Managing Urban Water Resources: A Review of Challenges, Techniques, and Sustainability Strategies

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ABSTRACT

This paper highlights key challenges in coastal urban water resource management, focusing on the environmental, socio-economic, and governance dimensions that widely contribute to these issues. It discusses assessment methods, such as hydrological modeling, involving the Soil and Water Assessment Tool (SWAT), the Hydrologic Engineering Center-Hydrologic Modeling System (HEC-HMS), Remote Sensing (RS), Geographic Information System (GIS), and water quality assessment, emphasizing their practical usage, benefits, and disadvantages. It also highlights sustainable development strategies, such as Integrated Water Resources Management (IWRM) and Source-to-Sea (S2S) approaches, community-based management, and hybrid strategies integrating Nature-Based Solutions (NBS) and engineered solutions. This paper also identifies the best practices, stresses gaps in the current methodologies, and provides practical recommendations to strengthen resilience and sustainability, drawing on global case studies. Finally, the need to integrate new technologies, participatory governance, and adaptive management requirements is emphasized, serving as a guide towards policymaking, and practices on how to deal with the development of water resource challenges.

Keywords-sustainable water management; water resources; environmental issues; efficiency; strategies

I. INTRODUCTION

Coastal urban environments are some of the world's most vibrant and multifaceted regions that support economic and social development, as well as biodiversity and cultural exchange. These areas face a growing number of threats that combine rapid urbanization rates, population growth, and increased impacts of climate change. Among the most vulnerable resources in the rapidly expanding coastal urban areas is water. Water is vulnerable to both natural environmental stressors and human-induced disruptions. Water scarcity, pollution, saline intrusion in freshwater resources, and flooding are some of the critical issues that threaten the very sustainability of coastal environments in both ecological and human terms.

Coastal cities are facing the increasing effects of climate change. The existing water-related challenges are aggravated by the rising sea levels, shifts in precipitation and temperature patterns, and extreme weather events, including storms and prolonged droughts. The evolution of these negative trends also partly occurs due to urbanization and growing populations, as water resources, land use conversion, land industrialization, and improper resource management increase competition among humans over the same resources. These factors reflect the critical need for creating new approaches to water management that integrate environmental, social, and technological elements into robust systems. Numerous tools and frameworks, ranging from traditional approaches to advanced methods, including hydrological models, RS, and GIS applications, have been created over the years to assess and enhance the conditions of water resources. The effectiveness of these tools is highly reliant on their suitability to coastal urban area conditions, such as access to data, spatial differences, and governance restrictions.

This review paper seeks to offer comprehensive insights into the challenging aspects, assessment tools, and prudent sustainability approaches for water resource assessment in rapidly expanding coastal urban regions. While numerous studies have explored water-related challenges in coastal cities, there is a significant gap in the integration of assessment techniques with sustainability approaches. The existing literature often focuses either on technical methodologies, such as hydrological modeling, RS, and GIS application, or on policy and governance frameworks, without adequately bridging them. Furthermore, many studies fail to account for the spatial heterogeneity of coastal urban environments, limiting the applicability of their findings to broader contexts [1]. A critical limitation in prior reviews is the fragmented assessment of water resources, where hydrological, socio-economic, and environmental factors are often considered in isolation rather than through a holistic, system-based approach. This review aims to synthesize contemporary studies across diverse coastal regions, identify successful interdisciplinary practices, and propose a more integrated research agenda. By addressing these knowledge gaps, it seeks to provide policymakers and practitioners with practical guidance on enhancing the resilience and sustainability of coastal urban water systems in the face of the evolving global challenges.

II. METHODOLOGY

The present study employs a systematic review approach to synthesize the research findings on urban water resource management. Research articles, reports, and policy documents were sourced from reputable academic and scientific databases, including Scopus, Google Scholar, and ScienceDirect. The search terms used were "urban water management," "challenges in coastal urban waters," "climate change impacts on water systems," "hydrological modeling", water resource assessment techniques," and "sustainability strategies in water management," with Boolean operators (AND, OR) applied to refine the search results. Screening procedures were conducted in two stages: title and abstract screening to exclude irrelevant studies, followed by full-text screening based on relevance, research rigor, and data validity. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed to ensure transparency and replicability. Moreover, interdisciplinary frameworks, such as IWRM and S2S guided the thematic synthesis of the findings.

III. WATER RESOURCE CHALLENGES

Managing water resources in coastal urban areas is a complex issue influenced by rapid urbanization, population growth, environmental threats, and governance inefficiencies. These challenges necessitate an integrated and sustainable approach to ensure long-term resilience and effective water resource management.

A. *Urbanization and Population Growth*

Rapid urbanization and population growth have intensified water-related issues in many coastal cities. The primary challenges include groundwater depletion, water pollution, saline water intrusion, and microplastic contamination.

1) Groundwater Depletion and Water Pollution

Rapid urbanization has led to excessive groundwater extraction and declining water quality in several regions. Mismanaged land conversion and industrial expansion have resulted in declining groundwater levels in cities, such as Abidjan, Cotonou, Lagos, and Douala in West Africa [2]. Similarly, in Shandong, China, over-extraction of groundwater, coupled with increasing pollution, has severely impacted water availability, necessitating ecological restoration measures [3]. In Pakistan, excessive groundwater pumping for agricultural and industrial use has exacerbated water shortage, leading to severe depletion and contamination of freshwater sources [4]. Governments and urban planners must implement groundwater recharge programs, regulate extraction, and enforce pollution controls to ensure the sustainable management of freshwater resources.

2) Saline Water Intrusion

Over-extraction of groundwater in urban and semi-urban coastal areas has resulted in the infiltration of saline water into freshwater reserves. This issue is particularly prevalent in Bangladesh, where rising domestic water demands and industrialization have led to saltwater intrusion, deteriorating drinking water quality, and affecting agricultural productivity [5]. It is, thus, essential to adopt managed aquifer recharge, improve freshwater conservation, and regulate groundwater use to maintain freshwater levels and prevent further saltwater intrusion.

3) Microplastic Contamination

Microplastic contamination in rivers and coastal waters has also been identified as a growing challenge, further exacerbating water quality degradation. Coastal and aquafarm areas in South Korea [6], as well as urban regions, like Shanghai and Changsha in China [7, 8], have revealed that densely populated and industrialized regions contribute significantly to microplastic pollution. Research suggests that human activities, such as industrial discharge, improper waste management, and runoff from urban areas, introduce substantial quantities of microplastics into coastal waters. This contamination poses severe risks to marine ecosystems, aquatic food chains, and public health. Efforts to address microplastic pollution must focus on improving waste management systems to prevent plastic debris from entering water bodies. Governments should implement strict regulations on industrial discharge and promote eco-friendly alternatives to plastic-based products.

B. *Influence of Environmental Challenges on Water Resources*

Climate change presents significant challenges for coastal cities, which are home to over 40% of the global population. Rising temperatures and altered precipitation patterns contribute to increased water stress, escalating demands for both water and energy. Extreme weather events, such as storms and flooding, further expose vulnerabilities in urban infrastructure and ecosystems, disrupting local water security by diminishing freshwater availability and quality. These challenges make it increasingly difficult to meet the growing demands of urban populations [9-11].

The following sections categorize key environmental challenges affecting coastal urban areas, highlighting their causes, consequences, and implications for sustainable water management.

1) Prolonged Droughts and Groundwater Depletion

Drought conditions are being intensified due to climate change, leading to significant reductions in water availability. Extreme heat events increase evaporation rates and extend drought durations, further straining water resources. In regions, such as Iran's Alborz Province, groundwater depletion has been observed due to the changing precipitation patterns and rising temperatures, which pose risks to agricultural, domestic, and industrial water supply. Limited data availability also hampers the accuracy of groundwater level predictions and the effectiveness of adaptation strategies. To combat these effects, the development of drought-resistant water management strategies is crucial. This includes investing in water-efficient irrigation techniques, promoting drought-tolerant crops, and expanding water recycling and reuse programs. Enhanced forecasting and early warning systems can help authorities prepare for drought conditions and manage water allocations effectively [11].

2) *Rising Sea Levels and Coastal Erosion*

Coastal cities are highly vulnerable to sea level rise, which exacerbates flooding and shoreline erosion. This issue is particularly concerning in low-lying coastal areas, where increased storm surges and high tides threaten infrastructure, livelihoods, and ecosystems. The rising frequency and intensity of storms worsen these effects, making flood mitigation and coastal resilience a priority. To reduce the rising sea level impact, cities must invest in coastal protection infrastructure, such as seawalls, levees, and storm surge barriers. Restoring natural buffers, such as mangroves and wetlands, can also help absorb storm impacts and reduce coastal erosion. Urban planning should incorporate flood-resistant designs to minimize damage to residential and commercial properties [12].

3) *Uncertainty in Climate Risk Assessments*

The complexity of climate models leads to uncertainty in predicting flood and drought risks, which affects the reliability of climate adaptation and water management strategies. For example, studies in South Korea's Hapcheon and Seomjingang Basins revealed significant biases in hydrological models, complicating flood risk assessments and disaster preparedness efforts. It is, thus, essential to enhance climate modeling accuracy, integrate risk assessment tools, and develop flexible adaptation strategies to improve disaster preparedness and water resource management [13].

4) *Adaptation Challenges in Small Coastal Cities*

Smaller coastal cities face unique climate-related challenges due to their limited adaptive capacity, socio-economic vulnerabilities, resource disparities, and dependence on ecological infrastructure. Case studies in Miami Beach and Milford (USA), Mandurah (Australia), Sundarbans (Bangladesh), and Knysna (South Africa) highlight how these cities struggle with balancing development and resilience. Authors in [14] underscore the need to bridge the gap between scientific research and practical implementation to enhance climate adaptation in these areas. It is substantial to increase funding for small city resilience programs, enhance ecological infrastructure, and foster community involvement to strengthen adaptive capacity and ensure long-term sustainability.

C. *Challenges on Political and Policy Framework*

Political and policy frameworks for water resource management, particularly in urban areas, face complex and interconnected challenges. These challenges often stem from fragmented governance structures, inadequate regulatory frameworks, and weak policy integration. According to [15, 16], these factors significantly hinder effective water management. Additional concerns include limited stakeholder engagement, inadequate data and monitoring, risks of corruption, barriers to investment, and the inability to address climate change.

1) *Policy Fragmentation and Lack of Integration*

In many countries, water governance is characterized by disjointed policies and a lack of coordination among government agencies. This fragmentation leads to conflicting objectives and inefficient resource allocation. For example, in Pakistan, ineffective policy integration in water resource management has resulted in poor coordination among governmental departments. This lack of alignment prevents comprehensive water conservation efforts and fails to incorporate climate change considerations, leaving the country vulnerable to altered precipitation patterns and increased drought frequency. Moreover, inequitable water distribution favors urban areas, leading to social tensions in rural communities experiencing water shortages. Governments must improve inter-agency coordination and develop integrated policies that align environmental, agricultural, and urban planning objectives. Establishing a unified water management framework will ensure that different sectors work together to optimize resource use [4].

2) *Weak Political Will and Regulatory Enforcement*

A lack of political will significantly hampers effective governance and policy implementation in water management and environmental sustainability. Without strong political commitment, efforts to fund and enforce regulatory frameworks are often inadequate. Political inaction can stall critical reforms, weaken stakeholder engagement, and ultimately prevent meaningful progress in addressing resource scarcity and climate change. This reluctance to take decisive action leads to missed opportunities for holistic and integrated water management strategies, further exacerbating the existing issues [15]. Strengthening regulatory frameworks and increasing enforcement capacity through dedicated agencies and legal mechanisms is crucial. Public-private partnerships can also be encouraged to invest in sustainable water management initiatives, ensuring long-term financial and policy support [17, 18].

3) *The "Tragedy of the Commons"*

A major governance challenge in water management is the "tragedy of the commons", where unregulated competition for shared water resources leads to depletion, degradation, and long-term sustainability issues. This concept, highlighted in [19], is particularly evident in groundwater overuse, where excessive withdrawals by industries, agriculture, and households result in aquifer depletion and saline intrusion**.** In the Mediterranean region, including Libya, Israel, Tunisia, Algeria, and Egypt, the lack of enforceable regulations and coordinated management efforts has led to unregulated groundwater extraction, causing unsustainable withdrawal rates, declining water tables, and deteriorating water quality.

Without strict governance, individual users exploit shared water resources without considering the long-term consequences, thus, exacerbating water scarcity, fueling resource depletion, and creating conflicts between competing users, particularly in regions where water is already a limited and politically sensitive resource. Governments must establish sustainable withdrawal limits and introduce frameworks for water rights that prevent resource overuse. Community-based water conservation programs can also encourage responsible water use and prevent conflicts among competing users.

4) Data Deficiencies and Methodology Gaps

Effective water management requires reliable data and sound methodologies to support decision-making and policy formulation. In Sub-Saharan Africa, many policy documents lack a comprehensive methodological framework for assessing water issues. The absence of clarity in data sources and analysis methods reinforces preconceived notions, limits policy acceptance, and undermines consensus among stakeholders. Additionally, the scarcity of accurate data on water supply, quality, and sectoral demands hinders the development of informed policies. Without robust data-sharing mechanisms, decision-makers struggle to create effective, evidence-based water management strategies. It is crucial to develop a comprehensive data collection framework, enhance monitoring systems, and promote transparency to ensure accurate, reliable, and accessible water resource information for informed decision-making [20].

5) Misalignment with International Standards and Sustainable Practices

Some regions face challenges in aligning their water management policies with international best practices. In Kuwait, for instance, water governance is constrained by environmental bylaws that restrict the safe and effective reuse of treated wastewater, despite the standards set by global organizations, such as the World Health Organization (WHO) and the Environmental Protection Agency (EPA). Additionally, water policies in Kuwait have traditionally prioritized expansion over sustainability, focusing on increasing water supply infrastructure rather than conservation. Even though initiatives, like Kuwait Vision 2035, aim to improve access to drinking water and sanitation, unchecked expansion can lead to higher consumption rates and greater pressure on the already limited resources. This inadvertently reinforces the "tragedy of the commons", where increased water availability encourages higher usage rates without effective conservation policies. Without a balanced approach that integrates expansion with sustainability, Kuwait risks long-term water insecurity and inefficient resource management. To address these issues, it is essential to align national policies with international standards through regulatory reforms, implementing best practices in water conservation, wastewater treatment, and supply management to enhance sustainability and ensure compliance with the global guidelines [21].

6) The Need for Integrated and Context-Specific Water Management Approaches

Water resource management is inherently interdisciplinary, requiring policies that address environmental, agricultural, urban, and public health concerns simultaneously. Authors in [22] stress the importance of interdisciplinary governance approaches to develop comprehensive and sustainable water management strategies. Strong policy frameworks must encourage equitable responsibility among stakeholders while integrating climate resilience measures into water governance. Examples from West Africa, China, and Pakistan demonstrate the shared global challenges of rapid urbanization, groundwater depletion, pollution, and policy mismanagement. Without integrated and context-specific approaches, these challenges will continue to undermine long-term water security and sustainability. The consequences of unregulated water use, as seen in cases of over-extraction, pollution, and policy misalignment, emphasize the urgent need for improved governance, stronger regulations, and coordinated efforts among stakeholders. To address these challenges, it is essential to encourage interdisciplinary water governance, integrate urban planning with water management, and foster stakeholder collaboration.

Table I provides a structured summary of the key challenges affecting water resources in coastal urban environments, categorizing them under urbanization, environmental concerns, and governance-related issues. It highlights the significant impacts of these challenges, which threaten water availability, quality, and sustainability. Furthermore, mitigation strategies, which are crucial for ensuring sustainable and effective water resource management in vulnerable coastal regions, are emphasized.

Addressing these challenges requires robust, data-driven assessment techniques capable of understanding and predicting water resource dynamics under varying scenarios.

IV. ASSESSMENT TECHNIQUES OF WATER RESOURCES IN URBAN COASTAL AREAS

This section explores key methodologies, such as hydrological modeling, RS, GIS applications, and water quality assessments, which provide critical insights into managing water resources effectively. These tools not only help identify the root causes of water stress, but also support the development of sustainable strategies tailored to the unique needs of coastal urban areas.

A. Hydrologicl and Hydraulic Modeling Tools

Hydrologic and hydraulic models are essential tools for evaluating water resources in urban coastal areas, providing insights into streamflow, sediment transport, nutrient cycling, flood forecasting, and floodplain mapping. Three widely used models, namely SWAT, HEC-HMS, and Hydraulic Engineering Center-River Analysis System (HEC-RAS), offer distinct approaches to water resource assessments, each with its strengths being suited for different applications. SWAT excels at long-term watershed-scale modeling, HEC-HMS specializes in event-based flood forecasting and peak flow estimation, and HEC-RAS provides detailed hydraulic analyses and flood risk assessments, collectively forming a comprehensive toolkit for sustainable water resource management in urban coastal environments.

TABLE I. SUMMARY OF WATER RESOURCE CHALLENGES

Challenges	Impact	Mitigation strategies
Urbanization and population growth		
Groundwater depletion and water pollution	Excessive groundwater extraction leads to declining water quality and availability.	Implement groundwater recharge programs, regulate extraction, and enforce pollution controls.
Saline water intrusion	Over-extraction allows saltwater to infiltrate freshwater reserves, affecting drinking water and agriculture.	Adopt managed aquifer recharge, improve freshwater conservation, and regulate groundwater use.
Microplastic contamination	Industrial discharge and poor waste management contribute to rising microplastic pollution in coastal waters.	Enhance waste management, promote biodegradable materials, and implement strict regulations on industrial discharge.
Environmental challenges		
Prolonged droughts and groundwater depletion	Changing climate increases drought severity, reducing water supply and straining ecosystems.	Develop drought-resistant water management strategies, invest in water recycling, and improve forecasting.
Rising sea levels and coastal erosion	Higher sea levels lead to coastal erosion, infrastructure damage, and loss of land.	Implement coastal defenses, restore mangroves, and improve flood management infrastructure.
uncertainty in climate risk assessments	Uncertainty in climate models complicates flood and drought risk assessments, affecting preparedness.	Enhance climate modeling accuracy, integrate risk assessment tools, and develop flexible adaptation strategies.
Adaptation challenges in small coastal cities	Limited adaptive capacity in small coastal cities exacerbates vulnerability to climate change.	Increase funding for small city resilience programs, enhance ecological infrastructure, and foster community involvement.
Political and policy framework		
Policy fragmentation and lack of integration	Fragmented governance leads to inefficiencies, poor resource allocation, and ineffective policies.	Improve inter-agency coordination, develop integrated policies, and ensure holistic water governance.
Weak political will and regulatory enforcement	Lack of political commitment hinders the enforcement of regulations and water management initiatives.	Strengthen regulatory frameworks, increase enforcement capacity, and foster public-private partnerships.
The "tragedy of the commons"	Unregulated water use depletes resources and leads to conflicts among users.	Establish water use regulations, introduce sustainable withdrawal limits, and implement community-based water conservation programs.
Data deficiencies and methodological gaps	Lack of reliable data limits effective decision-making in water management.	Develop comprehensive data collection frameworks, enhance monitoring systems, and promote transparency.
Misalignment with international standards	Policies fail to align with global standards, leading to inefficient water governance.	Align national policies with international water management standards, promote best practices, and improve regulatory compliance.
Need for integrated water management approaches	Lack of cross-sectoral coordination hampers effective water resource management.	Encourage interdisciplinary water governance, integrate urban planning with water management, and foster stakeholder collaboration.

1) Soil and Water Assessment Tool

SWAT operates on a continuous, long-term basis, allowing for the simulation of hydrological processes across diverse landscapes by dividing a watershed into sub-basins and Hydrologic Response Units (HRUs). This semi-distributed approach enables the model to account for spatial variability in soil, land use, and topography, rendering it particularly effective in data-scarce regions. SWAT is employed to evaluate streamflow, sediment transport, and nutrient cycling, providing insights into water availability and quality. Its application has been instrumental in understanding the effects of climate change on hydrological regimes, as demonstrated in studies focused on mountainous and highland ecosystems [23].

SWAT is widely used in Mediterranean catchments to simulate the hydrological cycle, including surface and groundwater interactions, streamflow, and water quality dynamics. Besides assessing the impacts of land use changes and climate change on water resources, it is instrumental in evaluating the effectiveness of Best Management Practices (BMPs) for soil and water conservation. Various studies have modified SWAT to enhance its performance in specific hydrological contexts, such as karstic environments. Moreover, comparative analyses carried out between SWAT and other models have highlighted the former's strengths and limitations [24]. SWAT supports decision-making in water resource management and land use planning by identifying practices that enhance ecosystem services while minimizing negative environmental impacts. Its ability to simulate potential future scenarios makes it a valuable tool for developing adaptive management strategies to mitigate the effects of climate change. Overall, SWAT provides a comprehensive framework for understanding and managing the interconnectedness of water resources, land use, and ecosystem services in a sustainable manner [25]. Utilizing the SWAT method, successfully characterized streamflow regimes at ungauged locations in the Wailua watershed on Kauai Island. By employing high-resolution (250 m) gridded daily rainfall data, the model significantly improved the accuracy of flow statistics, enhancing the understanding of daily, seasonal, and annual surface water availability. This improved characterization was crucial for evaluating potential environmental flow scenarios, which are essential for maintaining ecological and cultural values in island communities. While the SWAT model effectively depicted saturation-excess runoff, it faced challenges, such as consistently under-predicting peak discharge during storm events and over-predicting the recession limb of the hydrograph. Despite these limitations, SWAT's potential as a valuable tool for sustainable water resource management is highlighted, particularly in regions with limited long-term hydrological data, thereby aiding informed decision-making in water resource planning [26].

In El Grou watershed, authors in [27] utilized the SWAT method, demonstrating the significant impact of climate change and land use changes on water resources. The SWAT model effectively simulated changes in hydrological components, such as precipitation patterns, evapotranspiration rates, and total water yield, under different climate scenarios. These findings stress the urgent need for sustainable water resource management strategies to mitigate the adverse effects of climate variability and ensure water security in the region, demonstrating the model's effectiveness in providing valuable insights for decision-making in semi-arid areas facing significant environmental challenges.

SWAT is also widely utilized in assessing non-point source pollution and water quality in both urban and rural areas. Developed by the USDA-Agricultural Research Service, SWAT integrates multiple modules for hydrology, erosion, and chemical transport, rendering it suitable for simulating complex hydrological processes at the basin scale. In China, SWAT has been employed to evaluate the impacts of land-use changes, such as the conversion of agricultural land to urban areas, on nutrient loads and to analyze the effectiveness of BMPs in mitigating pollution. Although SWAT is praised for its ability to simulate variable processes and assess the effects of land management practices, it faces limitations in urban settings, where it often lacks detail regarding urban drainage and treats built-up areas as a single land-use type [28].

In India, SWAT, particularly its modified version SWATrw, is utilized for effectively modeling hydrological interactions between groundwater and surface water especially in complex environments, like wetlands and coastal areas. The SWATrw model's bidirectional approach enhances the understanding of aquifer seepage and its impact on wetland hydrology, making it a valuable tool for water resource management. However, the need for extensive data collection and the adoption of advanced modeling techniques is also emphasized, to address the challenges posed by spatial and temporal complexities in groundwater-surface water interactions. By integrating modern methodologies and improving data acquisition, SWAT can significantly contribute to sustainable water management strategies in India, helping to mitigate the adverse effects of over-exploitation and environmental changes on water resources [29].

2) Hydrologic Engineering Center - Hydrologic Modeling System

HEC-HMS is a widely utilized tool in hydrological modeling techniques, designed to simulate the rainfall-runoff process in various catchment systems. Developed by the U.S. Army Corps of Engineers, HEC-HMS allows researchers and engineers to analyze and predict hydrological responses to rainfall events, making it essential for flood forecasting and water resource management. The model incorporates advanced numerical and physical options, enabling simulations that reflect both real data and ideal conditions. Its flexibility allows for the assessment of diverse hydrological scenarios, including flood risk analysis, reservoir operations, and watershed management. Calibration and validation processes, often involving statistical indices, such as RMSE, PBIAS, and MAE, ensure the model's accuracy in representing real-world conditions. The integration of HEC-HMS with meteorological models, such as Weather Research and Forecasting (WRF), enhances its predictive capabilities, rendering it a vital tool for effective flood risk management and decision-making in hydrology [30, 31].

3) Hydraulic Engineering Center - RiverAnalysis System

HEC-RAS is a widely implemented hydrodynamic modeling tool developed by the US Army Corps of Engineers, primarily employed for analyzing flood risk and hydraulic performance in waterways, including urban coastal areas. HEC-RAS simulates one-dimensional (1D) and two-dimensional (2D) steady and unsteady flow scenarios, enabling detailed floodplain delineation, water surface profiling, and hydraulic assessments [32].

In urban coastal regions, HEC-RAS effectively addresses challenges, such as urban flooding, storm surge impacts, tidal dynamics, and drainage efficiency. Its integration with GIS significantly enhances spatial visualization, identifying flood-prone zones and infrastructure vulnerabilities [33].

HEC-RAS also models sediment transport dynamics, helping manage sedimentation and erosion issues common in urban coastal settings. Practical applications, such as flood risk studies on Iraq’s Khassa Chai and Tigris Rivers, display its accuracy and utility in developing flood mitigation strategies and preparedness plans, especially valuable in areas with limited data and complex hydrological conditions [32, 34].

Even though HEC-RAS specializes in detailed hydraulic modeling and floodplain mapping, other tools, like SWAT and HEC-HMS, also play a crucial role in hydrological assessments. SWAT is highly effective for long-term watershed-scale modeling, capturing sediment transport, nutrient cycling, and land use changes, making it ideal for comprehensive environmental impact assessments. Conversely, HEC-HMS is tailored for short-term, event-based hydrological modeling, especially useful in flood forecasting and peak flow estimation. Integrating HEC-RAS with SWAT and HEC-HMS can yield a holistic view of hydrological processes. SWAT addresses broader watershed dynamics over extended periods, while HEC-HMS provides detailed insights into specific hydrological events and flood risk analyses. Combining these models leverages their unique strengths, enhancing overall water resource management capabilities.

Table II outlines the key differences between SWAT, HEC-HMS, and HEC-RAS ensuring a structured and concise presentation of their applications and capabilities.

B. Remote Sensing and Geographic Information System Technique

GIS and RS have revolutionized hydrological modeling, enabling the integration of spatial and temporal data for assessing hydrological components, such as precipitation, runoff, and groundwater recharge. GIS provides a robust platform for managing and visualizing large datasets, allowing for the creation of detailed hydrological models that incorporate factors, like land use, soil type, and topography. GIS plays a critical role in spatial analysis and decision-making, helping water managers identify vulnerable areas, optimize resource allocation, and support land-use planning [35-37].

TABLE II. COMPARISON OF SWAT, HEC-HMS, AND HEC-RAS

Feature/ aspect	**SWAT**	**HEC-HMS**	**HEC-RAS**
Purpose	Long-term watershed-scale hydrological modeling	Short-term event-based hydrological simulation	Hydraulic modeling and floodplain mapping
Applications	Water quality, sediment transport, land use changes	Flood forecasting, peak flow estimation, floodplain mapping	Flood risk analysis, hydraulic performance assessment
Time Scale	Daily to annual simulations	Sub-hourly to daily simulations	Event-based to long-term scenarios
Processes modeled	Hydrology, sediment transport, nutrient cycling, agricultural impacts	Rainfall-runoff, streamflow routing, reservoir operations	Hydrodynamics, sediment transport, water surface profiling
Best for	Large-scale watershed management and environmental assessments	Extreme hydrological event simulations and flood risk analysis	Detailed hydraulic analysis and floodplain delineation
Model type	Continuous, process-based	Event-based, conceptual	Steady and unsteady hydrodynamics
Data requirement	Extensive (land use, soil properties, climate, management practices)	Moderate (rainfall, streamflow, land use data)	Moderate to extensive (topography, hydrology, hydraulics)

Meanwhile, RS offers valuable information on surface conditions and changes over time, enhancing the understanding of hydrological processes. RS is particularly effective for large-scale assessments, providing real-time or periodic updates on surface water changes, land use alterations, and vegetation cover. The integration of RS and GIS improves the accuracy of hydrological predictions, supports effective water resource management, and aids in the identification of potential areas for groundwater recharge, ultimately contributing to sustainable water resource development and planning [38-40].

Mapping groundwater potential zones through RS and GIS involves analyzing various factors, such as land use, soil type, topography, and rainfall patterns to identify areas conducive to groundwater recharge. RS technologies provide critical data on land cover and surface conditions, while GIS facilitates the integration and spatial analysis of this information. By overlaying different datasets, researchers can create detailed maps that highlight regions with high recharge potential, which is essential for sustainable water resource management. Understanding these zones allows water managers to implement protective strategies, promote sustainable land use, and enhance groundwater recharge through artificial means, ultimately ensuring a reliable water supply for the future [41].

To illustrate the complementary roles of RS and GIS in water resource assessment, Table III presents a comparative analysis of their distinct contributions. Table III highlights how RS provides large-scale, real-time environmental data, while GIS integrates and analyzes spatial information, enhancing decision-making in hydrological modeling.

TABLE III. COMPLEMENTARY ROLES OF RS AND GIS IN WATER RESOURCE ASSESSMENT

Aspect	**RS**	**GIS**
Primary role	Captures large-scale environmental data	Manages, analyzes, and visualizes spatial data
Data source	Satellites, drones, aerial imagery	RS, field surveys, hydrological models
Key applications	Land use mapping, rainfall estimation, flood detection	Watershed modeling, risk assessment, spatial planning
Strengths	Real-time updates, wide coverage, cost-effective	Integrates multiple data sources, enables scenario analysis
Limitations	Affected by cloud cover, lower spatial resolution	Requires high-quality input data for accurate analysis
Contribution to hydrology	Monitors water bodies, detects changes in surface conditions	Supports decision-making through spatial analysis

The integration of RS and GIS in hydrological modeling techniques emphasizes their significant contribution to enhancing the accuracy and efficiency of water resource assessments. This integration allows for the creation of detailed thematic maps that inform decision-making processes related to water management [42-44].

The RS and GIS software are widely accessible, with various open-source and commercial platforms being available for hydrological applications. Open-source GIS tools, like QGIS and Google Earth Engine, provide cost-effective solutions for spatial analysis, while RS platforms, such as Sentinel Hub, offer free satellite imagery for environmental monitoring. Additionally, proprietary software, like ArcGIS and ENVI, provides advanced functionalities for high-resolution analysis. The availability of diverse tools enhances usability, making RS and GIS valuable resources for researchers, policymakers, and water managers. Furthermore, the cost-effectiveness and high-resolution capabilities of RS data enable researchers to conduct comprehensive analyses without the extensive financial burden associated with traditional field surveys. Ultimately, the application of RS and GIS in hydrological modeling not only improves the understanding of water dynamics, but also supports sustainable water resource management practices, making them invaluable tools in addressing contemporary water challenges [45, 46].

C. Water Quality Assessment Techniques

Water quality assessment is fundamental to hydrological modeling, providing essential data for managing water resources and ensuring ecosystem health. While traditional Water Quality Index (WQI) models offer a simplified water quality evaluation, their reliance on fixed parameter weightings limits their adaptability to dynamic environmental conditions. This limitation has driven the adoption of advanced techniques, such as Machine Learning (ML), Bayesian Model Averaging (BMA), and statistical modeling to enhance predictive accuracy and analytical robustness [47, 48]

1) Machine Learning-based Water Quality Assessment

ML has transformed water quality assessment by enabling data-driven, real-time monitoring and predictive modeling. Unlike traditional methods that rely on fixed parameter weightings, ML models analyze large datasets to identify patterns and forecast key water quality parameters, such as turbidity, pH, and Dissolved Oxygen (DO), with greater accuracy [49].

Ensemble learning models, like CatBoost, Random Forest, and Gradient Boosting Machines (GBM) enhance prediction accuracy by integrating multiple environmental variables, making them effective in dynamic and pollution-prone areas. To improve interpretability, SHapley Additive exPlanations (SHAP) help identify the key factors influencing water quality, aiding policymakers in targeting pollution sources [50]. Additionally, ML techniques handle missing data efficiently, ensuring reliable assessments even in regions with limited monitoring capacity [51].

2) *Statistical and Stochastic Modeling Approaches*

Statistical and stochastic modeling techniques play a crucial role in water quality assessment by incorporating uncertainties, variability, and probabilistic analysis to enhance predictive accuracy. In contrast to deterministic models, which rely on fixed input parameters, stochastic approaches account for fluctuations in environmental conditions, rendering them particularly useful for dynamic and complex water systems. These models help quantify the likelihood of pollution events, assess seasonal variations, and improve long-term water quality forecasting [49].

One widely used method is BMA, which combines multiple predictive models to reduce uncertainties and enhance the reliability of water quality forecasts. BMA assigns probabilistic weights to different models based on their performance, ensuring a more robust and data-driven prediction framework [49]. Another effective approach is time-series forecasting, particularly Seasonal Autoregressive Integrated Moving Average (SARIMA) models, which analyze historical trends and seasonal variations to predict future changes in water quality. These models have proven effective in detecting long-term pollution patterns and forecasting harmful algal blooms, which are critical for ecosystem management [51].

To address missing or incomplete water quality data, multiple imputation techniques and probabilistic algorithms are employed, ensuring that the model outputs remain consistent and reliable despite the data gaps. This capability is essential for maintaining the integrity of long-term monitoring programs, particularly in developing regions or remote areas where data collection may be inconsistent [51].

3) *Integrated Assessment Frameworks*

Integrated assessment frameworks combine multiple analytical approaches to provide a comprehensive and holistic evaluation of water quality dynamics. By merging ML, statistical modeling, and probabilistic analysis, these frameworks address the limitations of single-method approaches and enhance decision-making for sustainable water resource management. Such frameworks allow for a multi-dimensional understanding of water quality, considering environmental, hydrological, and anthropogenic factors to generate more accurate predictions and policy-relevant insights [52].

A key component of integrated assessment is the coupling of catchment and coastal water quality evaluations, which helps identify interactions between upstream pollution sources and downstream water bodies. This approach is particularly useful in urban and agricultural landscapes, where runoff, industrial discharge, and land-use changes significantly impact water quality. By linking hydrological and ecological models, researchers can develop more effective mitigation strategies for pollution control and resource conservation [53].

Another essential aspect is the multi-model approach, which incorporates ML, Bayesian analysis, and stochastic simulations to enhance forecasting capabilities. These methods provide data-driven insights into water quality trends, allowing policymakers to anticipate seasonal fluctuations, pollution hotspots, and long-term environmental changes. Additionally, integrating multiple techniques reduces uncertainties, leading to more reliable water management decisions [52, 53].

4) *Empirical and Case Study-based Approaches*

Empirical and case study-based approaches provide real-world validation of advanced water quality assessment techniques, demonstrating their effectiveness in diverse hydrological and environmental contexts. By applying ML models, statistical techniques, and integrated assessment frameworks to actual water bodies, these studies offer practical insights into pollution dynamics, seasonal variability, and the impact of anthropogenic activities on water quality. They also serve as benchmarks for developing scalable methodologies that can be applied in different regions [54].

a) *Groundwater Quality Assessments*

One notable study in the Morphou (Güzelyurt) region of Northern Cyprus assessed groundwater contamination, highlighting the impact of seasonal variations and agricultural runoff on water suitability. The findings revealed high levels of contamination and over-extraction, resulting in groundwater that failed to meet WHO water quality standards, emphasizing the necessity of integrated monitoring and management approaches [54]. Similarly, a groundwater evaluation in the Paliganj distributary of India demonstrated how seasonal fluctuations and human activities significantly alter water quality. By incorporating hydrological models with water quality assessments, researchers improved predictive capabilities for regional water management [55].

b) *Surface Water Quality Monitoring*

Surface water studies have also showcased the effectiveness of advanced modeling techniques. A study in Tubay River, Agusan del Norte, Philippines, successfully applied regression analysis with Landsat 8 satellite imagery, achieving strong correlations between RS-derived data and in-situ water quality measurements. This approach demonstrated the feasibility of large-scale, cost-effective water quality monitoring, particularly in developing regions with limited ground-based data collection [56]. A subsequent study in the same region developed a Geoinformatics-based framework, integrating RS, GIS, and ground-based data to enhance water quality assessments. This methodology provided accurate estimations of key parameters, such as pH and Biological Oxygen Demand (BOD), validated against Environment Management Bureau

(EMB) data, further underscoring the reliability of such integrated approaches [52].

c) Advanced Predictive Modeling for Water Quality

The use of statistical and ML models in case studies has also proven beneficial in predicting long-term water quality trends. Research utilizing SARIMA models and neural networks has demonstrated their ability to analyze complex, non-linear relationships in water quality data, particularly in turbid and shallow water environments. Additionally, the incorporation of multiple imputation techniques ensures robust model performance despite missing data, making these methodologies more applicable for large-scale water resource management [51].

To effectively assess water resources in urban coastal areas, a combination of hydrological and hydraulic modeling tools, RS and GIS techniques, and water quality assessment methodologies is essential. These approaches provide valuable insights into hydrological processes, spatial dynamics, and environmental impacts, facilitating informed decision-making for sustainable water management.

To ensure a comprehensive understanding of the various water resource assessment techniques, Table IV provides a structured comparison of key methodologies, highlighting their applications, strengths, limitations, and successful implementations. This summary serves as a valuable reference for selecting the most appropriate approach based on specific hydrological and environmental assessment needs.

TABLE IV. SUMMARY OF WATER RESOURCE ASSESSMENT TECHNIQUES

Technique	Key Function	Applications	Strengths	Limitations	Successful applications
Hydrologic and hydraulic modeling tools (SWAT, HEC-HMS, and HEC-RAS)	Watershed-scale hydrologic modeling, event-based hydrologic analysis, hydraulic modeling, and floodplain mapping.	Streamflow modeling, sediment transport, flood forecasting, flood risk assessment, hydraulic performance evaluation.	Comprehensive tools covering long-term watershed management (SWAT), short-term flood forecasting (HEC-HMS), and detailed hydraulic analyses (HEC-RAS).	SWAT less accurate for peak discharges; HEC-HMS requires careful calibration; HEC-RAS requires detailed topographical and hydrological data.	Applied successfully in Mediterranean catchments, South Korea watershed studies, and urban flood risk analyses of Khassa Chai and Tigris Rivers in Iraq.
RS and GIS	Integrated spatial analysis and satellite-based monitoring.	Groundwater recharge mapping, land-use change detection, flood risk assessment.	High-resolution spatial data, robust for visualizing large datasets.	RS is cloud-sensitive; GIS depends on data quality.	Applied in flood risk assessment in Jakarta, Indonesia; used for drought monitoring in Sub-Saharan Africa.
Water Quality Assessment	Evaluation of pollution impacts and water quality trends.	Aquatic ecosystem monitoring, pollution hotspot prediction, water quality forecasting.	Integrates statistical and ML approaches.	Data-intensive, requires advanced modeling techniques.	Applied in Shenzhen, China, to assess urban water quality and pollution control measures.

V. SUSTAINABILITY STRATEGIES FOR COASTAL WATER MANAGEMENT

Sustainability strategies for coastal water management emphasize the need for a robust sustainability approach that integrates constraint functions to prevent the depletion of natural capital in complex social-ecological systems. This approach is particularly relevant to Sustainable Development Goal (SDG) 14, which aims to conserve and sustainably use marine resources. However, achieving this goal presents challenges and trade-offs, particularly in implementing SDG 6, which focuses on water resource management, and SDG 13, which addresses climate resilience. The interconnected nature of these goals underscores the necessity for clear sustainable management practices that minimize adverse impacts on coastal ecosystems while balancing environmental protection with social and economic needs [57].

To address these challenges, a normative framework is proposed to guide sustainability strategies, aligning them with broader SDG objectives to ensure long-term conservation and responsible marine resource use. The ongoing SDG process offers an opportunity to enhance coastal management practices by providing a structured approach based on normative sustainability principles.

A. Integrated Water Resource Management

IWRM provides a comprehensive approach designed to restore coastal ecosystems and support sustainable development by efficiently managing water resources. This approach emphasizes inter-sectoral coordination, resource efficiency, and holistic environmental management. For example, its successful implementation in coastal cities in Brazil demonstrates how integrating multiple sectors ensures improved water resource sustainability and ecosystem health [17]. The encountered challenges and comparative analyses performed in Alexandria, Egypt, and Barcelona, Spain further highlight the universal relevance and adaptability of IWRM in urban coastal contexts [19].

B. Source-to-Sea Framework

The S2S framework enhances the coordination of land and marine governance systems by bridging institutional and policy gaps across freshwater and coastal domains. This comprehensive perspective is essential for overcoming inefficiencies arising when freshwater and marine resources are managed in silos [58, 59]. Case studies from the Stockholm Archipelago (Sweden) and Negombo Lagoon (Sri Lanka) emphasize how S2S can support ecosystem restoration and integrated management practices [17, 58]. Recent advancements propose the S2S Landscape approach, which broadens traditional S2S governance by explicitly incorporating terrestrial landscapes into integrated water and coastal management. Grounded in adaptive governance, system thinking, and active stakeholder participation, the S2S Landscape approach offers an inclusive framework to address complex socio-ecological challenges, enhancing resilience and sustainability across the entire freshwater-to-marine continuum [60].

C. Nature-based Solutions

NBS offer effective, low-impact alternatives for managing stormwater, reducing flood risk, and enhancing climate resilience. These solutions include wetlands, green roofs, permeable pavements, and mangrove restoration. Authors in [61, 62] demonstrate that such approaches align with SDGs 6, 11, 13, and 14, contributing to both biodiversity conservation and urban resilience. For instance, Miami Beach (USA) uses NBS in its climate-adaptive planning, while the East Kolkata Wetlands (India) and Jakarta (Indonesia) integrate green infrastructure to improve water quality and mitigate urban flooding [61, 63].

D. Community Involvement

Engaging local stakeholders is crucial to tailoring sustainability strategies to the unique socio-ecological contexts of coastal regions. Community involvement supports the development of responsive, ecosystem-specific management practices and enhances ownership and implementation. Case studies from small coastal cities in the USA, Australia, Bangladesh, and South Africa show how localized adaptation strengthens resilience. In Fortaleza, Brazil, stakeholder-driven coastal sustainability frameworks have yielded positive outcomes [14, 59].

E. Sustainable Urban Planning

Urban planning that incorporates ecological health, effective zoning, and green infrastructure investments is vital for resilient coastal areas. Sustainable urban design mitigates climate change effects, enhances stormwater management, and supports multifunctional green spaces. Authors in [63, 64] emphasize that urban planning strategies, such as retention ponds, green corridors, and eco-sensitive development, are essential in cities, like Colombo (Sri Lanka) and Da Nang (Vietnam). These strategies contribute to SDGs 11 and 13 by fostering livable and resilient urban environments.

F. Adaptive and Collaborative Management

Adaptive and collaborative management emphasizes flexibility, continuous learning, and inclusive governance. This strategy allows policies to evolve based on the changing environmental conditions and scientific insights. Collaborative mechanisms engage multiple stakeholders in co-developing context-sensitive solutions, enhancing long-term coastal resilience. Examples include IWRM efforts in Cape Town (South Africa) and Jakarta (Indonesia), and adaptive water governance in Amman (Jordan), where evolving water scarcity challenges have required dynamic policy adjustments [15, 16].

G. Shoreline Management Strategies

Shoreline management strategies typically fall into three categories, protect, accommodate, and retreat, based on local socio-economic and environmental conditions. This framework, as categorized in [65], is critical in assessing the most appropriate action for different coastal regions. In Ghana, the shoreline retreat strategy in Ada Foah provides a practical example of reducing coastal vulnerability through managed realignment and relocation.

H. Policy and Governance Reforms

Effective coastal water management relies heavily on robust governance frameworks. Policy and governance reforms are essential to create legally enforceable sustainability measures, promote transparency, and enhance institutional coordination. Regulatory training, digital monitoring tools, and interagency collaboration strengthen policy implementation. For instance, Venice, Italy has enforced strict water policies to protect coastal resources [22]. Moreover, incentives, such as tax benefits and subsidies for green infrastructure, promote stakeholder compliance and innovation in sustainable practices.

To further illustrate these strategies, Table V presents a comparative overview of various sustainability approaches in coastal water management, highlighting their intended outcomes and successful case studies.

VI. CONCLUSION, RESEARCH GAPS, AND RECOMMENDATIONS

Rapid urbanization and population growth significantly contribute to water-related challenges in coastal urban areas. Water scarcity remains a critical issue as demand often surpasses available resources, leading to the over-extraction of groundwater, which in turn causes saline water intrusion and contamination of freshwater aquifers. Additionally, unregulated urban sprawl and industrial pollution degrade water quality, while climate change exacerbates these challenges by intensifying storms, rising sea levels, and prolonging droughts. These factors threaten infrastructure, disrupt water security, and increase competition for limited resources. Furthermore, inequitable water distribution can lead to social tensions, particularly between urban and rural communities. Addressing these challenges requires an integrated and sustainable approach to water resource management that incorporates advanced assessment techniques, such as hydrological modeling, RS, and GIS. While these methods offer valuable insights into water dynamics, they also present several limitations and challenges that must be considered to ensure effective decision-making.

A. Technical Limitations of the Assessment Methods

Each assessment method has inherent constraints that can impact its accuracy and applicability. Hydrological models often rely on assumptions that may not fully capture the complex interactions between urban development, climate change, and water resources, potentially leading to inaccurate predictions. RS data may be compromised by atmospheric interference or gaps in coverage, affecting their reliability. GIS-based analyses, while useful for spatial planning, are highly dependent on the quality and resolution of input data, which can vary significantly across regions. These limitations stress the need to integrate multiple methods to enhance predictive accuracy and improve water resource assessments.

TABLE V. SUSTAINABILITY STRATEGIES FOR COASTAL WATER MANAGEMENT

Strategy	Description	Intended outcomes	Case studies of successful implementation
IWRM	Restores coastal ecosystem while promoting sustainable development	Enhances water resource efficiency and ecosystem health	• IWRM applications in coastal cities in Brazil [17] • Water resource sustainability challenges in Alexandria, Egypt, and Barcelona, Spain [19]
S2S framework	Addresses overlapping management systems from land to sea	Improves coordination of land and marine resource governance	• S2S governance case study in Stockholm Archipelago, Sweden [17] • Coastal ecosystem restoration in Negombo Lagoon, Sri Lanka [58]
NBS	Uses wetlands, retention ponds, and green infrastructure for stormwater management	Enhances climate adaptation, flood mitigation, and biodiversity	• Climate-adaptive coastal planning in Miami Beach, Florida, USA [61] • Wetlands-based urban resilience in East Kolkata Wetlands, India [62] • Green infrastructure implementation in Jakarta, Indonesia [63]
Community involvement	Engages local stakeholders to enhance ecosystem-specific management practices	Strengthens local participation and tailored solutions for ecosystems	• Small coastal cities adaptation in Miami Beach (USA), Mandurah (Australia), Sundarbans (Bangladesh), Knysna (South Africa) [14] • Coastal sustainability framework in Fortaleza, Brazil [59]
Sustainable urban planning	Integrates ecological health, zoning regulations, and infrastructure investments	Creates climate-resilient, environmentally sustainable urban areas	• Urban resilience strategies in Colombo, Sri Lanka [64] • Green city planning for flood resilience in Da Nang, Vietnam [12]
Adaptive and collaborative management	Ensures responsiveness to climate change uncertainties with multiple stakeholders	Enhances policy adaptability and stakeholder cooperation	• IWRM in Cape Town, South Africa and Jakarta, Indonesia [15] • Water policy challenges in Amman, Jordan [16]
Shoreline management strategies	Protects, or retreats based on local socio-economic and environmental conditions	Reduces coastal vulnerability and enhances resilience	• Shoreline retreat and management case study in Ada Foah, Ghana [65]
Policy and governance reforms	Enhances regulatory frameworks, transparency, and institutional cooperation in water management	Strengthens legal structures, enforcement, and governance capacity	• Water policy and governance assessment in Venice, Italy [22]

B. Data Quality and Availability Challenges

The effectiveness of water resource assessments is heavily dependent on the availability of reliable, high-resolution, and real-time data. However, many developing coastal cities lack the infrastructure and resources to maintain comprehensive water monitoring systems. Inconsistent data collection methods, limited access to hydrological information, and the absence of standardized protocols further hinder decision-making. To address these issues, there is a need for improved data collection strategies, increased investment in advanced RS technologies, and the establishment of open-access databases to support research and policy development. Additionally, real-time monitoring systems can significantly enhance data accuracy and responsiveness in water management.

C. Implementation Barriers

Even when assessment tools and data are available, translating scientific insights into actionable policies remains a challenge. Institutional fragmentation, bureaucratic inefficiencies, and political inertia often delay the adoption of integrated water management strategies. A critical limiting factor is the lack of financial resources, which restricts investments in sustainable infrastructure, innovative technologies, and long-term water security measures. Many developing coastal cities operate under tight fiscal constraints, leading to inadequate government budget allocations for water management programs. Additionally, securing external financing remains difficult due to administrative bottlenecks, creditworthiness concerns, and limited access to international grants or private-sector investments. Revenue-generation mechanisms, such as water tariffs, taxation, and user fees may not be optimized to support the maintenance and expansion of critical water infrastructure. Furthermore, budget fragmentation across multiple agencies and overlapping responsibilities often result in suboptimal investment decisions. Overcoming these financial barriers requires innovative funding approaches, strategic resource allocation, and multi-sector collaboration to ensure financial sustainability and maximize the long-term impact in water resource management.

D. Research Needs and Emerging Technologies

Further research is required to refine assessment techniques and develop context-specific models that are tailored to local environmental, social, and economic conditions. Advances in ML and Artificial Intelligence (AI) can enhance predictive modeling capabilities, reducing uncertainties and improving decision support. Additionally, the integration of blockchain technology can enhance transparency and accountability in water governance, ensuring fair and efficient resource allocation. Future studies should also explore the socio-economic impacts of water management policies to develop more equitable and sustainable solutions.

E. Key Recommendations

To address these gaps and challenges, the following priority actions are proposed:

1. Interdisciplinary Collaboration Enhancement: Involves fostering cooperation among hydrologists, ecologists, urban planners, and social scientists to develop holistic assessment frameworks that integrate environmental,

economic, and social dimensions of water resource management.

2. Data Collection and Accessibility Improvement: Entails standardizing hydrological data collection methods, investing in advanced RS and IoT-based monitoring systems, and establishing publicly accessible databases to ensure reliable and up-to-date information.
3. Development of Context-Specific and Adaptive Models: Involves hydrological model improvement by incorporating real-time data, ML, and AI-driven analysis to enhance predictive accuracy and applicability in diverse coastal environments.
4. Strengthening of Institutional Coordination and Policy Implementation: Enhancing coordination among government agencies, local water authorities, and private stakeholders is crucial for optimizing resource allocation and avoiding redundant expenditures. Establishing a "Centralized Water Management Fund" can streamline financial planning and ensure that investments are directed toward high-priority projects. Additionally, empowering local water governance bodies with direct budget oversight will improve efficiency by enabling targeted, community-driven investments. To enhance transparency, implementing annual public audits and real-time financial tracking can prevent mismanagement and ensure accountability in fund utilization. Strengthening institutional coordination will lead to more effective financial management, reducing inefficiencies and ensuring long-term sustainability in water resource initiatives.
5. Stakeholder Engagement Promotion: Entails active involvement of local communities, industries, and policymakers in water resource assessments and decision-making processes to align strategies with on-the-ground needs.
6. Continuous Monitoring and Adaptive Management Implementation: Encompasses the establishment of dynamic management frameworks that allow for real-time monitoring and responsive policy adjustments based on evolving hydrological and climatic conditions.
7. Leveraging of Emerging Technologies: Involves exploring the potential of AI, blockchain, and automated decision-support systems to improve data accuracy, enhance governance, and optimize water distribution in coastal urban areas.

By addressing these challenges through a combination of technological advancements, policy reforms, and stakeholder collaboration, water resource management in coastal urban environments can become more resilient, equitable, and sustainable. The integration of multiple assessment techniques will enhance decision-making, maximize their strengths, and mitigate individual limitations, leading to more effective long-term water management solutions. Moreover, strengthening governance structures, ensuring reliable data availability, and fostering community involvement are crucial steps toward achieving sustainable water resource management.

However, several open questions remain for future exploration:

- How can assessment methods be improved to adapt to climate change and urban expansion?
- What role can local communities play in supporting government water management policies?
- How can technologies, like AI, improve water management transparency and accuracy?
- What policies or incentives can encourage industries and developers to adopt sustainable water practices?
- How can successful water management strategies be adapted to different coastal cities with varying resources and challenges?

Addressing these questions will be essential in refining assessment methods, strengthening policy implementation, and ensuring that water management strategies remain adaptive and effective in the face of evolving environmental and socio-economic conditions. Moving forward, a proactive, data-driven, and inclusive approach will be key to securing sustainable water resources for coastal urban areas in the future.

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