Integrated Approaches to Water Quality and Resource Resilience: Advances in Hydrology, Treatment, and Climate Adaptation

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ABSTRACT

Water resources are being subjected to unprecedented pressure due to population growth, urbanization, industries, intensive farming and the increasing effects of global warming. These stressors are compromising the quality and quantity of freshwater resources, escalating threats to human health, life forms, and to socio-economic conditions. Traditional methods that consider hydrology, water quality, treatment technologies, and resilience planning as stand-alone areas are increasingly less sufficient, since the development of one area is often reliant on the development of the others. The present review synthesizes the recent studies that were published within 2014-2025 in four interconnected pillars, namely: hydrological modelling and climate effects study, water quality and transport of contaminants, water and wastewater treatment innovations, and integrated management through resilience. The usefulness of integrated approaches is demonstrated in case studies conducted in different areas such as Singapore, the Netherlands, California, and Africa, among others. The review finds conclusively that combined solutions are the key to sustainable and resilient water future, because only integrated development in the fields of hydrology, treatment, and resilience will guarantee water security in the environment of growing uncertainty.

Keywords: Water quality, Hydrology, Wastewater treatment, Climate adaptation, Water resilience, Integrated approaches

INTRODUCTION

Water is fundamental to survival, ecological well-being, and economic growth of human beings (Kumar et al., 2023). However, in the twenty-first century, water resources all over the world have never been as much challenged. Over the last few decades, the swift population increase, urbanization, industrialization, and intensive agriculture have led to the rise of water demand and has also diminished water quality due to pollution and excessive use (Gude, 2015; Wang et al., 2024). Climate change also magnifies these problems by changing the precipitation patterns, rising the number of severe weather events, and the severity of droughts and floods (Brown et al., 2015; Gupta et al., 2024). All these stressors endanger the sustainability of freshwater resources and cause severe threats to the health of the population, food security, and ecological integrity (Islam et al., 2025; O'Donnell et al., 2024).

The solution to such complicated issues lies in the fact that the current approach to these issues is fragmented and approach-specific, and the transition to integrated solutions should be made (Sivapalan et al., 2025). Conventional approaches that treat hydrology, water quality, treatment technologies and climate adaptation as independent systems do not fully embrace the interdependence of water systems (Nelson et al., 2023; Chu, 2022).

The purpose of this review is to synthesize across current research and offer a synthesis that spans across hydrology, water quality, treatment technologies, and climate adaptation. The paper examines progress in these four pillars to identify the ways in which integration can be used to enhance water resilience in the face of global challenges (Sharvelle, 2022; Snow et al., 2023). The review relies on the literature published 2014-2025 in order to define the new trends, recent innovations, unresolved gaps, and the prospects of future interdisciplinary research (Dai, 2020; McKay, 2024). By doing that, it aims to educate scholars, policymakers, and practitioners on the avenues of creating sustainable water systems that are adaptive and resilient (Mostafavi et al., 2023; Edwards, 2024).

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CONCEPTUAL FRAMEWORK

The conceptual basis of this review consists in the acknowledgment that water systems are all interconnected and hydrology, water quality, treatment technologies, and resilience strategies are functioning components and not separate domains. These areas have frequently been tackled in isolation in traditional approaches thereby limiting effectiveness of interventions and resulting in disjointed results. In comparison, integrated framework is focused on the feedback loops between the following pillars: hydrological forecasts is used in designing treatment systems, performance of the treatment in terms of ecological and human health resiliency, and adaptive governance is used to sustainability over time.

Defining Integrated Approaches

Integrated approaches in water management is the conceptual term used to describe the intention to incorporate hydrological science, water quality monitoring, treatment technologies, and resilience strategies into one system (Sivapalan et al., 2025; Kumar et al., 2023). In contrast with other methods that address them individually, integration highlights the fact that natural processes and artificial systems are interrelated and should be controlled as one (Gupta et al., 2024; McKay, 2024).

Traditional vs. Integrated Perspectives

Historically, the discipline of water studies developed in silos. Hydrologists studied the dynamics of precipitation-runoff and aquifer storage as well as surface water flow, but with minimal or no connection to treatment or adaptation requirements (Zeng et al., 2023; McIntosh et al., 2023). Treatment engineers did not consider hydrological variability and resilience in their designs and were working on such systems mostly to remove contaminants (Gude, 2015; Dai, 2020). The policymakers placed too little attention on hydrological and technological evidence by focusing on climate adaptation frameworks (Hagen, 2022; Edwards, 2024).

This disjointed method yielded solutions that were not aligned: such as, hydrological flood risk was neglected in the construction of treatment plants, and hydrological models did not take into consideration the requirements of treatment and governance (Condon et al., 2021; O'Donnell et al., 2024). A more integrated approach, in turn, would couple all areas in the sense that hydrological forecasting is used to inform treatment planning, treatment systems are used to enable resilience to climate stress, and scientifically based adaptation policies are made based on this knowledge (Konar et al., 2024; Sharvelle, 2022).

Framework for Linking Hydrology, Treatment, and Resilience

The water system is disregarded as an integrated system where hydrological processes, pollutant transport, treatment technologies, and resilience strategies interact with each other in an integrated perspective (Nelson et al., 2023; Ma, 2022). The next line of action is hydrology, which defines the availability and quality of water and treatment systems as engineered interventions, which preserve water resources and reclaim value (Snow et al., 2023; Bradley et al., 2024). These components are overlapped by the resilience strategies to make sure that the water system can survive and adjust to the extremes in the climate, floods, droughts, and even the event of contamination (Mostafavi et al., 2023; Sivapalan et al., 2025).

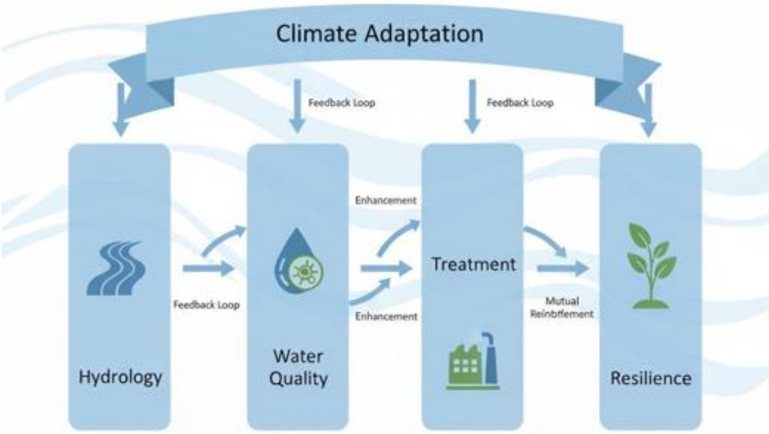

Figure 1. Conceptual framework of integrated approaches to water quality and resource resilience.

The diagram illustrates four interconnected pillars: Hydrology, Water Quality, Treatment, and Resilience. Arrows between them represent feedback loops, showing how progress in one area reinforces the others. Climate Adaptation is placed as an overarching layer spanning all four pillars, symbolizing its cross-cutting influence on water system integration (Sivapalan et al., 2025; Wang et al., 2024; McIntosh et al., 2023).

This framework underscores that resilience is not achieved by advancing one pillar alone, but through coordinated progress across hydrology, treatment, and policy dimensions (Wang et al., 2024; Chu, 2022).

ADVANCES IN HYDROLOGY AND CLIMATE IMPACT STUDIES

Over the past few decades, mathematical science has made numerous advances in hydrology, especially in the use of computational modeling, big data analytics, and satellite data. Physical models like SWAT, VIC, and MODFLOW continue to be a basis of watershed hydrology and groundwater flow simulation, but are commonly limited by parameter uncertainty and a lack of data (Brown et al., 2015; McIntosh et al., 2023). Recently, it has been advanced with the incorporation of machine learning algorithms like long short-term memory (LSTM) networks, which enhance prediction of rainfall-runoff and streamflow in different climatic conditions (Islam et al., 2025; Nelson et al., 2023).

Hydrological Modelling and Big Data Tools

The use of hydrological modelling has been at the center of the water availability, runoff formation, and watershed dynamics. Conventional frameworks, including the Soil and Water Assessment Tool (SWAT), Variable Infiltration Capacity (VIC), and MODFLOW have been used to offer strong models of simulating surface and subsurface processes (Brown et al., 2015; McIntosh et al., 2023). Nevertheless, the models tend to be limited by parameter uncertainties and lack scalability in large basins.

The satellite remote sensing and global reanalysis data have become sources of unprecedented amounts of hydrology data allowing to track almost real-time on a regional and even continental level (Andreadis & Clark, 2023; Zeng et al., 2023). The innovations have also enhanced water balance simulation, as well as aiding early flood and drought prediction systems.

Model/Approach	Application	Strengths	Limitations
SWAT	Watershed hydrology & water quality	Integrates land use & management	Sensitive to calibration uncertainty
VIC	Large-scale hydrology & climate	Captures land–atmosphere interactions	Requires extensive data
MODFLOW	Groundwater flow	Robust, widely applied	Weak in climate extremes
LSTM	(AI) Streamflow prediction	Learns nonlinear dynamics	Needs large datasets
PARFLOW	Integrated surface–subsurface hydrology	High-resolution 3D simulations	Computationally expensive

Table 1. Summary of selected hydrological and climate models

Climate Change Impacts on Hydrological Processes

Climate change has a major impact on the processes of the global hydrological cycle: it increases the severity of precipitation events and alters the evapotranspiration patterns and snowmelt regimes (O'Donnell et al., 2024; Hagen, 2022). Increased floods and extended droughts are being recorded in many areas, weakening reliability in water supply and ecosystem stability (Behrangi et al., 2020; Segura et al., 2020). The future risks are now shown in detail in coupled climate-hydrology models under CMIP5 and CMIP6 scenarios, showing vulnerability of semi-arid basins, coastal deltas and snow-fed catchments (Nelson et al., 2023; Gupta et al., 2024).

Groundwater–Surface Water Interactions

Surface water and groundwater are interdependent parts of the hydrological cycle, historical studies of which have been segmented. It is becoming problematic due to the fact that these interactions between aquifers, rivers and wetlands define the quality and availability of water (McIntosh et al., 2023; Edwards, 2024). As an illustration, river base flow is maintained by the groundwater discharge in times of droughts, but excess extraction and pollution diminishes this buffer (Chu, 2022; Al-Hashimi et al., 2021).

Now, with the development of modelling tools like ParFlow and MODFLOW, it is possible to simulate the dynamics of coupled surface-subsurface systems to gain a better insight into the processes of recharge, discharge, and contaminant transportation (Condon et al., 2021; Tsai, 2023). The tracer-based studies and isotopic tracing also indicate recharge routes and routing times of different landscapes, which streamline more sustainable water resource distribution (McKay, 2024; Nelson et al., 2023).

WATER QUALITY AND CONTAMINANT TRANSPORT

The quality of water is increasingly being posed by various traditional and emerging contaminants that are making management strategies difficult to control and harmful to human health and the environment. Particularly worrisome are emerging contaminants like per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, and microplastics due to their persistence, the ability to bio accumulate, and inability to be treated using traditional methods (Ma, 2022; Bradley et al., 2024). PFAS are found in drinking water and groundwater systems, wastes discharged into waterways via effluents, and microplastics are vectors of toxic substances and microbial communities, which contributes to increasing ecological stress (Nguyen et al., 2024; Schramm et al., 2024).

Emerging Contaminants: PFAS, Pharmaceuticals, and Microplastics

Over the last few decades, there has been an increase in the emergence of contaminants that are of concern to the water quality including per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, and microplastics. They are persistent and bioaccumulative with the possibility of being toxic and frequently found in trace amounts that go undetected by traditional treatment systems (Wang et al., 2024; Chu, 2022). PFAS, in particular, are extremely recalcitrant to degradation and have been found in groundwater and drinking water sources all over the world (Ma, 2022; Bradley et al., 2024).

Nutrient and Sediment Pollution

The nutrient loading of rivers, lakes, and coastal areas has persisted as eutrophication and harmful algal blooms due to especially high levels of nitrogen and phosphorus (O'Donnell et al., 2024; Konar et al., 2024). The primary sources include agricultural run-off, urban stormwater and insufficient treatment of wastewater. The water quality is also compromised by the rapid transport of sediments, which land use change and deforestation tend to speed up and make water turbid, smother, and carry the attached pollutants (Segura et al., 2020; McKay, 2024).

Riparian buffers and cover cropping are examples of best management practices (BMPs) that have been extensively used, but their outcomes depend on watershed and climate conditions (Schramm et al., 2024; Hathaway, 2017). Meta-analyses are now enabled by watershed modeling advances to estimate BMP performance in regions and inform evidence-based policy-making (Gupta et al., 2024; Brown et al., 2015).

Groundwater Contamination and Remediation

The reason that groundwater systems are particularly susceptible to contamination is because of their low rates of recharge as well as their long contaminant residence times. Wide contamination issues are caused by industrial wastes and agricultural pesticides and landfill effluents (McIntosh et al., 2023; Al-Hashimi et al., 2021). Of special interest are PFAS, nitrate, and heavy metals, which are persistent and dangerous to human health (Chu, 2022; Tsai, 2023).

Pump-and-treat systems, in-situ bioremediation, and adsorption-based techniques are such remediation strategies, although the latter tend to focus more on physical, chemical, and biological approaches, which are most effective together (Saifur and Gardner, 2021; Silva, 2023).

Advances in Monitoring Technologies

Monitoring of any contaminants is critical and timely in effective water quality management. Conventional monitoring systems that are laboratory based, though very accurate, tend to be expensive and time-consuming. The recent years are characterized by increased availability of real-time sensing and molecular diagnostic-based tools to identify microbial and chemical contamination (Nguyen et al., 2024; Snow et al., 2023).

Remote sensing has become useful in tracking large-scale water quality parameters e.g. turbidity and chlorophyll concentrations, which could be used as a proxy of nutrient and sediment loads (Andreadis and Clark, 2023; Zeng et al., 2023). These technologies will enable the rapid interventions because it will be more proactive and predictive and make monitoring easier.

Contaminant	**Source**	**Environmental Concern**	**Treatment/Remediation Approach**
PFAS	Firefighting foams, industry	Persistent, bioaccumulative	Adsorption (activated carbon, resins), nanomaterials
Pharmaceuticals (PPCPs)	Wastewater effluent	Endocrine disruption, ecosystem toxicity	Advanced oxidation, membrane filtration
Microplastics	Urban runoff, plastics degradation	Vectors for pollutants, ecological stress	Membrane separation, coagulation/flocculation
Nitrate	Agriculture (fertilizer)	Groundwater contamination, health risks	Bioremediation, denitrification reactors
Heavy metals	Industrial discharge, mining	Toxicity, bioaccumulation	Adsorption, precipitation, permeable reactive barriers

Table 2. Emerging contaminants and their treatment/remediation strategies

INNOVATIONS IN WATER AND WASTEWATER TREATMENT

Innovation in water and wastewater treatment technologies has been very high in the past few years in order to treat not only traditional pollutants but also new polluting substances. Activated sludge systems and biofilm reactors have continued to be a key process in wastewater management, particularly when paired with chemical treatment such as coagulation, chlorination, and advanced oxidation as a method to enhance efficiency and expand contaminant destruction (Silva, 2023; Dai, 2020).

Biological and Chemical Treatment Methods

Wastewater management is still based on biological treatment procedures, especially activated sludge systems, biofilm reactor, and anaerobic digestion (Butler, 2018; Gude, 2015). Such systems perform well in breaking down organic matter and nutrients, but do not do well to eliminate emerging contaminants like pharmaceuticals and PFAS. Integrations of biological treatment and chemical processes are also considered as a growing field to cope with such limitations (Silva, 2023; Saifur and Gardner, 2021). Coagulation-flocculation, chlorination, and the advanced oxidation methods have been established to be effective in disinfection and breaking down contaminants (Chellam, 2025; Dai, 2020).

Nanotechnology and Advanced Oxidation Processes (AOPs)

Carbon nanotubes, graphene oxide, and nano-zerovalent iron are nanotechnology-based materials that exhibit high potential in adsorbing and degrading the emerging contaminants (Ma, 2022; Lanzarini-Lopes et al., 2021). The materials are highly reactive and have high surface area, which is especially efficient in tackling PFAS, microplastics, and pharmaceuticals (Bradley et al., 2024; Chu, 2022).

The application of advanced oxidation processes (AOPs) to treat recalcitrant organic contaminants, such as ozonation, UV/H 2 O2, and photocatalysis, is becoming more popular, as it is able to treat water without harmful residues (Snow et al., 2023; Moe, 2023).

Constructed Wetlands and Green Infrastructure

Constructed wetlands (CWs) and other green infrastructure systems have become in popularity as low cost, nature-based wastewater treatment and stormwater management (Biswal & Balasubramanian, 2022; Hathaway, 2017). CWs integrate physical, chemical, and biological activities to eliminate nutrients, pathogens, and sediments, and also have co-beneficial properties, including the increase of biodiversity and carbon sequestration (Chang, 2016; Schramm et al., 2024).

Green spaces like bio-retention systems, permeable pavements, and green roofs have also presented themselves as effective tools of reducing stormwater pollution and peak flows (Hathaway, 2017; Konar et al., 2024).

Water Reuse and Circular Economy Models

Going to the models of the circular economy, water use becomes linear and therefore focuses on wastewater as a resource instead of a waste product (Sharvelle, 2022; Gude, 2015). In developed treatment systems, wastewater is becoming more and more reused to irrigate or in industries, and in some cases to drinkable water (Silva, 2023; Moe, 2023).

Technology	Application	Strengths	Limitations
Activated sludge & biofilm reactors	Nutrient and organic removal	Proven, widely used	Ineffective against emerging contaminants
Chemical oxidation & coagulation	Disinfection, pollutant removal	Effective, flexible	Byproduct formation, cost
Nanotechnology (CNTs, nZVI)	Emerging contaminants	High reactivity, versatile	Cost, environmental risk of nanoparticles
Advanced oxidation (UV, ozone, photocatalysis)	Pharmaceuticals, PFAS, pathogens	High efficiency, clean residues	Energy-intensive, scaling issues
Constructed wetlands	Nutrient & stormwater treatment	Low-cost, co-benefits	Land requirement, variable performance
Circular economy (reuse & recovery)	Water reuse, resource recovery	Promotes sustainability	Regulatory & public acceptance barriers

Table 3. Innovations in wastewater treatment technologies

INTEGRATED WATER MANAGEMENT AND RESILIENCE

The need to develop resilience in water systems has risen with the exacerbation of flood, drought and coastal risks by climate change. The approaches to adaptation are now integrated with engineering solutions, including groundwater banking, desalination, and wastewater reuse, along with the ecological ones like wetlands restoration and afforestation that can increase the hydrological stability and co-benefits of the ecology (Mostafavi et al., 2023; Edwards, 2024). The hybrid infrastructure combining grey defenses and green is gaining more and more popularity in managing coastal and floodplain areas with the assistance of better hydrological modeling and early-warning systems (Hagen, 2022; Zeng et al., 2023).

Climate Adaptation Strategies

The water sector needs climate adaptation strategies, which are anticipatory, absorptive, and recuperative of climate-related shocks of drought, flood, and heatwave (Hagen, 2022; O'Donnell et al., 2024). Some of the strategies are to diversify the water supply sources (e.g. groundwater banking, desalination, and wastewater reuse), enhance water efficiency, and adopt dynamic governance models that dynamically respond to new data

(Nelson et al., 2023; Edwards, 2024).

Adaptation techniques like wetland restoration and afforestation have also been shown to have a positive impact on managing hydrological extremes in addition to providing co-benefits such as carbon sequestration (Schramm et al., 2024; Chang, 2016).

Flood and Coastal Resilience

The raising of the sea level, intensification of storms, and adjustments in the precipitation patterns have made the areas of coastal and flood plain susceptible (Behrangi et al., 2020; Segura et al., 2020). The structural defenses, e.g., levees and seawalls, do not lose their significance, yet combined strategies now focus on a hybrid infrastructure, i.e. grey (engineered) and green (ecosystem-based) strategies (Biswal & Balasubramanian, 2022; Hathaway, 2017).

Hydrological and climate models have become important in reducing the risk of disasters through the flood forecasting and early warning systems because they work together with community preparedness (Condon et al., 2021; Zeng et al., 2023). In the same vein, strategic land-use planning and managed retreat become controversial yet some of the most needed actions in very vulnerable coastal areas (Edwards, 2024; Nelson et al., 2023).

The Water–Energy–Food (WEF) Nexus

The framework of the water-energy-food nexus underlines the fact that resiliency in water systems cannot be established without considering interdependencies with energy and food production (Hoff, 2011; Sharvelle, 2022). As an example, the growth of irrigation enhances food security at the expense of aquifer depletion, and energy-demanding desalination increases water availability at the cost of carbon emissions (Gude, 2015; Moe, 2023).

The recent works emphasize combined policies which maximize the trade-off between sectors, including wastewater reuse to irrigate agricultural land, biogas extraction of the natural wastewater sludge, and desalination with renewable energy sources (Snow et al., 2023; Bradley et al., 2024).

Case Studies of Integrated Systems

There are a number of real-life case studies which show efficacy of combined water management practices. The Four National Taps Strategy in Singapore is a mixture of imported water, the local catchment water, the desalination water, and the reclaimed waste water to form a more resilient water supply system (Tortajada, 2006; Nguyen et al., 2024). Room for the River projects in the Netherlands combine flood risk management with ecological restoration and city development, which provides a worldwide example of adaptive river basin management (Edwards, 2024; Hagen, 2022).

Water-reuse-related projects in California can show how a circular economy model, together with highly developed treatment methods, can reinforce water supply and climate resilience (Sharvelle, 2022; Silva, 2023). The same pattern can be found in the use of African case studies to focus on community-based solutions to create

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resilience in semi-arid settings, combining hydrology, agriculture, and green infrastructure (McKay, 2024; Schramm et al., 2024).

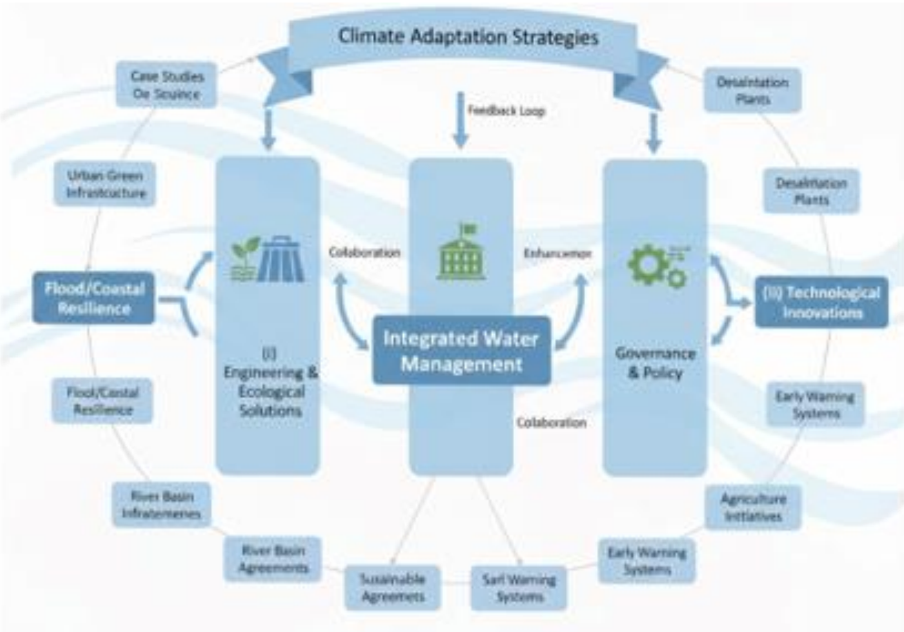

Figure 2. Integrated resilience strategies across hydrology, treatment, and policy.

The diagram illustrates the interconnections between climate adaptation strategies, flood and coastal resilience, and the water–energy–food nexus. Central to the figure is "Integrated Water Management," connected by arrows to three pillars: (i) Engineering and Ecological Solutions, (ii) Governance and Policy, and (iii) Technological Innovations. Case studies are represented as applied examples at the outer layer, showing how theory translates into practice (Mostafavi et al., 2023; Konar et al., 2024; Edwards, 2024; Schramm et al., 2024).

SYNTHESIS OF INTEGRATED APPROACHES

The synthesis of integrated approaches highlights the balance between incremental and transformational solutions in advancing water security. Incremental actions such as refining hydrological models, enhancing monitoring systems, and improving treatment operations deliver near-term benefits but often fall short against the scale of climate and pollution challenges (Brown et al., 2015; Hagen, 2022).

Incremental versus transformational solutions

Interventions that can help achieve tangible near-term advantages are incremental actions, which include enhancing the efficiency of operational processes in current treatment facilities, calibration of hydrological models, and the development of monitoring networks (Brown et al., 2015). Nevertheless, when faced with compound trends and accelerating stressors such as climate change, urban sprawl and the development of intractable new contaminants, incrementalism is often not adequate to change system courses in deep uncertainty (Hagen, 2022; Konar et al., 2024).

Transformational strategies, in their turn, are aimed at re-architecturing water systems fundamentally, such as switching to models of circular water economies, mainstreaming nature-based solutions in place of grey infrastructure only, and embedding advanced forecasting analytics across basin-wide management, actions that have to be systemic investments, institutional changes, and multi-sector coordination (Sharvelle, 2022; Nelson et al., 2023).

Linking Hydrology, Treatment, And Resilience

When hydrology, treatment and resilience are considered not as independent domains but as mutually reliant aspects of a single adaptive system, since hydrological predictions directly regulate expectations with regards to contaminant loads and treatment demands, and ecological and public-health outcomes in the downstream are regulated by the performance of treatment systems (Condon et al., 2021; McIntosh et al., 2023). As an example, hydrological predictions of high resolution allow operators to anticipate the pulses of stormborne pollutants and preemptively modify the configuration of treatment plants to reduce risk and increase cost-effectiveness (Gupta et al., 2024).

On the other hand, infrastructure that is resilient and resistant to hydrological extremes, like flood-tolerant plant placement and redundancy in vital systems, cushions the capacity to endure shocks in treatment capacity and reduces the time to recuperate after an event occurs (Edwards, 2024; O'Donnell et al., 2024). Simply put, linkage of hydrologic intelligence to adaptive treatment operations and resilience planning bridges feedbacks that would permit vulnerability in one pillar to circulate through the system (Wang et al., 2024; Mostafavi et al., 2023).

Multi-disciplinary Pathways for Water Security

It takes a multi-disciplinary journey to move past a lone success to a water security that is sustainable and that incorporates scientific integration, technological scaling, governance reform, and meaningful community involvement into one program of action (Silva, 2023; Snow et al., 2023). Scientifically, integration involves interoperating modeling frameworks that connect hydrological forecasting, contaminant transport simulations and resilience measures in such a way that model outputs can be directly operationalized in such a way as to translate into operational decisions and policy signals (Condon et al., 2021; McIntosh et al., 2023).

Lastly, the social aspect cannot be an auxiliary one; participation in the community and active decision-making enhance legitimacy, expose local knowledge that is critical to context-sensitive responses, and increase the likelihood of long-term adoption of integrated action (Schramm et al., 2024; McKay, 2024). When all these threads are strategically combined, integrated approaches have the most opportunities to go beyond pilot projects and create systemic, long-lasting water quality and resilience improvements (Mostafavi et al., 2023; Wang et al., 2024).

CHALLENGES AND FUTURE DIRECTIONS

Despite rapid progress, several challenges hinder the full realization of integrated water management. Technical limitations such as data gaps, model uncertainties, and the complexity of simulating coupled surface–subsurface interactions restrict predictive accuracy, especially in regions with sparse monitoring networks (McIntosh et al., 2023; Zeng et al., 2023). Analytical difficulties with emerging contaminants like PFAS and microplastics further complicate water quality management (Ma, 2022; Bradley et al., 2024).

Technical Limitations: Data Gaps and Model Uncertainties

Substantial technical constraints still exist despite recent improvements in hydrological modelling, treatment technologies and resilience planning. Numerous hydrological frameworks are limited by parameterization uncertainties, scale differences, and the lack of those complicated feedbacks between surface and subsurface systems (Brown et al., 2015; McIntosh et al., 2023). Another essential bottleneck is the data scarcity, especially in developing regions where the monitoring networks are few, and there are no long-term records of observations (Gupta et al., 2024; Zeng et al., 2023).

The problem of data differences in quality, resolution, and availability impedes the incorporation of datasets into predictive systems even in the presence of such datasets (Andreadis and Clark, 2023; Candon et al., 2021). Besides that, newer contaminants, including PFAS and microplastics, are problematic to analyze due to the need to use sophisticated equipment and provide inconsistent results across facilities (Ma, 2022; Bradley et al., 2024). These constraints are going to be overcome through technical optimization and expansion of global monitoring systems and data-exchange systems.

Socio-Economic and Governance Barriers

Technical innovation would not ensure increased water security in case socio-economic and governance issues are not addressed. Poor long-term underinvestment in water infrastructure is a problem in many low- and middle-income countries, which restricts their ability to implement modern treatment technologies or even resilience strategies (Hagen, 2022; Chu, 2022). In a higher-income setting, the lack of an integrated approach is often facilitated by strict institutional structures and divided governance where hydrology, water quality, and resilience are divided into more than two agencies and little coordination takes place (Edwards, 2024; O'Donnell et al., 2024).

Future Opportunities: AI, IoT, And Interdisciplinary Research

The challenges are tough, but new opportunities are quickly coming up that are able to transform integrated water management. Machine learning and artificial intelligence present specific opportunities to increase predictive precision in hydrology, optimize the work of treatment plants, and identify anomalies in real time (Islam et al., 2025; Nelson et al., 2023). The implementation of the Internet of Things (IoT), with its smart sensors, networked monitoring platforms, etc., is facilitating continuous water quality measurement on a previously unimaginable scale in both space and time (Nguyen et al., 2024; Snow et al., 2023).

Analytics with AI and IoT-enabled sensing when combined present the possibility of proactive and adaptive management that minimizes risks prior to intensification. In addition to technology, further interdisciplinary cooperation becomes the future. Combining the knowledge of hydrology, environmental engineering, governance studies, and community-based research can produce comprehensive solutions that would facilitate technical viability and social legitimacy (Mostafavi et al., 2023; McKay, 2024).

CONCLUSION

This review points out that combined strategies are needed to promote water quality and resiliency in the context of global issues. Modelling and innovation of hydrology, big data, and new treatment methods- e.g. nanotechnology, advanced oxidation, and constructed wetlands- present promising resources to tackle traditional and new contaminants. Meanwhile, flood protection, coastal adaptation, and the water-energy-food nexus as resilience frameworks show that multidisciplinary and cross-sector solutions are required.

Water security of the future cannot be realised with disjointed endeavours, but hydrology, treatment, and resilience should operate as symbiotic structures. Although small changes add value, transformational solutions such as the idea of a circular economy, nature-based solutions, and AI-led management offer higher long-term potential. Going forward, the centralization of interdisciplinary integration, adaptive governance, global data infrastructure and community participation is essential in shifting to sustainable and fair water futures.

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