMS (Hydrologic modeling system): Best suited for event-based hydrological analysis, such as flood forecasting, HEC-HMS offers flexibility in modeling rainfall-runoff processes but has limited groundwater and water quality capabilities (Liu et al. 2024).

MODFLOW (Modular groundwater flow model): A robust tool for simulating groundwater flow systems, MODFLOW excels in subsurface hydrology but requires coupling with surface models for integrated analysis (Bailey et al. 2025).

Each model has specific strengths and limitations. SWAT simplifies subsurface processes and demands extensive input data. HEC-HMS is less effective for long-term simulations, while MODFLOW lacks surface water dynamics unless integrated with other models (Bailey et al. 2025). To overcome these limitations, integrated modeling frameworks are increasingly adopted (Table 12).

SWAT + MODFLOW: Combines surface hydrology (SWAT+) with groundwater flow (MODFLOW), enabling daily, spatially distributed simulations of interactions like recharge, irrigation, and canal seepage (Hussain et al. 2025).

GSFLOW: Integrates PRMS (Precipitation-Runoff Modeling System) with MODFLOW to simulate the full hydrologic cycle, including snowmelt and groundwater–stream interactions, making it ideal for regions with seasonal variability (Guan et al. 2019).

Machine learning/Optimization tools: Machine learning tools like CSO and SMOTE improve model calibration, bias correction, and forecasting by automating tuning and handling imbalanced data, though they need expertise and may lack physical interpretability.

These integrated models provide a more realistic representation of hydrological processes and support scenario-based assessments for sustainable water planning under climate uncertainty.

5.2 Remote sensing and GIS for monitoring water resources

Remote sensing (RS) and Geographic Information Systems (GIS) have brought about a paradigm shift in water resource monitoring by enabling the acquisition and analysis of spatially explicit data through advanced analytical tools (Wang and Xie 2018). These technologies facilitate the continuous observation of water bodies, allow for the assessment of water quality, and support the detection of changes in water availability over time (Gholizadeh et al. 2016). A notable example of their application is seen in the Ganges–Brahmaputra basin, where the integration of satellite imagery and

Table 12 Hydrological models

Calibration and validation/uncertainty analysis practices	Multi-objective calibration; sensitivity analysis; uncertainty via GLUE, Monte Carlo; statistical validation (NSE, R^2, RMSE)	Manual/automatic calibration; event-based validation; limited uncertainty analysis	Parameter estimation tools; sensitivity analysis; uncertainty via PEST, UCODE	Advanced multi-objective calibration; scenario-based uncertainty analysis; machine learning optimization (e.g., CSO)	Integrated sensitivity/uncertainty analysis; ensemble modeling; statistical validation	Scenario testing; uncertainty via scenario analysis; basic calibration tools	Cross-validation; statistical metrics (RMSE, MAE); uncertainty quantification
Data requirements	High (climate, land use, soil, management)	Moderate (precipitation, land cover, topography)	High (hydrogeology, aquifer properties, pumping)	Very high (all)	Very high (climate, snow, hydrogeology)	Moderate (hydrology, demand, infrastructure)	Data-driven
Limitations	Simplifies subsurface hydrology; requires extensive input data	Limited groundwater and water quality simulation; less effective long-term	Lacks surface water dynamics unless coupled; complex setup	Increased complexity; challenging calibration and data integration	Complex setup; high computational cost	Less physically based; limited groundwater detail	Require expertise; may lack physical interpretability
Strengths/key characteristics	Strong in long-term, spatially distributed simulations; effective for land use and climate assessment	Flexible rainfall-runoff modeling; widely used for floods	Industry standard for groundwater; detailed subsurface simulation	Integrates surface and subsurface hydrology; supports daily, spatially distributed simulations	Combines PRMS and MODFLOW; simulates snowmelt, groundwater-stream interaction, seasonal variability	Decision-support focus; user-friendly interface; supports policy analysis	Improve calibration efficiency; handle imbalanced data; automate parameter tuning
Key applications	Long-term, watershed-scale surface water; land use & climate impact studies	Event-based hydrology; flood forecasting	Groundwater flow and management	Integrated surface/groundwater, recharge, irrigation, canal seepage	Full hydrologic cycle, snowmelt, stream-aquifer interaction	Integrated water resources planning; scenario analysis	Model calibration, bias correction, forecasting
Hydrological models	SWAT	HEC-HMS	MODFLOW	SWAT + MODFLOW	GSFLOW	WEAP	Machine learning/optimization tools (e.g., CSO, SMOTE)

GIS has significantly enhanced flood forecasting and management efforts (Rahmani 2021). Furthermore, advanced RS techniques such as LiDAR and multispectral imaging provide high-resolution datasets that are essential for accurate mapping and analysis of hydrological features (Liu et al. 2024) (Table 13).

Despite the substantial benefits of Remote Sensing (RS) and Geographic Information Systems (GIS), several limitations hinder their full potential in hydrological applications. The effectiveness of these technologies is often constrained by the spatial and temporal resolution of the data, the necessity for ground-truthing to validate remotely sensed observations, and the high costs associated with acquiring and maintaining advanced sensors (Badamasi 2022).

Optical remote sensing, in particular, is susceptible to cloud cover, which can obscure surface features and limit data availability. Moreover, high-resolution imagery is not always accessible for all regions or at frequent intervals, further complicating consistent monitoring (Thakur et al. 2017). GIS, while offering powerful tools for spatial data integration, analysis, and visualization, is similarly dependent on the availability, accuracy, and timeliness of input datasets. These often require supplemental field-based observations to ensure reliability and relevance (Badamasi 2022).

To address these limitations, the integration of RS and GIS with traditional hydrological models has emerged as a particularly effective strategy. This integrated approach helps fill critical spatial and temporal data gaps, thereby enhancing the performance and accuracy of hydrological models, especially in data-scarce or logistically challenging regions (Thakur et al. 2017). For instance, models such as the Soil and Water Assessment Tool (SWAT) and the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) benefit significantly from RS-derived inputs. These include land cover data from Sentinel-2, precipitation estimates from the Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM), and evapotranspiration rates derived from MODIS products like MOD16 (Kherde et al. 2013),

To support this integration, platforms such as OpenET demonstrate how satellite observations can be coupled with energy balance models like METRIC (Mapping EvapoTranspiration at High Resolution with Internalized Calibration) and SEBAL (Surface Energy Balance Algorithm for Land) to generate spatially distributed evapotranspiration estimates. These estimates play a critical role in water accounting and irrigation planning, particularly across water-stressed regions such as the western United States (Bastiaanssen et al. 1998). In parallel, cloud-based platforms like Google Earth Engine (GEE) have transformed the processing and analysis of large-scale RS data. GEE enables a range of water-related applications, including flood mapping, drought monitoring, and water quality assessment, by offering real-time access to vast archives of satellite imagery and geospatial datasets (Gorelick et al. 2017). A practical and impactful application of this integrated framework is again evident in the Ganges–Brahmaputra basin, where the use of RS and GIS technologies has significantly improved flood forecasting and disaster response. By enabling near real-time monitoring of river discharge and inundation extents, these tools support more timely and informed decision-making in disaster management. The synergistic use of RS, GIS, and hydrological modeling offers a comprehensive and dynamic framework

Table 13 Strengths and limitations of remote sensing and GIS

Approach	Strength	Limitation
Remote sensing (e.g.MODIS, Sentinel, LiDAR)	Wide spatial coverage; Frequent revisit times; Multi-spectral data for water quantity, vegetation, and land use	Affected by cloud cover (optical sensors); Limited spatial resolution for small scale features; Requires calibration with ground data
GIS	Integrates spatial data from multiple sources; Enables spatial analysis and visualization; Supports decision-making tools	Static unless updated with real-time data; Dependent on data quality and resolution
IoT sensors	Provides real-time, high-frequency data (e.g., water quality, flow rates); Enables automated alerts for anomalies (e.g., leaks)	High infrastructure costs and maintenance; Limited spatial coverage without dense networks
Machine learning (ML)	Identifies complex patterns in large datasets (e.g., drought prediction); Enhances predictive accuracy (e.g., reservoir forecasts)	Requires extensive training data; BLACK BOX models lack transparency
Drones	High-resolution, site-specific monitoring (e.g., soil moisture, crop health)	Limited coverage area compared to satellites; Operational costs and regulatory hurdles
Integrated modeling	Combines hydrological, climatic, and socioeconomic variables; Supports probabilistic risk assessments (e.g., water scarcity)	Computationally intensive; Calibration challenges due to data uncertainty

for water resource management. This integrated approach is particularly critical in the context of climate variability and increasing water stress, as it enhances the capacity for real-time monitoring, forecasting, and planning in both data-rich and data-scarce environments (Deshvena et al. 2024).

In the context of Managed Aquifer Recharge (MAR), Table 14 presents a structured overview of the key methodologies and tools employed in spatial analysis and modeling for effective water resource management. It highlights techniques for visualization, equity assessment, decision-making integration, uncertainty analysis, and model validation. The framework supports data-driven, equitable, and technically robust planning (Table 15, 16).

5.3 Socio-economic analysis for understanding community impacts

Socio-economic analysis is essential for understanding the complex impacts of water management strategies on communities. By evaluating the economic, social, and cultural consequences of water policies, this approach highlights the broader implications of governance decisions. Tools such as

Table 14 Spatial analysis and modeling in water resource management and managed MAR

Theme	Key concepts	Methods and tools	Purpose/application
Spatial visualization	Communicating spatial patterns in water systems	GIS-based maps; Flow diagrams; Time-series maps; 3D hydrogeological models	Visualize MAR zones, aquifer dynamics, and water balance
Spatial variability and equity	Assessing spatial disparities in water access and recharge	Moran's I (spatial autocorrelation); Geographically Weighted Regression (GWR); Spatial Gini Index	Identify inequities and spatial clusters in recharge potential and governance
Integration with decision frameworks	Supporting robust spatial planning	Spatial Multi-Criteria Decision Analysis (SMCDA); Criteria weighting (AHP, entropy); Standardization and overlay analysis; Sensitivity analysis	Integrate technical and stakeholder inputs for MAR site selection and water planning
Uncertainty and sensitivity analysis	Evaluating model robustness and input influence	Monte Carlo simulations; Sobol sensitivity analysis; Bootstrapping; Ensemble modeling; SHAP values, permutation importance (for ML)	Quantify uncertainty and identify key drivers in hydrological and ML models
Calibration and validation	Ensuring model accuracy and generalizability	Optimization: Genetic Algorithms, PSO, Nelder-Mead; Validation metrics: RMSE, NSE, R^2, MAE; Cross-validation (K-fold, LOOCV); SMOTE (Synthetic Minority Over-sampling Technique) for imbalanced data; Split-sample validation	Improve reliability of hydrological and ML models for water resource ma

Table 15 Socio-economic analysis tools for water management

Tool	Methodology	Key strengths	Limitations	Application examples
Cost–benefit analysis (CBA)	Quantifies costs and benefits in monetary terms	Provides clear economic indicators	Difficult to value non-market benefits	Water pricing reforms in South Africa
Multi-criteria decision analysis (MCDA)	Evaluates alternatives against multiple criteria	Handles qualitative and quantitative data	Subjective weight assignments	Transboundary water allocation
Participatory rural appraisal (PRA)	Engages local stakeholders in assessment	Captures community perspectives	Time-intensive process	Rural water access projects
Social impact assessment (SIA)	Evaluates social consequences of policies	Identifies vulnerable groups	Challenging to predict long-term effects	Dam construction projects

Table 16 Integrated modeling frameworks for water management

Framework	Components	Key capabilities	Spatial scale	Example applications
WEAP-MODFLOW	Water allocation + groundwater model	Surface–groundwater interactions	Basin-scale	Zeuss Koutine basin, Tunisia
SWAT-GIS	Hydrological model + spatial analysis	Land-use change impacts	Watershed	Climate adaptation planning
DSSAT-WEAP	Crop model + water resources model	Irrigation optimization	Field to regional	Semi-arid agriculture
Hydro-economic models	Hydrological + economic models	Economic impact assessment	Regional	Water policy evaluation
Agent-based models	Stakeholder behavior simulation	Human-water system feedbacks	Local to basin	Transboundary negotiations

Table 17 Adaptive management case studies

Region	Strategy	Outcome	Challenge
Mediterranean	Drought-resistant crops	20% water savings	Farmer adoption rates
Australia	Dynamic reservoir operations	Improved drought resilience	Legal conflicts over releases
California	Groundwater recharge incentives	15% aquifer recovery (2015–2025)	Landowner participation

Table 18 Technology performance evaluation

Technology	Accuracy	Cost	Scalability	Best use case
Satellite RS	Moderate	Medium	High	Regional land-use change
IoT sensors	High	Low	Medium	Urban pipe networks
Drone-based monitoring	Very High	High	Low	Precision agriculture

Cost–Benefit Analysis (CBA), Social Impact Assessment (SIA), and participatory methods help assess the trade-offs and benefits of different water interventions (Alomoto et al. 2022; Huggins and Thompson 2021) (Tables 17, 18).

In South Africa, a socio-economic review of water pricing revealed the importance of equitable distribution and social equity in policy-making. Yet, such analyses face challenges, including the complexity of social systems, difficulties in quantifying qualitative impacts, and the need for broad stakeholder engagement (Mankad and Tapsuwan 2011). Despite these issues, socio-economic tools continue to provide crucial insights into affordability, equity, institutional behavior, and cultural values (Mulligan 2013).

Key methods include CBA, which quantifies the monetary costs and benefits of projects—particularly effective for evaluating water supply and sanitation (Bitterman and Koliba 2020). Multi-Criteria Decision Analysis (MCDA), which handles conflicting objectives across economic, environmental, and social domains (Mulligan 2013), and Participatory Rural Appraisal (PRA), which integrates local knowledge and amplifies marginalized voices in water governance (Mosavi et al. 2024).

Increasingly, these tools are being integrated with hydrological and spatial models to develop more holistic and inclusive water governance strategies. For example, water pricing reforms in South Africa incorporated equity into economic modeling (Tewari and Kushwaha 2008) while a socio-hydrological study in Iran used root cause analysis and stakeholder interviews to uncover institutional barriers to sustainable water use (Javanbakht Sheikhahmad, et al. 2025). Hydro-economic models that combine flow data with economic input–output tables also enable evaluation of both direct and indirect socio-economic effects of water allocation (Almazan-Gomez et al. 2021).

Integrated frameworks like WEAP-MODFLOW simulate groundwater-surface water interactions under various scenarios, as demonstrated by Hadded et al. in Tunisia (Porhemmat et al. 2019). Similarly, SWAT-GIS supports spatial watershed modeling (Hussain 2023). DSSAT-WEAP links crop and water planning for irrigation strategy, and Agent-Based Models (ABMs) simulate stakeholder behavior in dynamic hydrological contexts.

Together, these approaches enable scenario planning, participatory modeling, and adaptive governance bridging the gap between technical modeling and policy-making to foster resilient, equitable, and sustainable water management systems.

6 Discussion

This section synthesizes key findings on integrated water management approaches, evaluating their effectiveness across different contexts while addressing implementation challenges and future directions.

6.1 Adaptive management for climate resilience

Adaptive management has become a cornerstone of sustainable water governance, particularly in the face of increasing hydrological variability driven by climate change. This approach emphasizes flexibility, learning, and iterative decision-making to respond to evolving environmental conditions.

Recent research highlights the value of flexible institutional frameworks that allow for dynamic adjustments to water allocation during droughts and floods. Tsakiris and Loucks (2023) underscore the importance of integrating scientific knowledge with stakeholder engagement to enhance resilience in water systems (Table 17).

In the Mediterranean region, adaptive strategies such as the adoption of drought-resistant crops and precision irrigation technologies have led to measurable water savings and improved agricultural productivity. Burak and Margat (2016) report a 20% reduction in water use in pilot areas, although farmer adoption remains uneven due to economic and cultural barriers.

However, the scalability of adaptive management is often hindered by data limitations, fragmented governance, and institutional inertia. Kourgialas et al. (2018) identify these as critical challenges, particularly in regions where water rights are contested or poorly defined.

6.2 Technological integration for decision support

Advanced technologies are reshaping the landscape of water monitoring and management, offering new tools for precision, efficiency, and resilience.

Remote sensing (RS) and **Geographic information systems (GIS)** have enabled basin-scale trend analysis and land-use monitoring. These tools support long-term planning by visualizing hydrological changes and infrastructure vulnerabilities. Mohan et al. (2025). highlights how satellite-based RS combined with GIS mapping has improved regional water resource assessments, particularly in arid and semi-arid zones.

Internet of things (IoT) and **Machine learning (ML)** integration is revolutionizing urban water systems. Real-time sensor networks detect leaks and anomalies, reducing non-revenue water by up to 25% in pilot projects, as demonstrated by Zulkifli et al. (2022). These systems also support predictive maintenance and optimize distribution efficiency (Table 18).

Despite these advances, high implementation costs and technical capacity requirements remain significant barriers. Palermo et al. (2022) emphasize that many utilities, especially in developing regions, struggle with the upfront investment and skilled workforce needed to deploy and maintain these technologies.

6.3 Conjunctive use and MAR: balancing supply sources

The strategic coordination of surface water and groundwater resources referred to as conjunctive use along with MAR, represents a robust approach for enhancing water security and building resilience to climate variability. By optimizing the combined strengths of both supply sources, these strategies can buffer water users against seasonal fluctuations and droughts, while supporting long-term sustainability (Table 19).

Key factors underpinning the success of conjunctive use and MAR initiatives include strong institutional frameworks and adaptable legal mechanisms. For example, the Ghataprabha Project in India illustrates how effective governance and the integration of canal and groundwater operations can significantly improve irrigation efficiency and mitigate the risks of groundwater over-extraction (Harsha 2016). Additionally, the development of hybrid legal frameworks that blend customary and statutory water rights, as highlighted by Zhang and Sato (2024), has enabled more equitable and adaptive water allocation in diverse socio-legal contexts.

Nevertheless, the benefits of conjunctive use and MAR are not universal. In regions where regulatory oversight is weak, unregulated groundwater extraction without adequate recharge has resulted in adverse outcomes such as land subsidence and aquifer degradation (De Wrachien and Fasso 2002). These challenges underscore the importance of comprehensive monitoring, enforcement, and stakeholder engagement to ensure the effectiveness and sustainability of conjunctive management (Table 20).

While conjunctive use and MAR can deliver substantial gains in water security, attention must also be paid to issues of equity and access. For instance, groundwater banking in California's Central Valley has provided a 30% buffer against droughts but has disproportionately benefited larger farms. Similarly, canal-groundwater cycling in Maharashtra has increased agricultural yields by 25%, yet access remains uneven for smallholder farmers.

Table 19 Conjunctive use implementation outcomes

Location	Approach	Water security gain	Equity concern
Central Valley, CA	Groundwater banking	30% drought buffer	Large farm dominance
Maharashtra, India	Canal-groundwater cycling	25% yield increase	Smallholder access gaps

Table 20 Success and failure of conjunctive use of surface and groundwater: comparative case studies

Factor	Success case	Failure case
Governance	Robust institutional frameworks and stakeholder coordination, as seen in the Ghataprabha Irrigation Project, Karnataka, India (Bhat et al. 2023)	Fragmented governance and lack of enforcement, such as in parts of the Walla Walla River Basin, USA (Fasser and Dunn 2022)
Infrastructure	Well-developed infrastructure and recharge systems in Piranshahr, Iran (Rezapour and Yazdi 2014)	Inadequate infrastructure in regions with poor canal maintenance or lack of recharge facilities (Zhang and Sato 2024)
Monitoring	Continuous monitoring and adaptive allocation in the Phraya Basin, Thailand (Yos 2023)	Lack of real-time data and coordinated pumping in decentralized systems (Zhang and Sato 2024)
Equity	Equitable access ensured through community-managed irrigation systems in parts of India (De Wrachien and Fasso 2002)	Wealthier users dominate groundwater access in unregulated areas (De Wrachien and Fasso 2002)
Environmental impact	Balanced use prevented over-extraction and supported aquifer recharge in managed systems (Rezapour and Yazdi 2014)	Over-extraction led to land subsidence and reduced river baseflows in poorly managed basins (Bertule et al. 2018; Zhang and Sato 2024)

6.4 Policy and governance innovations

Innovative governance models are essential for sustainable water management, particularly in the face of increasing demand and climate uncertainty. Effective institutional designs tend to share several key characteristics that enhance adaptability, equity, and resilience.

One such feature is inclusive stakeholder participation, as exemplified by the European Union's Water Framework Directive (WFD). The WFD mandates the establishment of river basin committees that include local stakeholders in planning and decision-making processes, promoting transparency and accountability (EEA 2000) (Table 21).

Another critical innovation is the use of adaptive legal instruments, such as California's Sustainable Groundwater Management Act (SGMA). SGMA empowers local Groundwater Sustainability Agencies (GSAs) to develop context-specific plans while aligning with overarching state goals. Cantor et al. (2018) emphasize how SGMA fosters legal flexibility and encourages proactive management of groundwater-surface water interactions.

Despite these advances, fragmented institutional responsibilities and conflicting water rights continue to hinder effective governance. Richardson (1996) identified these issues as persistent barriers, particularly in regions with overlapping jurisdictions and legacy water claims.

6.5 Key recommendations

Drawing from the synthesis of adaptive management strategies, technological innovations, and governance models, several cross-cutting recommendations emerge to inform future water management initiatives:

Integrate modeling tools with socio-economic assessments The integration of advanced hydrological models such as WEAP-MODFLOW with socio-economic datasets enables more comprehensive scenario planning and holistic decision-making. These integrated Decision Support Systems (DSS) facilitate dynamic simulations of water demand, supply, and policy impacts under diverse climate and development trajectories, thereby supporting more robust and adaptive management strategies (Yates et al. 2009).

Strengthen legal interoperability between surface and groundwater regimes Fragmented legal and policy frameworks frequently impede the coordinated management of water resources. Harmonizing laws and policies governing surface and groundwater particularly in transboundary or multi-jurisdictional settings can enhance both the efficiency and equity of water allocation (Albrecht, et al. 2017).

Scale low-cost monitoring technologies Expanding the deployment of affordable IoT sensors and citizen science platforms can help address persistent data gaps, especially in underserved regions. These technologies provide real-time

Table 21 Governance models comparison

Model	Strength	Weakness	Example
Centralized	Uniform standards	Low local responsiveness	China's water permits
Decentralized	Community engagement	Capacity gaps	Ghana village systems
Hybrid	Balances oversight/local needs	Complex coordination	South Africa WMAs

insights into water quality and usage patterns, enabling more responsive, transparent, and inclusive management (Murti et al. 2024).

Prioritize equity in infrastructure and policy design Infrastructure investments and regulatory reforms must explicitly address disparities in access and capacity. Ensuring that smallholder farmers, marginalized communities, and women are actively included in planning and benefit-sharing processes will promote more just and sustainable outcomes (Valipour et al. 2024).

7 Conclusion

This review underscores the critical importance of integrated groundwater and surface water management in achieving environmental sustainability. Effective management of these resources is essential to address the growing challenges posed by climate change, increasing demand, and policy impacts. The review highlights the necessity for cohesive, interdisciplinary approaches that can adapt to these dynamic conditions and ensure the long-term viability of water resources. One of the key recommendations is to enhance climate resilience in water management strategies. This involves developing robust forecasting models to predict changes in precipitation patterns and extreme weather events, implementing sustainable agricultural practices to reduce water usage, and restoring natural ecosystems such as wetlands and riparian zones to maintain water cycles. These measures can help mitigate the adverse effects of climate change on water resources.

Strengthening governance frameworks is another crucial recommendation. Effective governance ensures equitable distribution of water resources and prevents conflicts. This can be achieved by establishing clear policies and regulations that address water rights and usage, promoting stakeholder engagement to foster transparency and accountability, and enhancing cross-sector collaboration to integrate efforts across agriculture, industry, urban planning, and environmental conservation. Leveraging technology for real-time water resource monitoring is also emphasized. Technological advancements such as remote sensing, GIS, IoT devices, and data analytics provide powerful tools for monitoring water levels, quality, and usage patterns. These technologies enable prompt responses to issues and optimize water distribution, ensuring efficient and sustainable management.

Encouraging interdisciplinary research is essential to bridge knowledge gaps and address complex water management challenges. Collaboration between disciplines such as hydrology, climatology, engineering, economics, and social sciences can lead to comprehensive solutions. Supporting innovative research projects and facilitating knowledge exchange among researchers can drive advancements in water management methodologies and technologies. By implementing these recommendations, policymakers and researchers can work towards more effective and sustainable water management solutions for the future. Integrated approaches that enhance climate resilience, strengthen governance, leverage technology, and encourage interdisciplinary research will ensure that water resources are managed equitably and sustainably, supporting both human needs and ecological health.

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Declarations

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