smart cities

Article

Optimal Water Management Strategies: Paving the Way for Sustainability in Smart Cities

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Abstract: Global urbanization and increasing water demand make efficient water resource management crucial. This study employs Multi-Criteria Decision Making (MCDM) to evaluate smart city water management strategies. We use representative criteria, employ objective judgment, assign weights through the Analytic Hierarchy Process (AHP), and score strategies based on meeting these criteria. We find that the "Effectiveness and Risk Management" criterion carries the highest weight (15.28%), underscoring its pivotal role in strategy evaluation and robustness. Medium-weight criteria include "Resource Efficiency, Equity, and Social Considerations" (10.44%), "Integration with Existing Systems, Technological Feasibility, and Ease of Implementation" (10.10%), and "Environmental Impact" (9.84%) for ecological mitigation. "Community Engagement and Public Acceptance" (9.79%) recognizes involvement, while "Scalability and Adaptability" (9.35%) addresses changing conditions. "Return on Investment" (9.07%) and "Regulatory and Policy Alignment" (8.8%) balance financial and governance concerns. Two low-weight criteria, "Data Reliability" (8.78%) and "Long-Term Sustainability" (8.55%), stress data accuracy and sustainability. Highly weighted strategies like "Smart Metering and Monitoring, Demand Management, Behavior Change" and "Smart Irrigation Systems" are particularly effective in improving water management in smart cities. However, medium-weighted (e.g., "Educational Campaigns and Public Awareness", "Policy and Regulation", "Rainwater Harvesting", "Offshore Floating Photovoltaic Systems", "Collaboration and Partnerships", "Graywater Recycling and Reuse", and "Distributed Water Infrastructure") and low-weighted (e.g., "Water Desalination") strategies also contribute and can be combined with higher-ranked ones to create customized water management approaches for each smart city's unique context. This research is significant because it addresses urban water resource management complexity, offers a multi-criteria approach to enhance traditional single-focused methods, evaluates water strategies in smart cities comprehensively, and provides a criteria-weight-based resource allocation framework for sustainable decisions, boosting smart city resilience. Note that results may vary based on specific smart city needs and constraints. Future studies could explore factors like climate change on water management in smart cities and consider alternative MCDM methods like TOPSIS or ELECTRE for strategy evaluation.

Keywords: Analytic Hierarchy Process evaluation; Multi-Criteria Decision Making; smart cities resilience; water management strategies; water resource optimization

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Citation: Bouramdane, A.-A. Optimal Water Management Strategies: Paving the Way for Sustainability in Smart Cities. *Smart Cities* **2023**, *6*, 2849–2882. https://doi.org/10.3390/smartcities6050128

Academic Editors: Isam Shahrour and Aapo Huovila

Received: 28 August 2023
Revised: 18 September 2023
Accepted: 6 October 2023
Published: 18 October 2023

1. Introduction

1.1. Research Motivation

The burgeoning urbanization and escalating demand for water resources in contemporary cities have propelled the need for innovative and effective water management strategies [1,2].

Smart cities, driven by technological advancements and data-driven decision making [3], provide an opportune platform to tackle these challenges [4,5]. Within this context, the selection and prioritization of optimal water management strategies assume paramount importance. However, this complex decision-making process necessitates a comprehensive evaluation that considers a multitude of criteria to determine the most viable strategies for smart cities.

1.2. Existing Research and Knowledge Gap

Efficient and sustainable water management in urban areas, especially in the context of the fast-paced growth of smart cities, has been a subject of increasing research and attention [6]. Previous studies have highlighted the importance of implementing innovative strategies to address challenges related to water scarcity, pollution, and inefficient utilization [7]. Traditional approaches often focus on individual aspects of water management, neglecting the intricate connections between social, environmental, economic, and technological dimensions [8].

While existing research acknowledges the promise of smart city technologies, there is a notable gap in comprehensive evaluations that consider multiple criteria to rank and prioritize water management strategies tailored to smart city contexts. Some studies have investigated individual strategies, such as rainwater harvesting [9,10], desalination [11,12], and demand management [13], while others have focused on specific criteria like economic feasibility [14] or environmental impact [15]. However, limited research combines a diverse range of strategies and criteria in a systematic framework that caters to the complexities of smart cities' water management challenges.

1.3. Originality of This Study, Research Questions, and Methodology

This article addresses this critical gap in the literature by conducting a rigorous and holistic evaluation of ten distinct water management strategies ("Smart Metering and Monitoring, Demand Management, and Behavior Change", "Rainwater Harvesting", "Graywater Recycling and Reuse", "Distributed Water Infrastructure", "Smart Irrigation Systems", "Offshore Floating Photovoltaic Systems", "Water Desalination", "Policy and Regulation", "Educational Campaigns and Public Awareness", and "Collaboration and Partnerships") within the framework of smart cities. Our evaluation framework encompasses a diverse range of criteria ("Effectiveness and Risk Management", "Resource Efficiency, Equity, and Social Considerations", "Scalability and Adaptability", "Environmental Impact", "Integration with Existing Systems, Technological Feasibility, and Ease of Implementation", "Long-Term Sustainability", "Community Engagement and Public Acceptance", "Regulatory and Policy Alignment", "Return on Investment (ROI)", and "Data Reliability") that collectively influence the efficacy and feasibility of these strategies. Recognizing the complexity of such evaluations, we employ the Multi-Criteria Decision-Making (MCDM) technique, specifically the Analytic Hierarchy Process (AHP) [16,17], to assign relative weights to the criteria and rank the strategies accordingly.

Specifically, this article seeks to answer the following research question: "How can water management strategies in smart cities be systematically evaluated and prioritized based on a comprehensive set of criteria using the MCDM-AHP?

The integration of MCDM-AHP into the assessment process adds a layer of objectivity and rigor, enabling us to navigate the intricate interplay between diverse criteria and strategies (Figure 1). By utilizing AHP, we aim to derive an accurate representation of the strategies' strengths and weaknesses while considering various dimensions crucial to their success in smart city contexts.

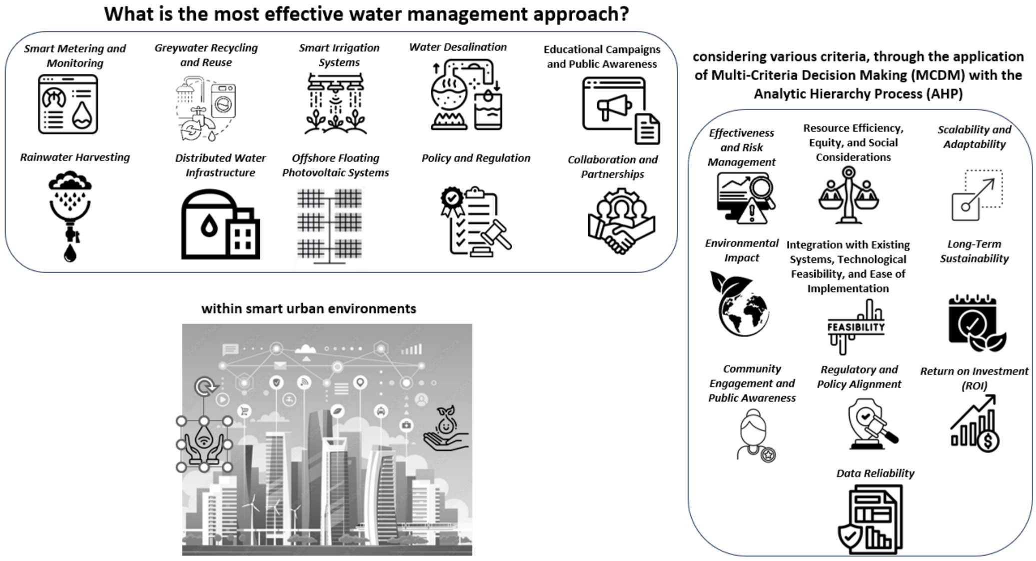

Figure 1. Illustration of the study's holistic framework: incorporating Multi-Criteria Decision Making (MCDM), particularly the Analytic Hierarchy Process (AHP), to assess optimal water management strategies in the context of smart cities, considering diverse criteria. Source: Own elaboration.

1.4. Practical Implications

This study is poised to make a significant contribution by not only presenting a comprehensive evaluation of water management strategies but also by offering actionable insights for urban planners, policymakers, and stakeholders. By leveraging the findings of this evaluation, decision-makers can make informed choices about water management strategies that align with their specific smart city goals and constraints. Ultimately, the synthesis of rigorous evaluation and intelligent decision making has the potential to drive sustainable and resilient water management practices, ensuring the prosperity of smart cities in an era of growing urbanization and resource constraints [18,19].

1.5. Outline

This article begins with an introduction (Section 1) that outlines the research motivation (Section 1.1), addressing the pressing need for efficient water management in the context of urbanization and smart cities. The existing research landscape is discussed, revealing a gap in comprehensive evaluations that combine multiple criteria to rank water management strategies tailored to smart city contexts (Section 1.2). Emphasizing the study's originality and contribution, the introduction introduces the research questions and outlines the methodology involving the Multi-Criteria Decision-Making (MCDM) technique of the Analytic Hierarchy Process (AHP) (Section 1.3). The introduction concludes by highlighting the practical implications of the study's findings for urban planners, policymakers, and the broader advancement of smart city development (Section 1.4).

Following the introduction, Section 2 delves into a comprehensive overview of smart cities.

Subsequently, Section 3 presents the theoretical framework of MCDM-AHP, elucidating the methodology that will be employed to assess and prioritize the identified strategies (Section 3.3) based on the established criteria (Section 3.2). This section provides a foundational understanding of the context within which the study operates.

Moving to Section 4, the article transitions to the presentation of results. This section entails the construction of pairwise comparison matrices between the criteria (Section 4.1), the derivation of relative weights for each criterion (Section 4.2), and the calculation of weighted sums associated with each water management strategy (Section 4.3). These quantitative outcomes offer a structured basis for strategy evaluation.

Section 5 engages in an in-depth discussion of the advantages and challenges linked to each water management strategy. This section integrates the quantitative results with qualitative insights, providing a comprehensive understanding of the implications and nuances associated with each strategy's adoption in smart cities.

The article culminates with Section 6, the conclusion. This section synthesizes the findings from the previous sections, reaffirms the study's contribution to the field and limitations, and addresses the research questions posed at the outset. It also underscores the broader implications of the study's outcomes for the advancement of smart city water management strategies and the sustainable development of urban environments.

2. Exploring Smart Cities: Harnessing Technology for Urban Evolution

In recent years, the concept of smart cities has gained significant traction as a promising avenue for addressing the challenges of rapid urbanization, resource scarcity, and environmental sustainability. At the heart of this concept lies the integration of cutting-edge technologies, particularly Information and Communication Technology (ICT) and the Internet of Things (IoT), to revolutionize urban infrastructure, governance, and quality of life [5,6]. This holistic approach touches upon various facets of urban living, from transportation and energy to healthcare and governance [4] (Figure 2). Below, we delve into key aspects of smart cities, showcasing their potential and impact.

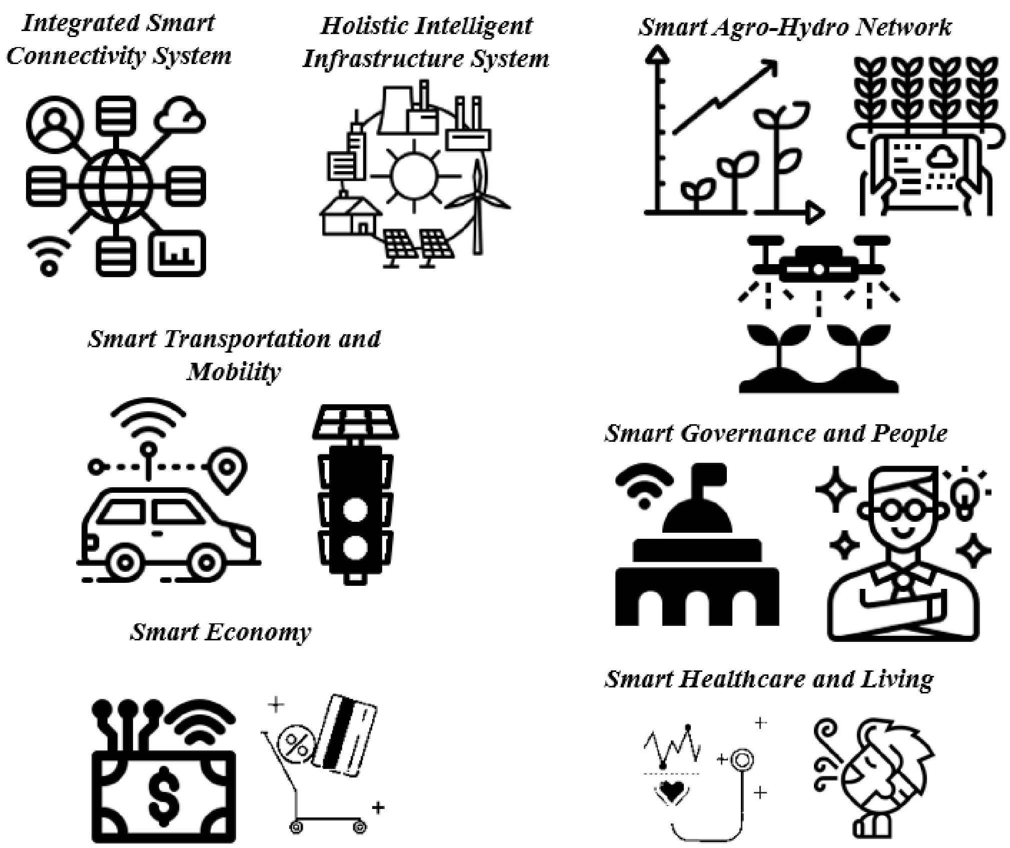

Figure 2. The different components of a smart city are interconnected and work together to improve the efficiency and sustainability of the city. For example, smart transportation systems can use data from sensors to optimize traffic flow and reduce emissions. Smart energy systems can use renewable energy sources and energy-efficient technologies to reduce the city's reliance on fossil fuels. Smart agro-hydro networks use data and technology to improve water efficiency, reduce leaks, monitor water quality, and improve food production, distribution, and safety. Smart buildings can use sensors to monitor energy usage and optimize comfort levels. And smart governance systems can use data to improve public services and make better decisions. Source: Author's own elaboration.

- **Information and Communication Technology (ICT) in the Smart City**: At the core of smart cities is a robust ICT framework that acts as the nervous system of the urban landscape. Advanced data networks, high-speed internet, and cloud computing enable seamless communication between devices, systems, and citizens. This interconnectivity forms the backbone for real-time data collection, analysis, and decision-making processes that optimize urban functions [20,21].
- **Internet of Things (IoT) for Smart Cities**: The IoT, a network of interconnected devices embedded with sensors and software, empowers smart cities by facilitating data-driven insights and automation. From smart traffic lights that adjust timings based on real-time traffic flow to waste bins that signal when they need emptying, IoT drives efficiency and resource optimization [22,23].
- **Smart Sensing**: Smart sensing involves deploying various sensors across the urban landscape to monitor environmental conditions, energy consumption, and other parameters. These sensors provide invaluable data to city planners, helping them make informed decisions about resource allocation and infrastructure development [24,25].
- **Smart Grids and Smart Infrastructures**: Smart grids leverage digital technology to optimize electricity distribution, manage demand, and integrate renewable energy sources. This results in a more reliable energy supply, reduced waste, and improved sustainability [26,27]. Similarly, smart infrastructures encompass intelligent designs that improve the efficiency of buildings, roads, and utilities, enhancing overall urban functionality [28,29].
- **Smart Transportation and Mobility**: Smart transportation systems utilize data and technology to enhance mobility, reduce congestion, and minimize environmental impact. This includes intelligent traffic management, electric vehicle charging networks, and even autonomous vehicles that promise safer and more efficient transportation [30,31].
- **Smart Energy**: Efficient energy use is a hallmark of smart cities [32,33]. Through real-time data analysis and monitoring, cities can identify patterns of energy consumption and implement strategies to reduce waste and reliance on fossil fuels [34].
- **Smart Water**: Amid the array of smart city components, water management strategies emerge as a pivotal aspect. Harnessing technology to optimize water usage, prevent wastage, and ensure equitable distribution forms a cornerstone of smart city sustainability [15,35].
- **Smart Buildings**: Smart buildings employ automation and data-driven systems to optimize energy consumption, security, and occupant comfort. From adaptive lighting to climate control systems, these structures contribute to resource conservation and improved quality of life [36,37].
- **Smart Food and Agriculture**: In the face of growing urban populations, smart cities explore innovative solutions for food production and distribution [38,39]. Vertical farming, urban agriculture, and intelligent supply chain management ensure a sustainable and resilient food ecosystem [40,41].
- **Smart Governance**: Smart governance involves leveraging technology to enhance citizen engagement, streamline administrative processes, and foster transparency. E-governance platforms, digital service delivery, and data-driven decision making contribute to more responsive and efficient city management [42,43].
- **Smart People**: The residents of a smart city play a pivotal role. Educated about sustainable practices and equipped with digital tools, citizens can actively contribute to resource conservation, waste reduction, and community well-being [44,45].
- **Smart Economy**: Technology-driven innovation and entrepreneurship thrive in smart cities. By fostering an environment conducive to start-ups and tech industries, these cities generate economic growth while addressing urban challenges [46,47].
- **Smart Healthcare**: Health services benefit from technology through telemedicine, wearable health monitoring devices, and predictive analytics that aid in disease outbreak detection and prevention [48,49].

- **Smart Living**: The culmination of these efforts is an enhanced quality of life for residents. Reduced congestion, cleaner air, efficient services, and improved access to resources contribute to a more comfortable and sustainable urban lifestyle [50,51].

In essence, smart cities are poised to reshape the urban landscape by infusing it with technology, connectivity, and data-driven insights. By addressing challenges through a multidimensional approach, these cities offer a glimpse into a future where urbanization and sustainability coexist harmoniously.

3. Methodology

The evaluation of water management strategies within the context of smart cities involves a complex decision-making process. To facilitate a structured approach to this assessment, we have employed the Multi-Criteria Decision Making (MCDM) with Analytic Hierarchy Process (AHP) approach. Appendix A outlines the theoretical framework of the MCDM-AHP.

3.1. Hierarchical Structure of the Decision-Making Framework

Figure 3 illustrates the hierarchical structure of our decision-making framework, emphasizing the organization of key elements.

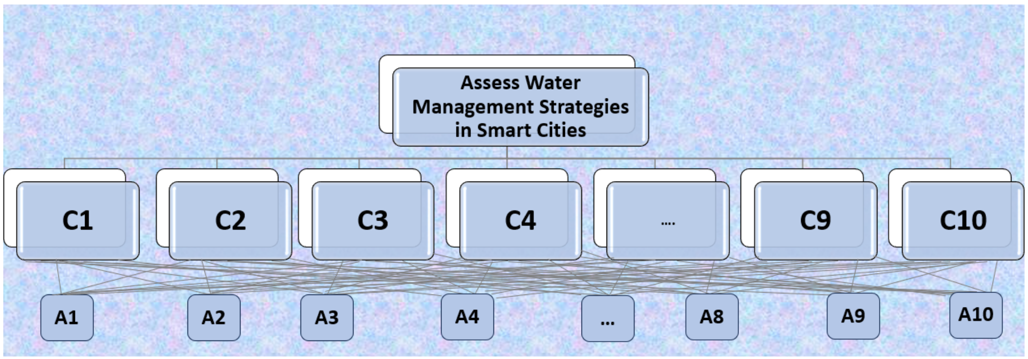

Figure 3. Hierarchical structure of water management strategy evaluation in smart cities using Multi-Criteria Decision Making—Analytic Hierarchy Process (MCDM-AHP), with the overarching goal situated at the top level. Criteria (C) (Section 3.2) are positioned in the middle level followed by the specific alternatives (A) (Section 3.3) at the bottom level. Source: Own elaboration, following a well-established and recognized hierarchy structure [16,17].

At the highest level of the hierarchy, we have the overarching goal of our study, which is to assess water management strategies in the context of smart cities. This goal serves as the ultimate objective that we aim to achieve through our evaluation.

In the second level of the hierarchy, we have identified a set of criteria (Section 3.2) that are integral to our decision-making process. These criteria encapsulate the diverse aspects and dimensions that are critical in the evaluation of water management strategies. The criteria encompass considerations such as effectiveness and risk management (C1), resource efficiency, equity, and social considerations (C2), scalability and adaptability (C3), environmental impact (C4), integration with existing systems, technological feasibility, and ease of implementation (C5), long-term sustainability (C6), community engagement and public acceptance (C7), regulatory and policy alignment (C8), return on investment (C9), and data reliability.

Finally, at the bottom level of the hierarchy, we have identified a range of water management strategies (Section 3.3) as our alternatives for evaluation. These alternatives encompass a broad spectrum of approaches, including Smart Metering and Monitoring, Demand Management, and Behavior Change (A1); Rainwater Harvesting (A2); Graywater Recycling and Reuse (A3); Distributed Water Infrastructure (A4); Smart Irrigation Systems (A5); Offshore Floating Photovoltaic Systems (A6); Water Desalination (A7); Policy and

Regulation (A8); Educational Campaigns and Public Awareness (A9); and Collaboration and Partnerships (A10).

This hierarchical structure is a well-known approach to decision making, which enables us to systematically assess and prioritize the water management strategies based on the defined criteria.

3.2. Key Criteria for Evaluating Water Management Strategies in Smart Cities

When evaluating water management strategies in smart cities, it is important to consider a range of criteria to ensure that the chosen strategies are effective, sustainable, and aligned with the city's goals and needs [52]. Some common criteria to consider when evaluating water management strategies in smart cities are:

1. **(C1) Effectiveness and Risk Management**: How well does the strategy achieve its intended goals, such as water conservation, improved water quality, or increased water availability [53,54]? Does the strategy address potential risks and vulnerabilities, such as water scarcity [1], extreme weather events [55–57], or technological failures [58]?
2. **(C2) Resource Efficiency, Equity, and Social Considerations**: Does the strategy make efficient use of water resources, energy, and other inputs? Does it provide a positive cost–benefit ratio? Does the strategy ensure equitable access to water resources across different socioeconomic groups? Does it consider social and cultural factors [53,59,60]?
3. **(C3) Scalability and Adaptability**: Can the strategy be scaled up or expanded to meet the needs of a growing population or changing urban landscape? Can the strategy be adjusted or modified as conditions change or new technologies emerge [61,62]?
4. **(C4) Environmental Impact**: What are the environmental consequences of implementing the strategy? Does it minimize negative impacts on ecosystems and natural resources [63]?
5. **(C5) Integration with Existing Systems, Technological Feasibility, and Ease of Implementation**: Can the strategy be integrated with the city's existing water supply and distribution infrastructure without major disruptions? How complex is the implementation process? Are there potential barriers or challenges that need to be addressed [64–66]?
6. **(C6) Long-Term Sustainability**: Will the strategy maintain its effectiveness and benefits over the long term [67]? Is it resilient to changing conditions and future challenges [68,69] (SMRY [70])?
7. **(C7) Community Engagement and Public Acceptance**: How well does the strategy involve and engage the community in water conservation efforts? Is there public support and participation? Is the strategy likely to be accepted and embraced by residents, businesses, and other stakeholders [71,72]?
8. **(C8) Regulatory and Policy Alignment**: Is the strategy in alignment with local regulations, policies, and sustainability goals [73]?
9. **(C9) Return on Investment (ROI)**: What is the expected return on investment in terms of water savings, reduced costs, and other benefits [74]?
10. **(C10) Data Reliability**: Is the strategy based on accurate and reliable data, especially if it involves data-driven decision making [75]?

By evaluating water management strategies against these common criteria, smart cities can make well-informed decisions that lead to sustainable, efficient, and resilient water management practices [76,77].

3.3. Alternatives: Water Management Strategies in Smart Cities

Water management is a critical aspect of creating sustainable and efficient smart cities. Smart cities use technology and data-driven approaches to enhance the management of water resources, reduce waste, and ensure equitable distribution [78,79]. Some water management strategies commonly implemented in smart cities include the following:

1. **(A1) Smart Metering and Monitoring, Demand Management, and Behavior Change**: Integrating smart water meters offers real-time consumption data for tracking patterns, identifying leaks, and maintaining systems. Smart sensors monitor water quality, reservoir levels, and infrastructure conditions, with advanced networks detecting anomalies and alerting maintenance teams. Early warning systems predict flooding or contamination [80,81]. Additionally, smart cities foster water conservation through real-time consumption information, empowering individuals to make conscious usage decisions. Data analytics and predictive modeling anticipate demand, optimize resources, and enhance infrastructure planning for reduced demand and balanced supply [13].
2. **(A2) Rainwater Harvesting**: Collecting rainwater from rooftops and paved surfaces and storing it for later use can help replenish groundwater levels and provide an additional source of water for non-potable purposes such as irrigation, flushing toilets, and washing [9,10].
3. **(A3) Graywater Recycling and Reuse**: Implementing systems to treat and recycle wastewater (e.g., from sinks and showers) for non-potable uses like irrigation, industrial processes, and toilet flushing can significantly reduce the demand for fresh water. This also minimizes pollution of natural water bodies and reduces the load on the sewage system [82,83].
4. **(A4) Distributed Water Infrastructure**: Implementing decentralized water treatment and distribution systems reduces energy and water loss associated with centralized systems [84].
5. **(A5) Smart Irrigation Systems**: Automated irrigation systems that use weather forecasts and soil moisture data can optimize irrigation schedules, reducing water consumption in urban landscaping [85,86].
6. **(A6) Offshore Floating Photovoltaic (OFPV) Systems**: OFPV systems consist of solar panels installed on floating platforms, typically in bodies of water. These platforms can be anchored or moored, and they have the advantage of utilizing underutilized water surfaces for solar energy generation. Offshore FPV systems offer several benefits: First, water bodies provide a cooling effect, which can enhance the efficiency of solar panels and increase their energy output. Second, by using water surfaces, offshore FPV systems free up land for other uses, such as agriculture or urban development. Third, offshore installations can help avoid conflicts over land use, which can be a challenge in densely populated areas. Fourth, the presence of solar panels on the water surface can reduce evaporation rates and enhance water quality through shading, potentially preserving water resources [2,87].
7. **(A7) Water Desalination**: Water desalination is the process of removing salt and other impurities from seawater or brackish water to make it suitable for human consumption, agriculture, and industrial use. There are different desalination technologies available, including reverse osmosis (RO) and multi-stage flash (MSF) distillation. Desalination requires a significant amount of energy, making it a suitable candidate for integration with renewable energy sources like OFPV [11,12].
8. **(A8) Policy and Regulation**: Implementing regulations that promote sustainable water management practices, such as water-use quotas and pricing structures, incentives for water-efficient technologies, and penalties for wasteful practices, can drive positive change [88,89].
9. **(A9) Educational Campaigns and Public Awareness**: Conducting campaigns and educational programs (i.e., workshops, seminars, and online resources) for residents, businesses, and students to raise awareness about water scarcity [1], conservation practices, and the impact of individual behaviors can foster a culture of responsible water usage within the community. Public awareness focuses on changing behavior through education, while other strategies involve implementing technology and infrastructure changes [90,91].

10. **(A10) Collaboration and Partnerships**: Smart cities often collaborate with academic institutions, technology companies, non-governmental organizations, and water utilities to leverage expertise, resources, and funding for effective water management solutions [92,93].

These strategies, when combined and tailored to the specific needs of a city, can contribute to improved water management in smart cities, fostering sustainability, resilience, and quality of life for residents.

3.4. Clarifying Dependencies between Criteria, Alternatives, and Criteria–Alternatives Interaction

In our comprehensive evaluation of water management strategies using the MCDM-AHP methodology (Appendix A), it is imperative to acknowledge the intricate web of dependencies that exist between the criteria, alternatives, and their interactions. These dependencies play a pivotal role in shaping our decision-making process.

- **Inter-Criteria Dependencies:** Within the criteria layer (Level 2 of our hierarchy, Figure 3), there exist relationships among the individual criteria (C1–C10). For example, effectiveness and risk management (C1) may influence long-term sustainability (C6), as a strategy's effectiveness in managing risks could determine its long-term viability. Similarly, the resource efficiency, equity, and social consideration (C2) criterion may interact with community engagement and public acceptance (C7), as social equity considerations can impact how a strategy is received by the community. Certain factors within our hierarchy exert dominance over others due to their significant influence on the decision-making process. These factors have a more substantial impact on the overall assessment of water management strategies (Section 4.2).
- **Alternative Interactions:** The water management strategy alternatives (A1–A10, at Level 3 of our hierarchy, Figure 3) do not exist in isolation. Instead, they interact with one another, sometimes complementing or conflicting with each other. For instance, the implementation of distributed water infrastructure (A4) could impact the feasibility and effectiveness of smart metering and monitoring (A1), as both strategies may involve the use of advanced technology and infrastructure within a city.
- **Criteria–Alternative Interplay:** Each criterion in Level 2 of our hierarchy, Figure 3, interacts with every alternative in Level 3, as the evaluation process involves assessing how well each strategy meets the specified criteria. These interactions are dynamic and can be highly context-dependent. For instance, the criteria related to environmental impact (C4) can influence the evaluation of individual water management strategies (A1–A10). Water desalination (A7), for example, may be more suitable in areas with limited freshwater resources, but its environmental impact must be weighed against its benefits. These dependencies are crucial to understanding the broader implications of each criterion for our decision-making process. In addition, policy and regulation alignment (C8) plays a role in evaluating the feasibility and compliance of all water management strategies (A1–A10) with the existing regulatory framework.

The hierarchy itself (Figure 3) implies dependencies. For instance, the overarching goal of assessing water management strategies in smart cities (Level 1) fundamentally guides the selection and prioritization of criteria (Level 2) and alternatives (Level 3), setting the context for the entire evaluation process.

Understanding these intricate dependencies is crucial for a holistic evaluation of water management strategies. It ensures that the evaluation process considers not only the individual merits of strategies but also how they align with the broader objectives and constraints defined by the criteria and the overarching goal. Our MCDM-AHP model accounts for these dependencies, enabling a nuanced and contextually rich assessment of the alternatives in the context of smart city water management.

3.5. Demonstration of the MCDM-AHP Model in Practice

In this section, we provide a practical demonstration of how the Multi-Criteria Decision Making with Analytic Hierarchy Process (MCDM-AHP) (Appendix A) model operates in the evaluation of water management strategies within smart cities.

3.5.1. Data Collection and Assessment

To begin, we gathered data and input from relevant stakeholders, experts, and decision-makers involved in the smart city water management domain. Through workshops found in the existing literature [94], we collected their preferences and judgments regarding the importance of each criterion (C1–C10).

While the workshops found in the literature provided valuable insights, they often offered broad findings that did not directly align with the specific criteria and alternatives requiring evaluation in our study. To address this limitation, we purposefully conducted our own objective judgment process. This involved a meticulous and structured consideration of the criteria, alternatives, and their relationships, drawing upon both logical reasoning and the extensive knowledge base available in the literature. Our objective judgment process was meticulously designed to ensure that assessments of criteria and alternatives adhered to a clear and consistent logic rooted in the domain knowledge found in the literature. We applied established principles, best practices, and empirical evidence from the smart city water management field to inform our assessments. This approach allowed us to tailor the judgments to the unique context of our study, ensuring their direct relevance to the criteria and alternatives under evaluation. Ultimately, our objective judgment approach played a pivotal role in bridging the gap between the general findings of existing workshops in the literature and the specific requirements of our study. It facilitated the creation of a comprehensive and contextually relevant decision-making framework that not only synthesized diverse viewpoints but also remained firmly grounded in the logical and knowledge-driven principles of the field.

The selection of criteria (C1–C10) (Section 3.2) and water management strategies (A1–A10) (Section 3.3) was driven by a comprehensive review of the existing literature [79], consultations with experts in the field [94], and an analysis of the specific challenges and goals of smart city water management [52]. We aimed to include criteria that cover a wide range of dimensions critical to the evaluation, such as environmental impact, social considerations, feasibility, and effectiveness. The chosen alternatives encompassed a diverse set of water management approaches to ensure a holistic evaluation of options commonly encountered in real-world scenarios.

3.5.2. Data Processing and Analysis

Next, the collected data underwent a pairwise comparison process to derive the importance of criteria relative to one another and the performance of alternatives against each criterion. The Saaty scale (Table 1), a widely accepted method for AHP [16,17], was used to convert qualitative expert judgments into numerical values. Eigenvalue calculations determined the consistency of expert judgments. If necessary, adjustments were made to ensure the reliability of the decision-making model (Figure 4) (Section 4.1).

Criteria and alternative weights were aggregated to establish the overall preference scores for each water management strategy, considering all criteria and their associated weights. With the aggregated scores, we ranked the water management strategies in order of preference, revealing which strategies best align with the objectives of our study, as represented by the overarching goal and criteria (Sections 4.2 and 4.3).

Table 1. Saaty scale for pairwise comparisons. Experts or decision-makers use these values to make pairwise comparisons between criteria or alternatives. For example, if criterion A is considered to be moderately more important than criterion B, a value of 3 might be assigned. If criterion A is considered much more important than criterion B, a value of 5 would be appropriate. The Saaty scale ensures a structured and consistent way of capturing relative importance or preference in AHP [16,95].

Value	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Absolute importance (extremely dominant)
2, 4, 6, 8	Intermediate values (when compromise is needed)

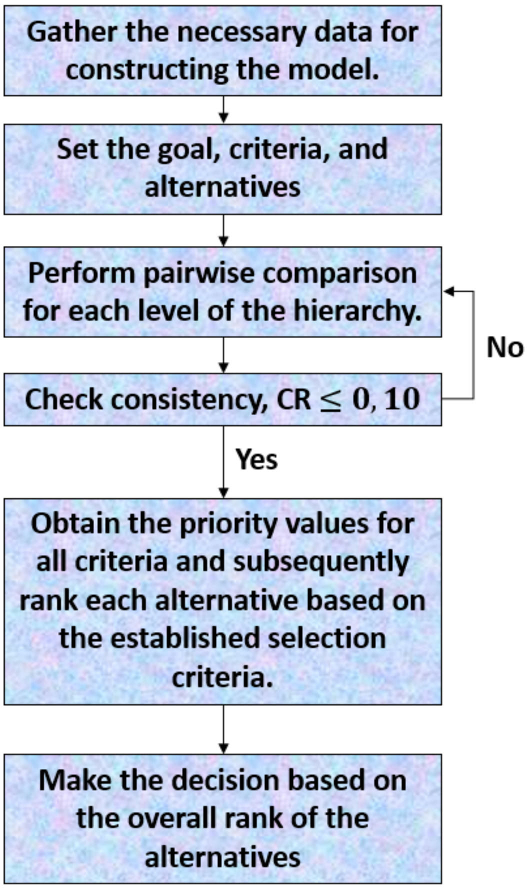

Figure 4. Analytic Hierarchy Process (AHP) algorithm. Source: Own elaboration.

3.5.3. Rationale for Method Selection

The choice of the MCDM-AHP methodology for our analysis was rooted in its ability to handle complex, multidimensional decision-making problems effectively. AHP is well-suited for situations where criteria are interrelated, dependencies exist between criteria and alternatives, and subjective expert judgment is essential [16,95]. Its transparency and robustness make it an ideal choice for our study.

In fact, the MCDM-AHP approach was deemed the best solution for our analysis due to its ability to achieve the following:

- **Systematically Address Multiple Criteria**: AHP provides a structured framework to consider a wide array of criteria, ensuring a comprehensive evaluation of water management strategies.

- **Capture Expert Knowledge**: By involving domain experts and decision-makers, we harnessed their expertise to inform the decision-making process and ensure real-world relevance.
- **Quantify Subjective Judgments**: AHP's pairwise comparison method allowed us to convert qualitative expert judgments into quantifiable data, enhancing the rigor and objectivity of our analysis.
- **Handle Complex Dependencies**: AHP accommodates the intricate dependencies between criteria, alternatives, and their interactions, aligning with the complexity of our evaluation problem.

4. Results

Within this section, we conduct an exhaustive analysis of water management strategies (Section 3.3) within the context of smart cities (Section 2). A thorough evaluation of these strategies is conducted based on a predefined set of criteria (Section 3.2). To facilitate this evaluative process, we construct a pairwise comparison matrix (refer to Table 2), enabling us to ascertain the relative significance of each criterion concerning others (as exemplified in Figure 5). Leveraging these established relative weights, we subsequently calculate cumulative weighted scores for each water management approach (refer to Figure 6). This computational approach yields a holistic score that comprehensively reflects the pivotal role of each criterion within the overarching assessment.

Table 2. Pairwise comparison matrix for criteria evaluation (Section 3.2) when assessing strategies (Section 3.3) for water management in smart cities. Employing a rating scale of 1 to 9, our approach signifies the relative importance of criteria, with 1 denoting equal significance and 9 indicating notably greater importance. Refer to Appendix A for comprehensive details.

Criteria	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
C1	1	3	5	3	4	5	3	4	3	4
C2	$\frac{1}{3}$	1	3	2	3	4	2	3	2	3
C3	$\frac{1}{5}$	$\frac{1}{3}$	1	$\frac{1}{3}$	2	3	$\frac{1}{3}$	$\frac{2}{3}$	$\frac{1}{2}$	2
C4	$\frac{1}{3}$	$\frac{1}{2}$	3	1	3	4	2	3	2	3
C5	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	1	2	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	2
C6	$\frac{1}{5}$	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{2}$	1	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{3}$	1
C7	$\frac{1}{3}$	$\frac{1}{2}$	3	$\frac{1}{2}$	3	4	1	3	2	3
C8	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{3}{2}$	$\frac{1}{3}$	2	3	$\frac{1}{3}$	1	$\frac{1}{2}$	2
C9	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{2}$	2	3	$\frac{1}{2}$	2	1	2
C10	$\frac{1}{4}$	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{2}$	1	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	1

4.1. Conducting Pairwise Comparison Matrix for Criteria Assessment

The pairwise comparison matrix (Table 2) is a crucial component of the Analytic Hierarchy Process (AHP) methodology (Appendix A, (A1)) used to quantify the relative importance of criteria when assessing water management strategies for smart cities. The matrix employs a rating scale from 1 to 9, where 1 signifies equal significance and 9 indicates notably greater importance. In this section, we provide an interpretation of this matrix, illustrating how the values can be obtained based on logical comparisons.

- **C1 (Effectiveness and Risk Management) vs. Other Criteria**: The value 3 in the cell (C1, C2) indicates that according to the judgment of experts or decision-makers, criterion C1 is considered three times more important than criterion C2 in the context of evaluating water management strategies. Similarly, the values in other cells in the same row (C1) reflect the relative importance of C1 compared to each of the other criteria (C3, C4, C5, etc.).

- **C2 (Resource Efficiency, Equity, and Social Consideration) vs. Other Criteria**: The value 1/3 in the cell (C2, C1) suggests that criterion C2 is considered one-third as important as criterion C1. This reflects the judgment that C1 holds higher significance than C2 in the assessment process. Similarly, the values in the row for C2 indicate its relative importance compared to the other criteria.
- **Reciprocal Relationships**: The matrix follows the principle of reciprocity, ensuring that if criterion A is considered x times more important than criterion B, then criterion B is seen as 1/x times as important as criterion A. For example, if C1 is three times more important than C2 (C1/C2 = 3), then C2 is considered one-third as important as C1 (C2/C1 = 1/3). This principle is maintained throughout the matrix.
- **Other Criteria Interactions**: The values in the matrix reflect the logical comparisons between each pair of criteria. For instance, the value 5 in the cell (C1, C3) suggests that criterion C1 is considered five times more important than criterion C3. The use of fractions like 1/5 or 2/3 indicates the relative strength of importance based on expert judgment.
- **Diagonal Elements**: The diagonal elements of the matrix have a fixed value of 1 since each criterion is equally important to itself (C1 compared to C1, C2 compared to C2, and so on).
- **Consistency Check**: After the matrix is completed, consistency checks can be performed to ensure that the judgments provided by experts are coherent and do not contain contradictions. These checks help ensure the reliability of the matrix and, subsequently, the calculated criteria weights. We find that the largest eigenvalue is approximately 6.02, CI = 0.558. The RI for a 10 × 10 matrix is approximately 1.58. The CR is 0.353. Since the calculated CR value (0.353) is less than 0.1, the consistency of the pairwise comparison matrix is considered acceptable.

In summary, the pairwise comparison matrix captures expert judgments regarding the relative importance of criteria in the evaluation of water management strategies for smart cities. These judgments are based on logical comparisons and are later used in the AHP methodology to calculate criteria weights (Section 4.2), which play a crucial role in prioritizing and assessing the strategies in a structured and objective manner (Section 4.3).

4.2. Assessment of Criteria Weights for Smart City Water Management Strategies

Figure 5 presents the relative weights assigned to different criteria used for evaluating water management strategies in smart cities. These weights indicate the proportional significance attributed to each criterion when assessing the effectiveness and overall viability of potential water management choices. The criteria are ranked based on their importance in shaping the success of the strategies.

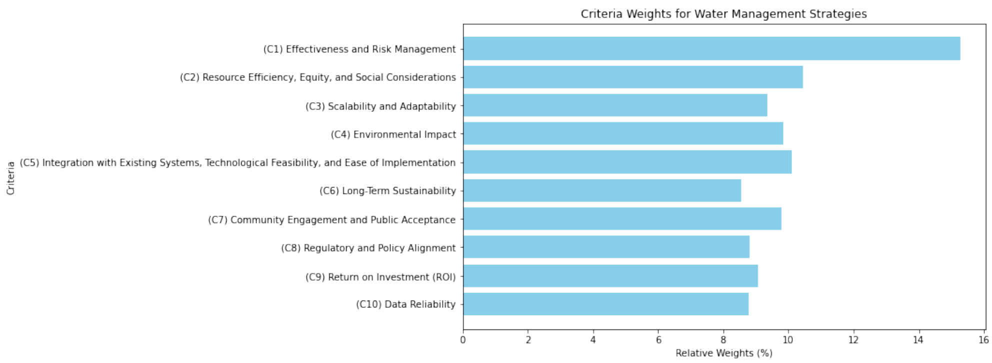

Figure 5. Criteria weights indicate the proportional significance attributed to individual criteria during the assessment of water management strategies in smart cities. These weights offer transparency regarding the varying importance of each criterion in shaping the overall efficacy of the potential choices. Source: Own elaboration.

4.2.1. High Relative Weights

Effectiveness and Risk Management (C1)—15.28%: This criterion holds the highest weight, indicating that the ability of a water management strategy to effectively manage risks and ensure its overall success is of primary importance.

4.2.2. Medium Relative Weights

- **Resource Efficiency, Equity, and Social Considerations (C2)—10.44%**: This criterion considers how efficiently the strategy utilizes resources, promotes equitable distribution of benefits, and addresses social concerns. Its medium weight reflects its significant role in evaluating strategies but is not as critical as effectiveness and risk management.
- **Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)—10.10%**: The moderate weight assigned to this criterion indicates that integrating with existing systems, technological feasibility, and ease of implementation are important but not the sole determinants of a strategy's success.
- **Environmental Impact (C4)—9.84%**: This criterion evaluates the environmental consequences of the strategy. Its medium weight signifies its relevance in the evaluation process, balancing environmental concerns with other considerations.
- **Community Engagement and Public Acceptance (C7)—9.79%**: The moderate weight assigned to this criterion suggests that involving the community and ensuring public acceptance are important, but they are not weighted as heavily as other factors.
- **Scalability and Adaptability (C3)—9.35%**: The ability of a strategy to scale up or adapt to changing conditions is moderately important. This weight suggests that while scalability and adaptability are vital, they are not the most crucial factors.
- **Return on Investment (ROI) (C9)—9.07%**: While the return on investment is considered, the lower weight indicates that financial gains are important but not the primary focus in evaluating water management strategies.
- **Regulatory and Policy Alignment (C8)—8.8%**: The weight placed on this criterion reflects its significance in ensuring that strategies align with regulations and policies, although it is not the most critical consideration.

4.2.3. Low Relative Weights

- **Data Reliability (C10)—8.78%**: This criterion has the lowest weight, suggesting that while data reliability is a consideration, it is not as critical as other factors in assessing the viability of strategies.
- **Long-Term Sustainability (C6)—8.55%**: While long-term sustainability is crucial for the success of smart city water management, the slightly lower weight suggests that it is considered moderately important compared to other criteria.

In summary, the criteria with higher weights (C1, C2, C3, C4, C5, C7, C8, and C9) collectively represent the core dimensions that influence the assessment of water management strategies, ranging from effectiveness and sustainability to societal acceptance and regulatory compliance. While the criteria with lower weights (C6, C10) are still significant, they might have a comparatively smaller impact on the overall evaluation process.

4.3. Evaluation of Smart City Water Management Strategies Based on Multiple Criteria

Figure 6 presents a list of different water management strategies for evaluating smart cities along with their corresponding overall weighted sums. The strategies are ranked based on these weighted sums, with higher values indicating enhanced overall performance.

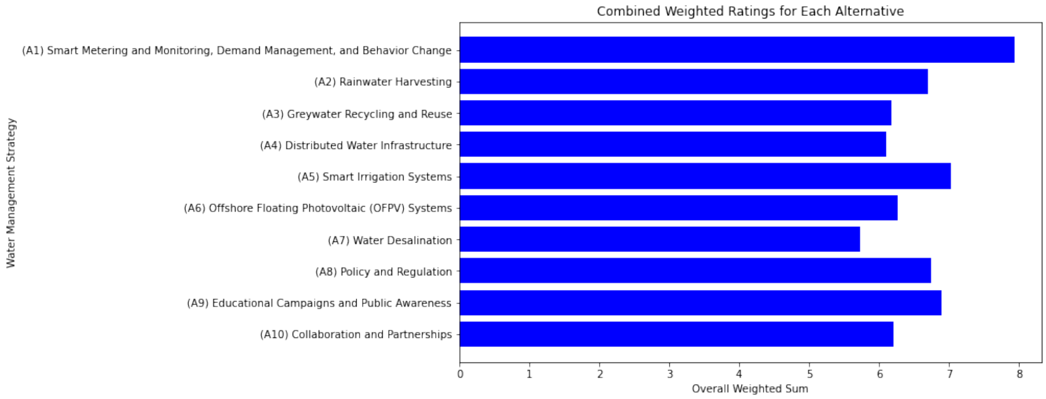

Figure 6. Combined weighted ratings for each alternative. Higher weighted sums indicate enhanced overall performance. Source: Own elaboration.

4.3.1. High Weighted Sum

Strategies with high relative weights (above 7) are considered to be particularly effective and important for enhancing water management in smart cities. These strategies should likely receive significant focus and allocation of resources due to their potential to achieve substantial improvements.

- **Smart Metering and Monitoring, Demand Management, and Behavior Change (A1)**: This strategy has the highest overall weighted sum of 7.9281, suggesting that it is considered the most effective strategy among the alternatives. This strategy likely involves using advanced technologies to monitor water consumption, manage demand through incentives or pricing mechanisms, and promote behavior change among residents and businesses to conserve water.
- **Smart Irrigation Systems (A5)**: This strategy, with a score of 7.0204, likely involves using technology to optimize irrigation practices, minimizing water waste in landscaping and agriculture.

4.3.2. Medium Weighted Sum

Strategies with medium relative weights (between 6 and 7) are still valuable and effective but might have certain limitations or dependencies that prevent them from being ranked as the highest. These strategies should be carefully considered and implemented alongside other strategies for a well-rounded water management approach.

- **Educational Campaigns and Public Awareness (A9)**: With a score of 6.8861, this strategy focuses on educating the public and raising awareness about water conservation and sustainable practices.
- **Policy and Regulation (A8)**: This strategy, with a score of 6.7465, emphasizes the importance of well-defined policies and regulations to govern water management practices effectively.
- **Rainwater Harvesting (A2)**: With an overall weighted sum of 6.6989, this strategy ranks second. Rainwater harvesting involves collecting and storing rainwater for various uses, which can help reduce demand on traditional water sources.
- **Offshore Floating Photovoltaic (OFPV) Systems (A6)**: This strategy, with a score of 6.2709, suggests using floating solar panels over bodies of water to generate renewable energy while reducing water evaporation.
- **Collaboration and Partnerships (A10)**: This strategy, with a score of 6.2122, highlights the significance of collaborative efforts between stakeholders, such as governments, industries, and communities
- **Graywater Recycling and Reuse (A3)**: This strategy focuses on recycling and reusing graywater (wastewater from sources like sinks and showers) for non-potable purposes. It has an overall weighted sum of 6.1812.

- **Distributed Water Infrastructure (A4)**: With a score of 6.0939, this strategy involves decentralizing water infrastructure, potentially reducing distribution losses and increasing efficiency.

4.3.3. Low Weighted Sum

Strategies with low relative weights (below 6) might have areas for improvement or face challenges in terms of feasibility, cost-effectiveness, or impact. While these strategies could still contribute to overall water management, they might require further refinement or integration with other strategies to maximize their benefits.

Water Desalination (A7)—With an overall weighted sum of 5.7211, this strategy involves the desalination of seawater or brackish water to augment water supplies in areas with water scarcity.

It is important to keep in mind that the interpretation of the relative weights may depend on the specific criteria and methodology used to evaluate these strategies, and additional context about the evaluation process would provide a more comprehensive understanding.

5. Discussion

Efficient water management is crucial for sustainable development in smart cities. Different strategies have been proposed to address water challenges, each with its own set of advantages and disadvantages. In this section, we will evaluate these strategies based on various criteria that encompass their effectiveness, feasibility, and impact.

5.1. Evaluation Criteria

The criteria outlined below shed light on the diverse aspects that influence the success of these strategies.

1. **Effectiveness and Risk Management (C1)**:
    - *Effectiveness*: This criterion assesses how well a water management strategy can address water-related challenges, such as scarcity, contamination risks, and supply–demand imbalances [2,87]. Effective strategies provide a foundation for secure water supplies and reduced risks. However, it is crucial to note that the effectiveness of a strategy may vary depending on the specific context in which it is applied [53].
    - *Risk Management*: Evaluating risk management involves considering how well a strategy can mitigate and manage risks associated with water management. Effective strategies should not only address current risks but also be adaptable to evolving challenges [54].
2. **Resource Efficiency, Equity, and Social Considerations (C2)**:
    - *Resource Efficiency*: This criterion measures how efficiently a strategy uses available water resources. Strategies that optimize resource use contribute to sustainable water management [53,59]. However, it is important to ensure that resource efficiency does not come at the expense of other factors, such as equity.
    - *Equity*: Equity focuses on the fair distribution of water resources among all residents regardless of social or economic status. Strategies that address equity concerns help ensure that vulnerable or marginalized communities have access to clean water [59].
    - *Social Considerations*: In addition to equity, this criterion assesses how a strategy takes into account social factors and the well-being of the community. Strategies should consider the social impact of water management decisions and aim to improve the overall quality of life [60].
3. **Scalability and Adaptability (C3)**:
    - *Scalability*: Scalability evaluates a strategy's capacity to accommodate increasing urban populations and changing water demands. Strategies that can expand or

contract in response to population growth or fluctuations are better equipped to meet the evolving needs of smart cities [61].

- *Adaptability*: Adaptability assesses how well a strategy can respond to changing circumstances, including shifts in climate, technology, or urban development. Strategies that can adjust and evolve are more likely to remain effective over time [62].

4. **Environmental Impact (C4)**: This criterion measures the effect of a water management strategy on the natural environment. Low-impact strategies contribute to environmental sustainability by minimizing harm to ecosystems, reducing energy consumption, and conserving water resources. On the other hand, strategies relying heavily on energy or resources may have unintended negative environmental consequences, underscoring the importance of balancing environmental concerns in smart cities [63].
5. **Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)**:
   - *Integration with Existing Systems*: Strategies that seamlessly integrate with the existing water infrastructure in a city are more likely to be adopted. Compatibility with established systems reduces disruptions and costs associated with implementation [64].
   - *Technological Feasibility*: This criterion assesses whether the technology required for a strategy is readily available and can be effectively implemented in the smart city context. Strategies that align with technological capabilities are more likely to succeed [65].
   - *Ease of Implementation*: The ease with which a strategy can be put into practice is a crucial factor in its success. Strategies that are straightforward to implement and do not require extensive infrastructure changes are more likely to gain acceptance [66].
6. **Long-Term Sustainability (C6)**: This criterion evaluates how well a water management strategy can ensure the continued availability and quality of water resources for future generations. Sustainable strategies consider the long-term impact of their actions and prioritize environmental and societal well-being [67].
7. **Community Engagement and Public Acceptance (C7)**:
   - *Community Engagement*: Strategies that actively involve the community and stakeholders in decision-making processes are more likely to gain support and be effectively implemented. Engaging the public fosters a sense of ownership and responsibility [72].
   - *Public Acceptance*: Public support and acceptance are critical for the success of any water management strategy. Strategies that resonate with local residents and address their concerns are more likely to be embraced [71].
8. **Regulatory and Policy Alignment (C8)**: This criterion assesses how well a strategy aligns with existing laws and regulations. Strategies that are in sync with governing frameworks are more likely to receive support, resources, and legal clearance for implementation [73].
9. **Return on Investment (ROI) (C9)**: ROI evaluates the financial viability of a water management strategy. Strategies that offer favorable ROI prospects can attract private investors and policymakers. However, high upfront costs associated with some strategies may act as barriers, especially if the benefits take time to materialize [74].
10. **Data Reliability (C10)**: For data-driven strategies, the reliability of information is crucial. Accurate and dependable data aid decision making and enhance the effectiveness of strategies. However, strategies relying on data may suffer from inaccuracies or insufficient data availability, potentially hampering their performance [75].

By examining water management strategies within this comprehensive framework of evaluation criteria, smart cities can make informed decisions that promote sustainable, efficient, and equitable water management practices for the benefit of their residents and the environment.

5.2. Strategies Evaluation

In this section, we will evaluate specific water management strategies within the framework of the criteria outlined above.

1. **Smart Metering and Monitoring, Demand Management, and Behavior Change (A1) [13,80,81]**
    (a) *Effectiveness and Risk Management (C1)*: These strategies excel in effectiveness by enabling real-time monitoring and data-driven decision making. This minimizes water waste, addresses supply–demand imbalances, and mitigates risks associated with water scarcity or contamination. However, initial implementation costs and the necessity for widespread behavior change may pose challenges.
    (b) *Resource Efficiency, Equity, and Social Considerations (C2)*: They contribute to resource efficiency by optimizing water distribution. However, ensuring equity and social considerations can be challenging, as certain demographics may struggle with technology adoption, potentially exacerbating social disparities.
    (c) *Scalability and Adaptability (C3)*: These strategies are scalable and adaptable, but their scalability might be limited by the availability of infrastructure and the willingness of residents to embrace behavioral changes.
    (d) *Environmental Impact (C4)*: Generally, they have a low environmental impact, focusing on reducing water waste. However, the production and disposal of smart metering equipment may have environmental consequences.
    (e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: They seamlessly integrate with existing water systems and are technologically feasible. However, changing resident behavior can be challenging, and the initial investment in equipment and infrastructure can be significant.
    (f) *Long-Term Sustainability (C6)*: These strategies contribute to long-term sustainability by reducing water consumption. However, maintaining behavior change over the long term and ensuring the longevity of technology infrastructure can be complex.
    (g) *Community Engagement and Public Acceptance (C7)*: Success here depends on educating and engaging the community. Public acceptance may be challenging due to concerns about data privacy and technology adoption.
    (h) *Regulatory and Policy Alignment (C8)*: Regulatory alignment is generally good, but data privacy regulations must be considered. Policies may need to evolve to fully support these strategies.
    (i) *Return on Investment (ROI) (C9)*: While the long-term ROI is positive, high initial costs may deter some municipalities or residents from adoption.
    (j) *Data Reliability (C10)*: Data reliability is high, given the use of advanced monitoring technology. However, data security and privacy must be carefully managed.
2. **Rainwater Harvesting (A2) [9,10]**
    (a) *Effectiveness and Risk Management (C1)*: Effective in harnessing rainwater as a local water source, reducing reliance on external supplies. However, effectiveness depends on local rainfall patterns, posing potential risks during dry periods [9,10].
    (b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Promotes resource efficiency and equity by reducing pressure on centralized water systems. However, adoption may vary based on property ownership, potentially leading to inequities.

(c) *Scalability and Adaptability (C3)*: Scalability may be limited by available space and infrastructure. Adaptability is high, especially in areas with frequent rainfall.
(d) *Environmental Impact (C4)*: Generally, low environmental impact is preferable, as it reduces the energy required for water distribution. However, proper management is needed to prevent contamination and ecosystem disruption.
(e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integrates well with existing systems but may require modifications to infrastructure. Technologically feasible but may require a learning curve for residents. Implementation can be straightforward for new constructions.
(f) *Long-Term Sustainability (C6)*: Contributes to long-term sustainability by reducing dependence on external water sources. However, maintenance and proper management are crucial to ensure system longevity.
(g) *Community Engagement and Public Acceptance (C7)*: Success depends on educating residents about the benefits of rainwater harvesting. Public acceptance is generally positive but can vary by region.
(h) *Regulatory and Policy Alignment (C8)*: Regulatory alignment varies by region. Policies supporting rainwater harvesting may need to be developed or modified.
(i) *Return on Investment (ROI) (C9)*: Positive ROI over the long term, but high initial costs can be a barrier.
(j) *Data Reliability (C10)*: Data reliability is less relevant for rainwater harvesting compared to technology-dependent strategies.

3. **Graywater Recycling and Reuse (A3) [82,83]**

(a) *Effectiveness and Risk Management (C1)*: Effective in reducing the strain on freshwater resources by recycling graywater. However, it may not fully address water scarcity risks in arid regions [82,83].
(b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Highly resource-efficient and promotes equity in water distribution. However, technological feasibility challenges and public acceptance may limit adoption.
(c) *Scalability and Adaptability (C3)*: Scalable, but adaptation may require modifications to plumbing systems. Effective in adapting to changing water demands.
(d) *Environmental Impact (C4)*: Generally low environmental impact, as it reduces the energy required for water treatment. However, improper treatment can lead to contamination concerns.
(e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integration may require plumbing changes, and technological feasibility depends on local infrastructure. Implementation can be straightforward for new constructions.
(f) *Long-Term Sustainability (C6)*: Contributes to long-term sustainability by reducing freshwater consumption. Proper maintenance is key to ensuring sustainability.
(g) *Community Engagement and Public Acceptance (C7)*: Success depends on educating and gaining acceptance from residents. Concerns about water quality may need to be addressed.
(h) *Regulatory and Policy Alignment (C8)*: Regulatory alignment varies, and policies may need to evolve to support graywater recycling.
(i) *Return on Investment (ROI) (C9)*: Positive ROI over the long term, but initial costs can be a barrier.
(j) *Data Reliability (C10)*: Data reliability is less relevant for graywater recycling compared to technology-dependent strategies.

4. **Distributed Water Infrastructure (A4) [84]**

(a) *Effectiveness and Risk Management (C1)*: Effective in ensuring water supply resilience and minimizing distribution losses. However, risks may arise if regulatory and policy alignment issues hinder decentralized systems [84].

(b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Promotes resource efficiency and equitable access to water. However, challenges in regulatory alignment and ensuring universal access may affect equity.
(c) *Scalability and Adaptability (C3)*: Highly scalable and adaptable, catering to urban growth effectively. Integration with existing systems may require planning and investment.
(d) *Environmental Impact (C4)*: Generally low environmental impact due to reduced energy usage for distribution. However, decentralized systems must be well-maintained to prevent environmental risks.
(e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integrates well with existing systems but may require infrastructure upgrades. The ease of implementation depends on local circumstances.
(f) *Long-Term Sustainability (C6)*: Contributes to long-term sustainability by reducing water distribution losses. Effective maintenance is crucial for sustainability.
(g) *Community Engagement and Public Acceptance (C7)*: Success depends on community involvement and acceptance. Public support may vary depending on local preferences.
(h) *Regulatory and Policy Alignment (C8)*: Alignment with regulations and policies is vital for successful implementation. Challenges may arise if existing policies favor centralized systems.
(i) *Return on Investment (ROI) (C9)*: Positive ROI, particularly in regions with high water distribution losses. However, initial investments may be substantial.
(j) *Data Reliability (C10)*: Data reliability is relevant for monitoring and optimizing decentralized systems.

5. **Smart Irrigation Systems (A5) [85,86]**

(a) *Effectiveness and Risk Management (C1)*: Effective in optimizing irrigation practices, conserving water, and reducing risks associated with over-irrigation. Technical complexities and initial investment costs may pose challenges [85,86].
(b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Promotes resource efficiency but may require technical expertise for installation and maintenance, potentially leading to inequities.
(c) *Scalability and Adaptability (C3)*: Scalability and adaptability may be constrained by technical complexities, particularly in small-scale agriculture.
(d) *Environmental Impact (C4)*: Reduces water waste and energy use, contributing to environmental sustainability. However, the production and disposal of high-tech irrigation equipment may have environmental implications.
(e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integration with existing irrigation systems may require upgrades. The ease of implementation depends on the complexity of the system.
(f) *Long-Term Sustainability (C6)*: Contributes to long-term sustainability by conserving water resources. Proper maintenance is essential for system longevity.
(g) *Community Engagement and Public Acceptance (C7)*: Success depends on educating users and gaining acceptance for advanced irrigation practices. Adoption may vary by region.
(h) *Regulatory and Policy Alignment (C8)*: Alignment with water-use regulations is crucial. Policies may need to incentivize the adoption of smart irrigation systems.
(i) *Return on Investment (ROI) (C9)*: Positive ROI over time, but high upfront costs may deter some users.
(j) *Data Reliability (C10)*: Data reliability is crucial for optimizing irrigation practices, making it a relevant consideration.

6. **Offshore Floating Photovoltaic (OFPV) Systems (A6) [2,87]**

(a) *Effectiveness and Risk Management (C1)*: Effective in generating renewable energy and reducing water evaporation in reservoirs. However, effectiveness may be compromised if not properly maintained or if installation disrupts aquatic ecosystems [2,87].

(b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Aligns with resource efficiency by generating clean energy. Equity is less relevant, given its large-scale nature.

(c) *Scalability and Adaptability (C3)*: Scalable but may face challenges in adapting to diverse aquatic environments.

(d) *Environmental Impact (C4)*: Reduces water evaporation and generates clean energy, contributing to environmental sustainability. However, potential ecological impacts must be carefully managed.

(e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Requires specialized infrastructure in aquatic environments. Technological feasibility depends on site-specific conditions. Implementation may be complex.

(f) *Long-Term Sustainability (C6)*: Sustainability depends on proper maintenance and ecological monitoring. Effective maintenance is crucial for system longevity.

(g) *Community Engagement and Public Acceptance (C7)*: Success depends on local acceptance and support for renewable energy initiatives. Ecological concerns may arise.

(h) *Regulatory and Policy Alignment (C8)*: Regulatory alignment is important, especially regarding environmental regulations and renewable energy policies.

(i) *Return on Investment (ROI) (C9)*: ROI can be positive over time, considering energy generation and water evaporation reduction benefits. However, initial costs are significant.

(j) *Data Reliability (C10)*: Data reliability is essential for monitoring system performance and ecological impacts.

7. **Water Desalination (A7) [11,12]**

(a) *Effectiveness and Risk Management (C1)*: Effective in addressing water scarcity but may have challenges related to environmental impact due to energy-intensive processes [2,96].

(b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Resource efficiency depends on the specific desalination technology used. Equity concerns may arise if desalinated water is not distributed equitably.

(c) *Scalability and Adaptability (C3)*: Scalability depends on technology and energy availability. Adaptability is constrained by the energy-intensive nature of desalination.

(d) *Environmental Impact (C4)*: Energy-intensive desalination processes may have a significant environmental impact. Proper disposal of brine is crucial to prevent harm to aquatic ecosystems.

(e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integration may require significant infrastructure changes. Technological feasibility depends on the specific technology used. Implementation can be complex.

(f) *Long-Term Sustainability (C6)*: Sustainability may be compromised if not properly managed, given the energy and environmental implications.

(g) *Community Engagement and Public Acceptance (C7)*: Public acceptance may vary based on environmental concerns and the perceived necessity of desalination.

(h) *Regulatory and Policy Alignment (C8)*: Regulatory alignment is essential for addressing environmental concerns and ensuring water quality standards.

(i) *Return on Investment (ROI) (C9)*: ROI may vary based on energy costs and water pricing. High initial costs may be a barrier to implementation.

(j) *Data Reliability (C10)*: Data reliability is crucial for monitoring water quality and system performance.

8. **Policy and Regulation (A8) [88,89]**
    (a) *Effectiveness and Risk Management (C1)*: Effective in shaping water management practices, but its success depends on alignment with local contexts, public involvement, and addressing challenges [88,89].
    (b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Can promote resource efficiency and equity if well-implemented, but effectiveness varies based on the policy's design and implementation.
    (c) *Scalability and Adaptability (C3)*: Scalable in influencing decision making but may require adjustments based on changing circumstances.
    (d) *Environmental Impact (C4)*: May indirectly impact the environment by shaping water management practices. Policies can incentivize environmentally friendly approaches.
    (e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integration with existing systems depends on policy objectives. Technological feasibility depends on policy goals.
    (f) *Long-Term Sustainability (C6)*: Long-term sustainability depends on the ability of policies to adapt to changing environmental and societal conditions.
    (g) *Community Engagement and Public Acceptance (C7)*: Public acceptance of policies varies based on transparency, inclusiveness, and perceived benefits.
    (h) *Regulatory and Policy Alignment (C8)*: Alignment with existing regulations and policies is essential for effective policy implementation.
    (i) *Return on Investment (ROI) (C9)*: ROI is indirect, as policies aim to shape water management practices rather than generate direct financial returns.
    (j) *Data Reliability (C10)*: Data reliability is crucial for evidence-based policy-making.
9. **Educational Campaigns and Public Awareness (A9) [90,91]**
    (a) *Effectiveness and Risk Management (C1)*: Effective in the long term by fostering a culture of responsible water use but may not yield immediate results [90,91].
    (b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Promotes resource efficiency and equity by encouraging responsible water consumption. However, impacts may take time to manifest.
    (c) *Scalability and Adaptability (C3)*: Scalable but may require ongoing efforts to maintain awareness. Adaptability is high as campaigns can address evolving challenges.
    (d) *Environmental Impact (C4)*: Indirectly reduces the environmental impact by promoting responsible water use. However, the impact is less direct than with technology-based strategies.
    (e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integrates with existing systems by influencing user behavior. Implementation is relatively straightforward.
    (f) *Long-Term Sustainability (C6)*: Contributes to long-term sustainability by instilling responsible water use habits. Sustainability depends on ongoing efforts.
    (g) *Community Engagement and Public Acceptance (C7)*: Success relies on community engagement and gaining public support for conservation efforts.
    (h) *Regulatory and Policy Alignment (C8)*: Alignment with regulations is essential, particularly in areas where conservation measures are mandated.
    (i) *Return on Investment (ROI) (C9)*: ROI is indirect, as educational campaigns aim to promote responsible behavior rather than generate direct financial returns.
    (j) *Data Reliability (C10)*: Data reliability is relevant for monitoring the effectiveness of campaigns and tracking behavior change.

10. **Collaboration and Partnerships (A10) [92,93]**
    (a) *Effectiveness and Risk Management (C1)*: Effective in fostering collaborative approaches to water management but may face challenges related to differing priorities [92,93].
    (b) *Resource Efficiency, Equity, and Social Considerations (C2)*: Can promote resource efficiency and equity by encouraging collective efforts. However, challenges may arise in ensuring equitable participation.
    (c) *Scalability and Adaptability (C3)*: Scalable by nature, as it encourages cooperation among stakeholders. Adaptability depends on the flexibility of partnerships.
    (d) *Environmental Impact (C4)*: Collaboration can lead to environmentally friendly approaches but may require alignment on sustainability goals.
    (e) *Integration with Existing Systems, Technological Feasibility, and Ease of Implementation (C5)*: Integration depends on the nature of partnerships. Implementation may require negotiation and coordination.
    (f) *Long-Term Sustainability (C6)*: Contributes to long-term sustainability by promoting collective responsibility for water management. Sustainability depends on the stability of partnerships.
    (g) *Community Engagement and Public Acceptance (C7)*: Public acceptance may vary based on the transparency and inclusiveness of collaboration efforts.
    (h) *Regulatory and Policy Alignment (C8)*: Regulatory alignment is crucial for collaboration success, particularly regarding resource allocation and decision making.
    (i) *Return on Investment (ROI) (C9)*: ROI is indirect, as collaboration aims to optimize resource use and achieve shared goals.
    (j) *Data Reliability (C10)*: Data reliability is relevant for monitoring the effectiveness of collaborative efforts and tracking shared goals.

In conclusion, evaluating water management strategies in smart cities involves a multidimensional analysis of criteria and strategies. Each strategy has unique advantages and disadvantages across these criteria, emphasizing the need for tailored approaches that address specific urban contexts and challenges.

By considering these aspects comprehensively, smart cities can implement effective water management strategies that align with their long-term sustainability goals and the well-being of their residents. This systematic evaluation of strategies within the framework of various criteria provides valuable insights for policymakers, urban planners, and stakeholders in making informed decisions regarding water management in smart cities.

5.3. Impact of the Results on Current Smart Cities

The findings of this study, which prioritize water management strategies based on a comprehensive set of criteria and weights, have significant implications for current smart cities striving to enhance their water management practices. These implications extend to urban planners, policymakers, and stakeholders involved in shaping the future of smart cities.

- **Strategic Investment**: The prioritization of criteria highlights the importance of "Effectiveness and Risk Management" as the most critical criterion. This underscores the need for smart cities to invest in strategies like "Smart Metering and Monitoring, Demand Management, and Behavior Change", which can effectively address water challenges while managing associated risks.
- **Resource Optimization**: The emphasis on "Resource Efficiency, Equity, and Social Considerations" encourages smart cities to prioritize strategies such as "Rainwater Harvesting" and "Graywater Recycling and Reuse" that not only conserve water but also ensure equitable access to clean water for all residents. Smart cities must consider the social implications of their water management decisions and work toward resource optimization.

- **Technological Integration**: "Integration with Existing Systems, Technological Feasibility, and Ease of Implementation" is another key criterion. Smart cities should focus on strategies like "Smart Irrigation Systems" that seamlessly integrate with their existing infrastructure while leveraging available technologies. This approach can facilitate smoother implementation and reduce resistance to change.
- **Environmental Responsibility**: Recognizing the importance of "Environmental Impact" encourages smart cities to adopt strategies such as "Offshore Floating Photovoltaic Systems" that minimize harm to the environment while addressing water management challenges.
- **Community Engagement**: The criterion of "Community Engagement and Public Acceptance" emphasizes the role of the community in successful water management. Smart cities should actively involve residents and gain their support for strategies like "Educational Campaigns and Public Awareness", recognizing that public acceptance is vital for strategy implementation.
- **Balancing Financial and Governance Concerns**: The inclusion of "Return on Investment" and "Regulatory and Policy Alignment" criteria highlights the need for smart cities to strike a balance between financial considerations and governance alignment. Policymakers must ensure that regulations support the adoption of effective water management strategies, such as "Policy and Regulation".
- **Data Accuracy and Sustainability**: "Data Reliability" and "Long-Term Sustainability" are two criteria that underscore the importance of data accuracy and long-term planning. Smart cities should invest in reliable data collection and analysis while focusing on strategies that promote sustainability, including "Collaboration and Partnerships".

In summary, the prioritization of criteria and strategies provides a roadmap for smart cities to tailor their water management approaches to their unique contexts. While highly weighted strategies offer significant benefits, medium- and low-weighted strategies should not be overlooked, as they can complement and enhance the overall water management framework. Smart cities should consider these findings when developing and implementing their water management strategies to ensure sustainability, efficiency, and equity in the use of this vital resource.

5.4. Limitations of Conducted Research

While this research provides valuable insights into the evaluation of water management strategies in smart cities, it is essential to acknowledge its limitations to ensure a comprehensive understanding of the study's scope and applicability:

- **Scope of Criteria**: The criteria used for evaluation were carefully selected, but there may be other relevant criteria that were not included in this study. Future research could explore additional criteria that may impact water management strategies, including the impact of climate change [68,69].
- **Weighting Process**: The determination of criteria weights using the MCDM-AHP method relies on objective judgments, and the results may vary based on the perspectives of different stakeholders. It is essential to recognize that the weighting process involves inherent uncertainties.
- **Context Dependency**: The study's findings are based on a generalized framework and may not fully capture the unique contexts and challenges of specific smart cities. Local factors and circumstances can significantly influence the choice and effectiveness of water management strategies.
- **Dynamic Nature of Smart Cities**: Smart cities are continually evolving, with technological advancements, population changes, and shifting priorities. The research may not account for the dynamic nature of smart city development and its impact on water management strategies over time.
- **Policy and Governance Factors**: The study assumes a certain level of policy and governance support for the implementation of strategies. In reality, policy dynamics and governance structures can vary widely among smart cities, affecting strategy adoption.

Addressing these limitations and conducting further research that considers the specific contexts of individual smart cities can contribute to a more robust understanding of effective water management in the evolving landscape of urban development.

6. Conclusions

6.1. Research Motivation, Research Questions, and Methodology

The efficient and sustainable management of water resources has become a critical concern for urban areas worldwide, particularly in the context of rapid urbanization and the increasing demand for water. Smart cities, characterized by the integration of digital technologies and data-driven approaches, offer a promising avenue to address these challenges. However, the selection of effective water management strategies for smart cities requires a comprehensive evaluation that considers multiple criteria. This study aims to fill a gap in the existing literature by providing a systematic and holistic assessment of water management strategies based on a diverse set of criteria, employing the Multi-Criteria Decision-Making (MCDM) technique of Analytic Hierarchy Process (AHP).

6.2. General Findings and Limitations

The relative weights assigned to different criteria provide insights into the importance of each criterion in shaping the success of these strategies. The results suggest that certain criteria hold higher significance than others, guiding the prioritization and allocation of resources for the implementation of water management strategies.

The criterion of "Effectiveness and Risk Management" holds the highest weight (15.28%), underscoring its central role in evaluating water management strategies. The ability of a strategy to effectively manage risks and ensure its overall success is crucial for its adoption and long-term sustainability. This emphasizes the need for strategies that not only perform well in terms of water conservation but also demonstrate robustness in the face of uncertainties and potential challenges.

Several criteria fall under the category of medium relative weights, indicating their significant but not dominant role in the evaluation process. The medium weight (10.44%) assigned to the "Resource Efficiency, Equity, and Social Considerations" criterion reflects its importance in promoting efficient resource use and ensuring equitable distribution of benefits. It also considers the social implications of the strategies, highlighting the need to address societal concerns such as accessibility, affordability, and inclusivity. The moderate weight (10.10%) assigned to the "Integration with Existing Systems, Technological Feasibility, and Ease of Implementation" criterion underscores the importance of strategies that can seamlessly integrate with existing systems and technologies, facilitating smooth implementation. However, this criterion is balanced with other considerations, acknowledging that technological feasibility is not the sole determinant of a strategy's success. The weight (9.84%) assigned to "Environmental Impact" reflects the need to assess the consequences of strategies on the environment. This criterion acknowledges the importance of minimizing negative ecological outcomes while achieving water management goals. The moderate weight (9.79%) assigned to "Community Engagement and Public Acceptance" recognizes the role of involving the public and ensuring their buy-in for successful strategy implementation. While important, this criterion is not weighted as heavily as others, indicating a balanced approach. The moderate weight (9.35%) assigned to "Scalability and Adaptability" highlights their significance in responding to changing conditions and expanding the scope of the strategies. While vital for long-term success, these factors are not considered the most critical determinants. The consideration of "Return on Investment (ROI)" emphasizes the financial aspect of the strategies. However, the lower weight (9.07%) suggests that while financial gains are important, they are not the primary focus in evaluating water management strategies. The weight (8.8%) placed on "Regulatory and Policy Alignment" reflects the need for strategies to adhere to established regulations and policies. This criterion ensures that strategies are compliant and supportive of broader governance frameworks.

Two criteria fall under the category of low relative weights, indicating their relatively lesser impact on the overall evaluation process. The lowest weight (8.78%) assigned to "Data Reliability" suggests that while data accuracy and reliability are considerations, they are not as critical as other factors in assessing the viability of strategies. This could be due to the availability of advanced data collection and analysis technologies that mitigate data-related concerns. The slightly lower weight (8.55%) assigned to "Long-Term Sustainability" underscores its importance for successful water management strategies. While a key consideration, it is deemed moderately important in comparison to other criteria.

In conclusion, the evaluation of water management strategies in smart cities involves a multi-criteria approach that considers diverse factors. The hierarchy of relative weights assigned to different criteria provides a structured framework for decision-makers to prioritize strategies based on their potential impact.

The strategies with high weighted sums, such as "Smart Metering and Monitoring, Demand Management, and Behavior Change", and "Smart Irrigation Systems", emerge as particularly effective and important for enhancing water management in smart cities. However, strategies with medium (i.e., "Educational Campaigns and Public Awareness", "Policy and Regulation", "Rainwater Harvesting", "Offshore Floating Photovoltaic Systems", "Collaboration and Partnerships", "Graywater Recycling and Reuse", and "Distributed Water Infrastructure") and low (i.e., "Water Desalination") weighted sums also play valuable roles and could be integrated with higher-ranked strategies to create comprehensive water management approaches tailored to the unique context of each smart city.

It is crucial to recognize that the interpretation of these results may depend on the specific evaluation methodology employed and the unique circumstances of each smart city, warranting careful consideration and contextualization.

6.3. Significance of This Research

Several factors underscore the significance of this research.

First, the management of water resources in urban areas is a complex endeavor that involves various interconnected factors, including environmental sustainability, social equity, economic viability, and technological feasibility. Traditional approaches often focus on a single aspect, neglecting the broader picture. This study seeks to overcome this limitation by considering multiple criteria that collectively influence the success of water management strategies.

Second, the concept of smart cities offers a new paradigm for urban development, leveraging technology to optimize resource utilization, enhance quality of life, and mitigate environmental impacts. However, there is a lack of comprehensive evaluations of water management strategies tailored to the unique context of smart cities. This study addresses this gap by analyzing strategies within the framework of smart city principles.

Third, with limited resources available for implementing water management strategies, it is essential to allocate resources effectively to strategies that offer the highest impact. By assigning relative weights to different criteria, this study assists in identifying strategies that align with the priorities and goals of a particular smart city.

The findings of this research hold practical implications for urban planners, policymakers, and other stakeholders involved in water resource management. The identified strategies, based on their relative weights, can guide the selection and implementation of water management initiatives, leading to more sustainable and resilient smart cities.

6.4. Future Directions

While this study has provided valuable insights into the evaluation of water management strategies using MCDM-AHP, there are several promising avenues for future research and exploration in the field of urban water management. These potential directions can further enhance our understanding and decision-making processes in smart cities:

- **Advanced Decision Support Systems**: Future research can focus on the development of advanced Decision Support Systems (DSSs) that integrate MCDM-AHP with real-time data, IoT sensors, and predictive analytics. These DSSs can provide dynamic, data-driven insights to aid decision-makers in selecting and implementing water management strategies.

- **Incorporating Climate Resilience**: Given the increasing impacts of climate change on urban water resources, future studies may delve deeper into the integration of climate resilience considerations into the evaluation framework. This includes assessing the adaptability of strategies to changing climate patterns and extreme events.
- **Machine Learning and AI Integration**: The integration of Machine Learning (ML) and Artificial Intelligence (AI) techniques can enhance the predictive capabilities of strategy evaluations. Future research can explore how ML and AI can automate criteria weighting, optimize strategy selection, and provide proactive alerts for potential issues.
- **Cross-City Comparisons**: Comparative studies between different smart cities can offer valuable insights into the effectiveness of water management strategies across various contexts. Future research can investigate the transferability of successful strategies between cities and identify key determinants of success.
- **Behavioral and Social Dynamics**: Understanding the behavioral and social aspects of water consumption and conservation is critical. Future studies can delve into the psychology of water use in urban settings, exploring strategies to promote behavioral change and community engagement effectively.
- **Circular Economy Principles**: The adoption of circular economy principles in water management can minimize waste and maximize resource efficiency. Future research can explore how strategies aligned with circular economy principles can be evaluated and integrated into smart city water management.
- **Data Standardization and Sharing**: Addressing challenges related to data reliability and availability is essential. Future efforts can focus on standardizing data collection methods, sharing best practices, and establishing data-sharing frameworks to improve the accuracy of evaluations.
- **Ethical Considerations**: Ethical considerations in water management, such as equity, environmental justice, and the impact on marginalized communities, deserve increased attention. Future research can delve into the ethical dimensions of strategy evaluation and decision making.
- **Policy Innovation**: Smart cities are often at the forefront of policy innovation. Future studies can explore how innovative policy frameworks and regulatory approaches can support the adoption of sustainable water management strategies.
- **Community-Centric Approaches**: Empowering local communities to actively participate in water management decisions is crucial. Future research can explore community-centric approaches and their impact on strategy selection and implementation.
- **Empirical Studies**: Conducting empirical studies to verify the effectiveness and practicality of the proposed approach in real-world situations is a promising direction. These studies can provide valuable insights into the applicability of the methodology in different contexts.
- **Scalability and Adaptation**: It would be valuable to examine how the approach can be scaled and adapted to different contexts and regions, gaining valuable insights into its versatility and effectiveness in diverse settings.
- **Interdisciplinary Collaborations**: Exploring potential synergies with related research areas and fostering interdisciplinary collaborations can expand the scope and impact of this work. Collaborations with experts in fields such as environmental science, urban planning, and data science can lead to innovative approaches and holistic solutions.

In conclusion, the field of urban water management is dynamic and evolving, presenting numerous opportunities for further research and exploration. These future directions aim to advance our understanding, decision-making capabilities, and sustainability efforts in smart cities, ultimately contributing to more resilient and efficient water management systems.

Funding: This research was supported by the Laboratory of Renewable Energies and Advanced Materials (LERMA) and the College of Engineering and Architecture of the International University of Rabat (IUR).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data used in this study, along with the details of the methodology adopted, are comprehensively described in the methodology section (Section 3) of this article.

Acknowledgments: The author extends sincere gratitude to the editorial office and the dedicated reviewers for their insightful feedback and meticulous review, which have enhanced the clarity of this article.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Multi-Criteria Decision Making (MCDM) Using the Analytic Hierarchy Process (AHP)

Appendix A.1. Defining Multi-Criteria Decision Making (MCDM)

Multi-Criteria Decision Making (MCDM) is a structured approach that helps individuals or groups make informed decisions when faced with complex choices involving multiple conflicting criteria. Unlike traditional decision-making methods that focus on single criteria, MCDM takes into account a variety of criteria that often have different units, scales, and levels of importance. By systematically analyzing and evaluating these criteria, MCDM provides a rational and comprehensive way to assess alternatives and select the most suitable course of action [97].

Appendix A.2. Types of MCDM Methods

In the realm of Multi-Criteria Decision Making (MCDM), the choice of technique hinges on the characteristics of the decision problem [98]. If the decision problem is well structured, it can be navigated through a hierarchical framework. In cases where preferences among alternatives are pivotal, the next distinction is whether the criteria are compensatory or non-compensatory. For compensatory criteria using additive models, the Analytic Hierarchy Process (AHP) offers a systematic approach to hierarchically structured decisions. Similarly, the Technique for Order of Preference by Similarity to an Ideal Solution (TOPSIS) ranks alternatives based on their proximity to an ideal solution, and it can be employed in both additive and multiplicative contexts.

On the other hand, if the decision problem is unstructured and lacks a clear hierarchy, techniques like the Decision-Making Trial and Evaluation Laboratory (DEMATEL) and its extension for complex systems (DEMATEL-CS) offer insights into unruly decision contexts.

In structured decision scenarios that emphasize rankings rather than preferences, the nature of criteria becomes essential. Non-compensatory criteria prompt techniques such as Elimination and Choice Expressing Reality (ELECTRE), which is a tool that eliminates alternatives that do not meet specific thresholds. The Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is also adept at handling non-compensatory scenarios by aggregating preference relations. In both structured preference-based and ranking-based decision problems, the versatile TOPSIS technique can be utilized as it adapts to both scenarios.

In summary, understanding whether a decision problem is structured or unstructured, preference-based or ranking-based, and whether it involves compensatory or non-compensatory criteria is pivotal in selecting an appropriate MCDM technique. This systematic approach ensures that decision-makers effectively navigate the complexities of their specific decision-making context, utilizing the appropriate MCDM tool to arrive at informed choices.

Appendix A.3. Applications of MCDM

MCDM finds applications in a wide range of fields, including business [99,100], engineering [101,102], environmental management [103,104], healthcare [105,106], finance [107,108], and public policy [109,110]. It is used for project selection [111], supplier evaluation [106], resource allocation [112], risk assessment [100,108], site selection (i.e., photovoltaic and concentrated solar power [113], onshore wind [114], offshore wind [115], and offshore floating photovoltaic plants [2]), and more. Its versatility makes it a valuable tool for handling complex decision-making scenarios where numerous factors need to be considered.

Appendix A.4. Analytic Hierarchy Process (AHP): Definition and Theoretical Framework

The Analytic Hierarchy Process (AHP) is a widely used MCDM technique that structures a decision problem as a hierarchical tree of criteria and alternatives. Developed by Thomas L. Saaty in the late 1970s, AHP enables decision-makers to decompose complex decisions into smaller, more manageable parts, facilitating a systematic evaluation process [16].

AHP has proven particularly effective when there are qualitative and quantitative criteria involved and when the decision involves both tangible and intangible factors.

The AHP can be broken down into the following steps:

- **Step 1—Define the Hierarchy**: The first step in AHP involves structuring the decision problem hierarchically. Consider a decision problem with n alternatives and m criteria. The hierarchy consists of three levels: the goal (G), criteria (C), and alternatives (A). Figure 3 illustrates the hierarchical framework employed for evaluating water management strategies within smart cities using the MCDM-AHP.
- **Step 2—Pairwise Comparisons**: Next, pairwise comparisons are conducted to determine the relative importance of criteria and sub-criteria, using a scale, such as 1 to 9, where 1 represents equal importance and 9 represents extreme importance [16,17] (Table 1). For each pair of elements i and j at level k, a comparison matrix is created (A1):

$$A_{ij}^{k} = \text{Preference\_Score}(i, j) \quad \text{for } i, j \in \text{Level } k \tag{A1}$$

- **Step 3—Normalize the Comparison Matrices**: The comparison matrices are normalized to obtain the corresponding normalized matrices (A2):

$$N_{ij}^{k} = \frac{A_{ij}^{k}}{\sum_{j=1}^{n} A_{ij}^{k}} \quad \text{for } i, j \in \text{Level } k \tag{A2}$$

- **Step 4—Calculate Criteria Weights**: The criteria weights are obtained by averaging the columns of the normalized comparison matrix (A3):

$$W_k = \frac{1}{n} \sum_{i=1}^{n} N_{ij}^{k} \quad \text{for } j \in \text{Level } k \tag{A3}$$

- **Step 5—Consistency Check**: A consistency ratio (CR) is calculated to ensure the consistency of the comparisons. The CR is calculated as (A4):

$$CR = \frac{\text{CI}}{\text{RI}} \tag{A4}$$

where CI is the Consistency Index (A5) and RI is the Random Index (A.4). If the CR value is acceptable (typically below 0.1), the pairwise comparisons are consistent. If the CR value is considered unacceptable, typically surpassing the threshold of 0.1, it indicates a lack of consistency in the pairwise comparisons. In such cases, it is recommended to review and revise the comparisons to improve their consistency (Figure 4). This can involve re-evaluating the relative importance assigned to certain elements, reviewing the decision-making process, or refining the criteria to enhance coherence and alignment. Consistency is crucial for the accuracy and reliability of the AHP results, so addressing inconsistencies is important to ensure robust decision outcomes.

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{A5}$$

$$\mathrm{RI} = \begin{cases} 0.00 & \text{for } n = 1 \\ 0.00 & \text{for } n = 2 \\ 0.58 & \text{for } n = 3 \\ 0.90 & \text{for } n = 4 \\ 1.12 & \text{for } n = 5 \\ \vdots & \vdots \end{cases}$$

- **Step 6—Calculate the Priority Vector**: The priority vector P_k for each level k is calculated by finding the principal eigenvector of the normalized comparison matrix (A6):

$$NP_k = \lambda_k P_k \tag{A6}$$

where λ_k is the eigenvalue corresponding to the principal eigenvector.
- **Step 7—Aggregate Priority Scores**: The priority scores for each alternative at the lower levels are calculated by aggregating the priority vectors (A7):

$$S_i = \sum_{k=1}^{m} P_{ki} \cdot W_k \quad \text{for } i \in \text{Alternatives} \tag{A7}$$

- **Step 8—Rank Alternatives**: Finally, the alternatives are ranked based on their priority scores S_i, and the alternative with the highest score is selected as the preferred choice.

This comprehensive framework illustrates the detailed mathematical foundation of the AHP, highlighting the systematic approach to structuring decision problems, conducting pairwise comparisons, normalizing matrices, calculating criteria weights, ensuring consistency, and deriving the final alternative rankings.

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