International Journal of Sustainable Development and Planning
Vol. 20, No. 1, January, 2025, pp. 227-244
Journal homepage: http://iieta.org/journals/ijsdp

Developing Cost Frameworks for Sustainable Water Supply Utility: A Bibliometric Analysis and Systematic Literature Review

Widyo Nugroho[1], Rita Ambarwati[2], Detak Prapanca[2*], Atik Wahyuni[3]

[1] Department of Technical Operations, PT. Adyatama, Malang 65116, Indonesia
[2] Department of Management, Faculty of Business, Law and Social Sciences, Universitas Muhammadiyah Sidoarjo, Sidoarjo 61215, Indonesia
[3] Department of Civil Engineering, Faculty of Science and Technology, Universitas Muhammadiyah Sidoarjo, Sidoarjo 61215, Indonesia

Corresponding Author Email: ritaambarwati@umsida.ac.id

https://doi.org/10.18280/ijsdp.200122

Received: 7 October 2024
Revised: 24 December 2024
Accepted: 8 January 2025
Available online: 24 January 2025

Keywords:
cost framework, sustainability, water supply

ABSTRACT

Sustainable water supply utilities involve entities that emphasize long-term viability for the environment, economy, and society in the design, implementation, and management of water supply-related systems and infrastructure. It includes developing and upholding water delivery, distribution, and treatment systems that meet the needs of both the current and upcoming generations while reducing harmful environmental effects. This article employs a bibliometric technique to investigate publication trends between 2018 and 2023, identify the most dominant clusters, and identify potential study areas and future directions, thereby enhancing our understanding of the subject's research trends. The bibliometric study's objective is to describe the cost assessment of water supply utility by identifying activities, issues, and topic interests; providing a detailed explanation of cost assessment; and presenting and analyzing results based on bibliometric data to determine performance, developments, and trends in the field of study. This research conducts a thorough literature review to identify the essential elements required for a comprehensive cost framework. The analysis highlights the necessity of integrating these diverse components into a cohesive framework to ensure effective design, engineering, and utility administration, thereby ensuring both current and future sustainability.

1. INTRODUCTION

Global environmental challenges and rising population demands have highlighted the urgent need for a sustainable water supply system. Access to clean water, a universally recognized human right, is vital for public health and socioeconomic development. However, rapid urbanization, inadequate funding, and aging infrastructure continue to widen disparities in water access [1]. These challenges emphasize the importance of adopting comprehensive strategies that address current demands while ensuring long-term sustainability [2]. Environmental degradation and climate change further compound these issues, creating significant obstacles to effective water management. Immediate rehabilitation and modernization of aging urban water utilities are critical to safeguarding water quality and supply [3]. Furthermore, limited financial and operational resources often leave communities more vulnerable. Addressing these challenges requires innovative solutions that adapt to evolving societal needs and dynamic environmental conditions. Recent technological advancements present promising opportunities to enhance water sustainability.

Establishing a cost structure that incorporates social and environmental expenses, along with construction and operational costs, is essential for the financial sustainability of water supply utilities [4]. To encourage conservation and investment in sustainable technologies, policies and pricing mechanisms must reflect the true cost of water services. Water pricing reforms implemented in some regions offer valuable insights into creating effective policies for sustainable water management [5]. Sustainable water utilities integrate environmental, economic, and social considerations into the design, implementation, and management of water systems and infrastructure [6]. Maintaining efficient water distribution, delivery, and treatment systems is vital to meeting current and future water demands while minimizing environmental impacts. By ensuring resilient and equitable access to clean water, sustainable water utilities aim to tackle issues such as pollution, water scarcity, and climate change [7].

A comprehensive cost framework serves as the foundation for driving sustainable practices in water utilities, ensuring that all expenditures, from environmental mitigation to infrastructure maintenance, are accounted for. This approach not only promotes long-term financial stability but also encourages innovation and the adoption of green technologies. By embedding sustainability into the economic structure of water utilities, policymakers and industry leaders can foster more resilient and adaptive water management systems that are equipped to handle future challenges and uncertainties.

2. METHODS

Bibliometric analysis has addressed the constraints of traditional narrative literature reviews by evaluating academic contributions, study qualities, and research trends for a growing body of literature. Technological innovation and continued funding for scientific research have made this possible. By addressing particular research topics, the systematic review provides up-to-date information by combining primary research findings. However, the currently available reviews typically focus on a specific aspect of the current situation and rarely provide a comprehensive overview of the research trends and development process. Our study efforts could help close a knowledge gap in this field. Our study efforts could help close a knowledge gap in this field. This work utilizes a bibliometric approach to understand and explore the state of research on applying cost analysis to government and organizational decision-making.

This article examines scholarly literature on the scope of water supply utility and contributes to advancing knowledge within environmental, economic, and social frameworks. Using specific search terms, we retrieved data from the Scopus database, chosen as the primary data source due to its comprehensive coverage of high-ranking journal articles from over 230 countries. For this study, we focused on journals in the Scopus top quartile (Q1 and Q2) to ensure credibility and maximize impact. These journals rank highest in their fields based on metrics such as CiteScore, h-index, and impact factor. The research period from 2018 to 2023 was selected to capture the latest trends in modern research within this subject area, considering the rapid developments in the field over the past five years. However, the downloaded documents contained discrepancies, such as duplicate and incomplete records, necessitating a thorough cleaning process. To address these issues, various methods were applied to remove inconsistent entries and ensure the reliability of the data.

This article outlines the steps for conducting the analysis:

1) Selection of sources and subject analysis using the Scopus database;
2) Bibliometric analysis;
3) Scientific development analysis;
4) Literature review.

This study employs bibliometric techniques to analyze publishing trends from 2018 to 2023, identify dominant research clusters, explore potential study areas, and highlight future research directions. The bibliometric analysis aims to describe the activities, challenges, and key topics related to the cost assessment of water supply utilities. Additionally, it provides a comprehensive explanation of the cost assessment process, evaluates findings based on bibliometric data, and assesses the field's performance, progress, and trends. To expand the scope of knowledge, this article also reviews previous research on relevant topics.

3. RESULTS AND DISCUSSIONS

3.1 Selection of sources

The PRISMA flow diagram outlines a structured process in four key stages: identification, screening, eligibility, and inclusion, as shown in Figure 1.

The data collection was conducted in January 2024 using a series of descriptors related to the term sustainable-water-supply-utility that were present in the title, abstract, and keywords, in conjunction with Boolean logical functions (AND, OR). The following configuration made it possible to conduct the search: (Topic Search) TS = (TITLE-ABS-KEY (“sustainable water supply utility”) OR TITLE-ABS-KEY (“sustainable water supply”) OR TITLE-ABS-KEY (“sustainable water utility”) OR TITLE-ABS-KEY (“sustainable water supply utilities”) OR TITLE-ABS-KEY (“sustainable water supply infrastructure”) OR TITLE-ABS-KEY (“sustainable water infrastructure”) OR TITLE-ABS-KEY (“sustainable water supply analysis”) OR TITLE-ABS-KEY (“water utility cost analysis”) OR TITLE-ABS-KEY (“water utility cost assessment”) OR TITLE-ABS-KEY (“water infrastructure cost analysis”) OR TITLE-ABS-KEY (“water infrastructure cost assessment”). As an initial search result, we acquired 3167 documents. After removing 103 duplicate records and 810 for other reasons, 2254 records remained for further analysis. We conducted a screening process based on the titles and abstracts of these records and excluded 2040 records that did not meet the primary criteria for further review. We still need to retrieve 214 reports for full-text examination. During the eligibility phase, we sought 214 full-text reports, but after a more thorough assessment, we either failed to retrieve or rejected 161 reports.

As a result, only 53 reports advanced to the eligibility assessment stage. Subsequently, the Scopus quartile eligibility criteria led to the exclusion of 17 reports. Finally, the review deemed 36 studies relevant and included them. These studies now form the foundation for developing cost frameworks aimed at enhancing sustainable water supply management. This thorough and systematic approach ensures that the resulting framework is based on high-quality, relevant research.

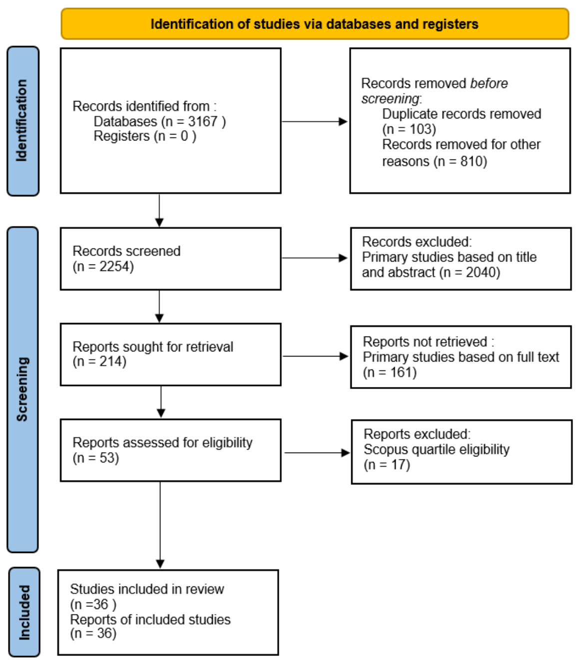

Figure 1. PRISMA flow diagram for source selection

3.2 Bibliometric analysis

This research compiles publications related to this field of study and body of knowledge. 36 journals from various academic fields comprise the total result. This study makes it possible to organize knowledge intellectually using a network of concepts that appear frequently. By utilizing thesaurus processing conditions such as minimizing related phrases, plural words, and keyword occurrences, this tool analyzes 270 keywords. 23 nodes are thus grouped into four clusters according to the previously mentioned attributes. Figure 2 presents a visual map of the topic, abstract, and keyword network, illustrating the connections between each discussion center. On the research topic, the colors red, blue, green, yellow, and purple stand for clusters. As more articles address the debate issue, the size of the nodes increases, indicating the intensity of the discussion. Small nodes serve as the new conversation focus, continuing the prior discussion emphasis characterized by networking. The bibliometric analysis using VOSviewer tools reveals five major thematic clusters: sustainability, water scarcity and resource costs, water pricing, cost recovery principles and environmental costs, and water markets and political economy.

There are seven occurrences of the word "Sustainability" in cluster 1. This cluster presents studies on greywater, affordable technology, and decision-making. The field of greywater remediation technologies may include low-cost innovations for community and home water reuse. The decision-making theme places a strong emphasis on data use, cost-benefit analysis, and community involvement when choosing effective water treatment systems. The sustainability subject highlights the environmental benefits, such as lower carbon emissions and more efficient water use.

With eight occurrences, cluster 2 is colored green and titled "Water Scarcity and Resources Cost". The debate in this cluster covers some important topics. An excessive amount of exploitation, population growth, or climate change can all contribute to a situation known as a "water deficit," whereby the demand for water exceeds the supply. This relates to accounting provision, which includes accounting techniques for estimating, regulating, and quantifying the supply and distribution of water while considering various environmental and economic factors. Using probabilistic simulation, one may estimate demand trends, simulate uncertainty in water distribution, and create strategies to lower the risks associated with impending water shortages. This cluster is critical to a thorough understanding of the dynamics of water management in the face of population expansion and climate change, as well as the development of sustainable policies.

Cluster 3, “Water Pricing” (blue color) represents a set of seven occurrences. The discourse surrounding water prices has developed into two primary subjects, specifically externality costing and single-block pricing principles. Secondary costing examines the integration of external costs, such as the ecological and societal consequences of water consumption, into the pricing framework. This method guarantees that water prices accurately represent the actual expenses, including those due to environmental harm or the potential for water shortage. Single-block pricing, on the other hand, charges customers a predetermined price per unit of water, regardless of the quantity they consume. Despite its simplicity, many perceive this structure to provide less incentive for water conservation, especially for large consumers, compared to the tiered model.

Cluster 4, "Cost Recovery Principle and Environmental Cost" (yellow color), represents a group of four occurrences. Research on the cost recovery principle and environmental cost focuses on mechanisms to ensure full payment of costs related to providing services, such as water, while considering the environment's effects. The cost recovery concept underscores the necessity of imposing tariffs that adequately cover investment and operational expenses to ensure the long-term sustainability of the service system. In addition, environmental costs incorporate unfavorable environmental impacts such as pollution and overuse into the pricing structure, thereby encouraging a more sustainable use of resources.

Purple-colored Cluster 5, "Water Markets and Political Economy," represents a combination of two occurrences. The field of study looks at how water markets function within the parameters of political economy. This topic examines the effective allocation of resources facilitated by water market mechanisms and the impact of policies and political power on these markets. The primary focus of water markets is the exchange of water rights, the determination of pricing, and the function of markets in the allocation of resources. Conversely, political economy examines the impact of policies, political power, and the interests of different stakeholders in water management, encompassing regulatory choices and resource distribution.

These clusters provide a structured framework for understanding key research trends, patterns, and gaps in water management studies. Each cluster highlights critical aspects of the field while also revealing areas that require deeper exploration and development. The first two clusters reflect dominant themes in water management research: sustainability and water scarcity. Sustainability underscores the global urgency to balance environmental conservation with the growing demand for water, driven by population growth and economic expansion. Research in this area highlights the role of technological innovations, such as greywater reuse, as well as community participation and policy-making. At the same time, water scarcity remains a critical challenge, particularly in regions affected by climate change, overexploitation, or inadequate infrastructure. While these studies emphasize technical solutions to sustainability, there is limited focus on the development of comprehensive cost frameworks that integrate socio-economic and environmental considerations. This leaves a significant gap in understanding how sustainable water utilities can be supported and financed over the long term.

Economic and policy mechanisms, emphasized in clusters three and four, provide valuable insights into the financial foundations of sustainable water management. Cost frameworks, such as water pricing strategies, cost recovery principles, and externality costing, are essential in ensuring the long-term viability of water supply utilities. Externality costing, for instance, integrates social and ecological impacts into water pricing frameworks, aligning economic incentives with ecological preservation. Such frameworks encourage responsible consumption and ensure that the full costs of water supply—including environmental degradation and resource depletion—are accounted for. However, disparities in the application of these frameworks remain evident, particularly in regions with underdeveloped infrastructure or vulnerable socio-economic conditions. This calls for adaptive, context-specific cost frameworks that address regional disparities while ensuring equitable access to water resources.

Cluster 5, which focuses on water markets and political economy, underscores the importance of regulatory frameworks and governance structures in shaping water management practices. While water markets are frequently discussed as tools for resource allocation, this cluster's small size suggests a gap in research on the cost frameworks necessary to support equitable and sustainable market-based solutions. Effective water markets rely on well-designed financial mechanisms that balance efficiency with equity, ensuring that access to water resources is not disproportionately influenced by political or economic power dynamics. Further research is needed to explore how such frameworks can be operationalized to address resource allocation, access, and equity in regions experiencing water stress or socio-political conflict.

Across all clusters, the integration of cost frameworks with technological, social, and environmental considerations emerges as a critical theme. Innovations such as probabilistic simulations and market-based mechanisms demonstrate the potential of interdisciplinary approaches to address complex water management challenges. However, much of the existing research remains compartmentalized, focusing on technical or economic solutions without adequately considering how these solutions can be embedded into sustainable and resilient cost structures. Collaborative efforts involving policymakers, financial experts, scientists, and local communities are vital to developing and operationalizing cost frameworks that are both effective and inclusive, ensuring the financial sustainability of water utilities while addressing diverse regional needs and contexts.

While sustainability and water pricing dominate the research landscape, critical gaps remain in the development of cost frameworks that support equitable access, financial sustainability, and resilience in water supply systems. Future research should prioritize the design of adaptive cost recovery models that address disparities in water access and incorporate long-term environmental costs. Additionally, exploring the socio-political dimensions of cost frameworks—such as their impact on equity and governance—will be essential to ensuring that water utilities can balance financial sustainability with broader social and environmental goals. By addressing these gaps, research can advance the design and implementation of cost frameworks that serve as a foundation for sustainable and resilient water supply utilities.

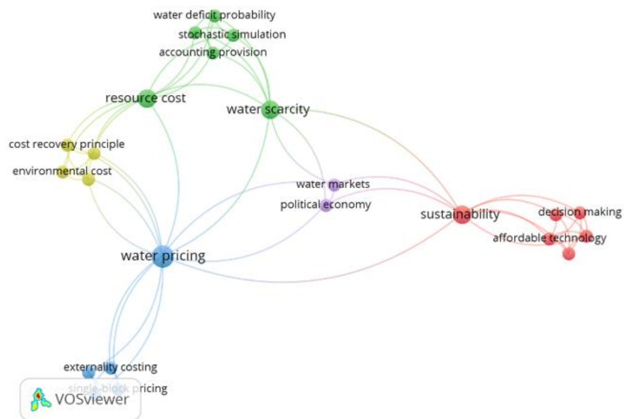

Figure 2. Bibliometric network visualization of topic and abstract fields

Figure 3 illustrates an overlay representation of the publication period, highlighting the temporal evolution of dominant research themes from 2018 to 2023. The data reveals a significant concentration of publications between 2020 and 2022, as indicated by the prevalence of green hues. This visualization not only maps the frequency of critical subjects but also identifies emerging trends within the domain of water supply cost assessments.

The initial phase in 2018 predominantly focused on resource costs, with studies emphasizing various life cycle expenses such as distribution, treatment, and procurement. These early investigations aimed to optimize operational efficiency and control expenditures to ensure sustainable water availability. However, this focus gradually shifted by 2020, driven by increasing concerns over water scarcity and pricing mechanisms. This shift reflects broader global challenges in resource management, as researchers explored how pricing strategies could incentivize conservation and shape consumer behavior.

By 2021, the research landscape evolved to incorporate more complex themes, notably political economy and water markets. This period witnessed heightened interest in the role of market systems in resource allocation and the influence of policy frameworks on water accessibility. The convergence of economic and political factors underscored the necessity to evaluate the equity and sustainability of water distribution policies, highlighting the interplay between governance structures and resource management.

From 2022 to early 2023, sustainability emerged as the dominant research focus, signaling a paradigm shift towards long-term resilience in water supply management. Studies during this period underscored the critical importance of integrating sustainability principles across all facets of water governance. The overarching objective became ensuring that present water demands are met without jeopardizing the ability of future generations to meet their needs. This trajectory reflects a growing recognition of the interconnectedness between environmental stewardship, economic viability, and social equity in shaping water management practices.

By contextualizing the temporal shifts in research themes, Figure 3 provides deeper insights into the evolving priorities and challenges faced by the water supply sector, offering a comprehensive perspective on the field's progression and future directions.

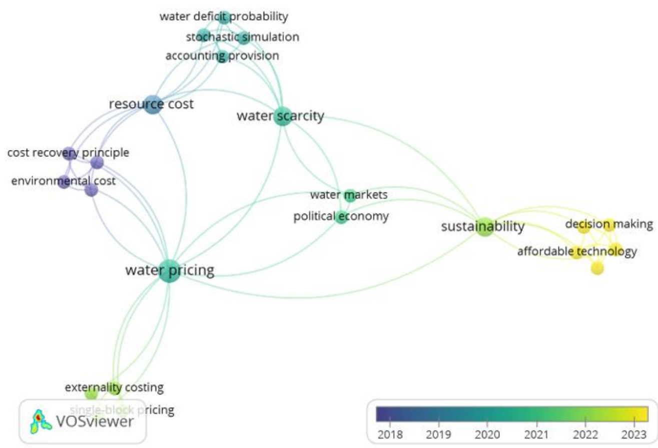

Figure 3. Overlay visualization of publishing period

The development of these study areas suggests a shift in our understanding and approaches to the problems associated with managing the water supply. A more thorough examination of prices, scarcity, markets, politics, and sustainability has replaced the previously restricted focus on costs and efficiency. This suggests that the increasing challenges of managing the water supply require the development of comprehensive and long-term solutions.

3.3 Literature review

3.3.1 Subject area of selected source journals

The predetermined research scope yielded a total of 36 articles that discuss various topics related to cost assessment in water supply utilities. Figure 4 illustrates the distribution of journals by subject, revealing that the subject area of Geography, Planning, and Development contributed the most articles. This indicates that the scope of research on cost assessment in water supply extends beyond technical and engineering aspects, incorporating elements of geographical planning and development. This subject area investigates the impact of water supply systems on regional planning and development, as well as the need to tailor water management strategies to the specific geographic context and planning requirements. The distribution of these journals reflects a diversity of perspectives and approaches to cost assessment in water supply, with significant contributions from civil engineering, environmental engineering, and geographic planning and development. This analysis provides a comprehensive picture of how different disciplines contribute to the understanding and management of water supply utilities. This significant portion highlights the spatial and urban planning aspects of water management.

In addition to publications in the Geography, Planning, and Development subject area, we can also observe that articles related to water utility cost analysis are published in other subject areas. The second most papers were contributed by journals covering the civil and structural engineering subject area. This field focuses on the design, construction, and operation of sustainable water supply systems, with a particular emphasis on the planning of water utilities. The resilience of infrastructure against climate change, creative building methods for water systems, and the longevity of materials are among the subjects covered.

Water Science and Technology journals include advances in water treatment, distribution efficiency, and monitoring systems, as well as the fundamental technologies and scientific ideas underlying water utility. Enhancing a water utility's technological and environmental performance is crucial. Journals on Development cover the socioeconomic issues of water utility management, particularly in developing nations. Journals on Development investigate how sustainable water systems can facilitate equal access to clean water, economic expansion, and social development.

Journals in the subject area of Renewable Energy, Sustainability, and the Environment are essential to the realization of sustainable water utilities by incorporating renewable energy sources and encouraging ecologically friendly practices in water management. These studies explore how renewable energy technologies can power desalination plants, distribution networks, and water treatment plants, significantly reducing operational costs and carbon footprints. They might also look for ways to lessen their impact on the environment, including carbon emissions. The journal supports sustainable water utility by covering a wide range of essential subject matters. Chemistry journals play a crucial role in helping to minimize expenses associated with pollution, chemical use, and environmental effects while also guaranteeing water quality and streamlining water treatment procedures.

Engineering journals under the category of miscellaneous offer interdisciplinary discoveries that improve operational efficiency and cut costs through technology advancements, like automation and systems engineering. Environmental science journals publish articles on how water utilities can reduce their ecological impact and cut the costs of extracting, treating, and distributing water while also promoting sustainable behaviors in the process. Similarly, journals in the subject area of Environmental Engineering integrate engineering solutions with environmental sustainability, developing technologies that reduce pollution, water loss, and resource inefficiencies, ultimately cutting long-term operational costs.

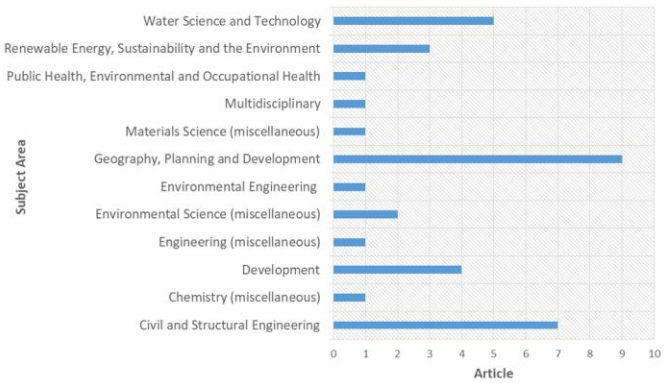

Figure 4. Subject area of selected source journals

Journals in the field of materials science contribute to the development of durable and environmentally friendly materials for water infrastructure, thereby reducing life-cycle costs through reduced maintenance and replacement. To ensure that cost evaluations take into account social, technological, and environmental concerns and produce a more comprehensive and sustainable solution, a multidisciplinary approach brings together multiple scientific and engineering views. Lastly, publications in the fields of environmental health, occupational health, and public health make sure that water utility systems adhere to public health regulations, preventing expensive waterborne illnesses and guaranteeing safe drinking water, all of which lower healthcare costs. When combined, these domains offer a comprehensive framework for cost evaluation, guaranteeing cost containment and sustainable water utility management.

The journal's wide range of subject areas demonstrates the multidisciplinary nature of cost assessments for sustainable water utilities. To create a comprehensive understanding of how water utilities can increase their sustainability while preserving their financial efficiency, it integrates technical, environmental, social, and economic factors. Each discipline makes distinct contributions to the overall objective of striking a balance between sustainability, economic viability, and social responsibility in water utility management.

3.3.2 Subject area of selected source journals

During our review, we found 36 manuscripts examined under restrictions due to either geographical obstacles unique to us or difficulties commonly acknowledged by the authors. Table 1 displays these papers, which represent the top Scopus Quartiles (Q1 and Q2) in a range of scientific topics. We note that the conventional method of cost evaluation in the water supply utility has primarily focused on step-by-step analysis, indicating an economic development that prioritizes human well-being over environmental equilibrium. Traditional energy use and the surrounding ecology are primarily responsible for the depletion of water resources. Several scientists have acknowledged the need to create environmentally friendly and energy-sector-friendly sustainable water management solutions.

Table 1. Selected source journals by SJR and quartiles

Source Journal	SJR	Quartiles	Article
Engineering, Construction and Architectural Management	0.9	Q1	1
Engineering Reports	0.41	Q2	1
Earth (Switzerland)	0.46	Q2	1
Environmental Engineering Research	0.68	Q2	1
International Journal of Life Cycle Assessment	1.2	Q1	1
Infrastructures	0.58	Q2	1
International Journal of Environmental Research and Public Health	0.81	Q2	1
Journal of Infrastructure System	0.58	Q2	1
Journal of Water Resources Planning and Management	0.81	Q1	2
Journal of Cleaner Production	2.06	Q1	2
Journal of Water, Sanitation and Hygiene for Development	0.45	Q2	2
Materials Today	5.95	Q1	1
Oeconomia Copernicana	0.99	Q1	1
Symmetry	0.49	Q2	1
Scientific African	0.58	Q1	1
Sustainable Energy Technologies and Assessments	1.57	Q1	1
Sustainability	0.67	Q1	1
Utilities Policy	0.89	Q1	1
Water (Switzerland)	0.72	Q1	8
Water Science and Technology: Water Supply	0.45	Q2	3
Water Research	3.6	Q1	2
Water Security	1.11	Q2	1
Water Resources Management	0.9	Q1	1

Life-cycle assessment (LCA) techniques generally contribute to a better understanding of water utility decision-making in a range of contexts, such as industrial raw material production, agricultural output, urban settlement in newly formed natural regions, desalination procedures, and examination of the quality of the water supply. On the other hand, the demand for domestic and industrial water supply has increased in recent decades due to economic growth. This industry's growth requires a new, sustainable approach that balances water supply and economic progress. However, the application of water supply and treatment systems has reduced value-added costs in industrial and urban water usage. Since renewable energy systems are less expensive to install than conventional systems, they are essential for providing electricity for the transport of water. In areas with limited funds, these renewable energy sources offer a profitable energy source that requires water and wastewater treatment operations.

3.3.3 Life-cycle based research

The bibliometric network, in the Figure 2, highlights the relationships between key themes in water management, such as sustainability, water scarcity, resource costs, water pricing, and water markets, all of which closely align with life cycle-based research approaches. In this context, life cycle-based research enables a comprehensive analysis of environmental impacts, economic costs, and technological efficiency from the planning and operational stages to the end of the water management system's lifespan. The sustainability cluster, which emphasizes affordable technology and decision-making, underscores the importance of low-cost innovations that can endure over time, aligning with the principles of Life Cycle Cost Analysis (LCCA) that evaluate total costs throughout the infrastructure's lifespan. Similarly, the water scarcity and resource cost cluster reflects the need for probabilistic simulations and long-term planning, which are also essential components of Life Cycle Assessment (LCA) to predict future resource availability and environmental impacts. This approach fosters the integration of economic efficiency, environmental preservation, and social sustainability, contributing to the development of resilient and sustainable water utilities.

Researchers have utilized life-cycle-based analysis in water supply utility management for several objectives. Sarkar [8] conducted a detailed analysis using Life-Cycle Cost Analysis (LCCA) and Cost-Benefit Analysis (CBA) to evaluate several options for wastewater recycling treatment facilities. This analysis evaluated the initial expenses and future advantages to ascertain the optimal alternatives. According to this research, both implemented strategies are useful in selecting an option of action based on long-term costs and benefits. Koseoglu et al. [9] promoted sustainable investment in community-based rural sanitation infrastructure by utilizing the LCCA. They emphasized how important it is to implement interventions that increase operational capacity and spark community demand. Researchers have extensively explored the balance between life-cycle costs and environmental effects. Furthermore, they proposed that it is feasible to support sustainable investment by considering the life-cycle cost. Pryce et al. [10] and López-Serrano et al. [11] proposed an evaluation of cost-effective water treatment technologies using LCCA. These studies illustrate that adopting a life-cycle-based strategy can be beneficial in the selection of such solutions. In summary, the aforementioned studies highlight the application of life-cycle-based research in asset replacement planning, assessment of technological options, and consideration of costs and environmental consequences, leading to more sustainable and economically cost-effective options.

In contrast to higher-cost Capital Expenditure (CAPEX) investments, Godfrey and Hailemichael [12] questioned the notion that low-cost CAPEX water supply utilities offer lower life-cycle costs. The study compares ten years' worth of financial data from piped water supply systems and point source water supplies in two areas of the Ethiopian Central Highland region of Amhara to test the premise. The research indicates that piped water supplies are more cost-effective than singular sources when considering capital expenditures and emergency water supply costs within a life cycle cost analysis. Lee et al. [13] created an inventory that is required for the life-cycle cost of a water supply system. Data elements were defined for every category of water supply asset based on an existing inventory system. Pumps, distribution centers, and pipelines constituted the water supply system. This study produced an inventory that thoroughly categorized every component of a water delivery system. They methodically categorized inventory items using a tree-shaped structure to enhance the management effectiveness of a water supply system. At certain times, this structure also helps the waterworks manager identify which items need to be replaced, repaired, or renovated.

For a comprehensive evaluation of infrastructure projects like Water Distribution Systems (WDS) and sanitation treatment facilities, the integration of Life Cycle Cost Analysis (LCCA) and Life Cycle Assessment (LCA) is crucial. The reason for integrating these two methodologies is that they offer complementary perspectives. LCCA focuses on the economic costs over the life cycle of a project, while LCA evaluates the environmental impacts. By combining these approaches, researchers can better understand both the financial and ecological sustainability of such systems. Water Distribution Systems (WDS) and sanitation treatment facilities were evaluated for costs and ecological effects by Mo et al. [14] and Harris et al. [15] using an integrated LCCA and LCA technique. This research emphasizes the need for LCCA to take environmental effects into account. A secondary function for LCC in its integration with LCA was suggested by Peña and Rovira-Val [16]. On the other hand, earlier research sometimes neglected to incorporate crucial expenditures like labor, infrastructure, maintenance, and end-of-life. Last but not least, they advised taking into account each step of the LCC process and utilizing additional financial techniques to supplement the LCC analysis, such as Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (PBP). Ilyas et al. [17] used LCCA as a supplemental tool to improve the life-cycle evaluation in an integrated study by using statistical and analytical techniques to guide cost estimation. This study recommended that future research focus on creating a LCCA framework that could account for and allocate all facility-related expenditures. Jocanovic et al. [18] created an LCA/LCCA model to evaluate the expenses, energy usage, and greenhouse gas emissions in WDS during the pump unit life cycle. Their provided approach monitors the pump, motor, and variable frequency drive as a system (pump unit) at each stage of their life cycle, including manufacturing, use, and disposal. Additionally, the proposed model analyzes other procedures, including pump unit reconstruction, testing, and maintenance. They used the pump unit of an operational WDS to illustrate the correct use of this model under various circumstances. In terms of energy usage, the data obtained demonstrate that the use of pump units is appropriate.

The trade-off between asset reliability and life-cycle cost is a critical factor in infrastructure management, particularly for water distribution systems. Several studies explore this concept by applying Life Cycle Cost Analysis (LCCA) alongside optimization techniques to determine the optimal strategies for asset replacement and maintenance. The goal is to balance the costs of maintaining system reliability against the expenses associated with asset degradation over time. Ghobadi et al. [19] used optimization algorithms and the LCCA technique to create a timetable for pipe replacement. They created an annual investment plan and the optimal schedule for pipe replacement based on the study of life-cycle costs, which included repair and replacement costs. They illustrated how to use LCCA to create a timetable for pipe replacement and assess system performance while taking into account several cost factors, such as operation, replacement, and repair. By utilizing information on pipe failures and associated costs, Nugroho et al. [20] used Bayesian statistical techniques and LCCA to determine the best period for replacing pipes. This method demonstrated how flexible it is for managing uncertain data. Elsebaie and Al-Khomairi [21] proposed an optimization method for pipeline projects that compares options with varying lifespans by applying the Life Cycle Cost Analysis (LCCA) and taking into account factors such as pipe material type, diameter, and age. They emphasized that the comparative annual cost is the main factor that determines efficiency and can forecast the future expenses of upkeep, operation, and replacement using the average inflation rate. Equivalent Real Annual Cost (ERAC), the appropriate cost form for comparing alternatives with varying life durations, is expressed using the average interest rate to represent all expenditures.

Content analysis and theoretical mapping of life-cycle based research are shown in Table 2.

Table 2. Content analysis of life-cycle based research

Authors	Main Concept	Research Objective
[8-13]	Life-cycle based investment analysis	Design evaluation [8], investment plan selection [9], life-cycle cost optimization [10], life-cycle cost assessment [11], LCC optimization [12], data inventory framework [13]
[14-18]	Integration of LCCA and LCA	Water system cost and environmental evaluation [14], water treatment plant preliminary evaluation [15], cost component evaluation [16], cost classification framework [17], pumping unit life-cycle costing and assessment [18]
[19-21]	The trade-off between asset reliability and life-cycle cost	Annual investment plan optimization [19], water network rehabilitation strategy [20] development plan decision making [21]

The Framework for Life-Cycle-Based Decision-Making in Water Utility Management integrates key methodologies, such as LCCA, LCA, and CBA, to inform decision-making in water utility projects, as shown in Figure 5. The design of this framework guides stakeholders through the processes of asset evaluation, investment planning, technology selection, and operational management, while balancing financial, environmental, and operational considerations. The framework comprises several stages that focus on different aspects of infrastructure management, each involving specific criteria and analytical tools. This framework fosters an integrated and holistic approach to water utility management, promoting decisions that enhance service delivery, sustainability, and long-term cost efficiency. Assessing current water utility assets based on elements including age, material, condition, and operating costs is the main goal of the asset evaluation stage. Nugroho et al. [20] emphasize the significance of assessing present circumstances and failure rates, while Elsebaie and Al-Khomairi [21] emphasize the value of characteristics like diameter and material type in predicting asset durability. Ghobadi et al. [19] emphasize operational efficiency even more, focusing on energy use and maintenance expenses in particular. Long-term operational, maintenance, and replacement costs can be estimated with the use of tools like LCCA, and data analytics can be used to monitor asset performance and failure rates. The technology and investment evaluation stage focuses on identifying cost-effective and environmentally sustainable technology options for water treatment and distribution systems. Sarkar [8] emphasizes the need to consider both initial capital costs and long-term operational expenses, while Pryce et al. [10] and López-Serrano et al. [11] argue for incorporating environmental impact assessments, such as carbon emissions and resource depletion. Koseoglu et al. [9] stress that technology choices should align with community needs and operational capacities. Tools such as LCCA estimate total costs over the asset's lifespan, LCA evaluates environmental impacts, and CBA balances economic and social benefits.

Trade-off analysis examines the balance between environmental costs and benefits. The studies by Pryce et al. [10] and López-Serrano et al. [11] compare traditional methods with alternatives such as vertical flow constructed wetlands (VFCWs), weighing how well they work against their environmental impact. Mo et al. [14] and Harris et al. [15] propose combining financial and environmental evaluations by integrating LCCA and LCA. Tools like Multi-Criteria Decision Analysis (MCDA) weigh these varied factors, ensuring that decision-makers can find sustainable solutions that are both economically and ecologically conscious.

In the optimal replacement scheduling stage, the goal is to create a maintenance and replacement schedule that minimizes costs while maximizing utility efficiency. Nugroho et al. [20] point to the importance of determining optimal replacement times based on failure probabilities, while Ghobadi et al. [19] advocate for optimizing investment levels to sustain system performance over the long term. Optimization algorithms and Bayesian statistics help forecast failure rates and manage uncertainty, enabling managers to allocate resources effectively and prevent premature failures.

Community and stakeholder involvement is crucial in ensuring that infrastructure decisions reflect the needs and priorities of local communities. Koseoglu et al. [9] emphasize the importance of stakeholder engagement in aligning proposed solutions with community demands for improvement. Feedback from stakeholders is essential for selecting appropriate technologies and investment strategies. We can integrate public input into the planning process, balancing community needs with financial and environmental considerations, through tools like stakeholder engagement processes and participatory decision-making frameworks.

Finally, in the Monitoring and Adaptation Stage, continuous performance monitoring and adaptation based on real-time data ensure that water utility systems remain effective and sustainable over time. Mo et al. [14] underscore the importance of using performance metrics, such as water loss rates and energy consumption, to assess system performance. LCCA is re-evaluated periodically to adjust investment strategies, while LCA is reassessed to monitor ongoing environmental impacts, enabling adaptation as new data emerges.

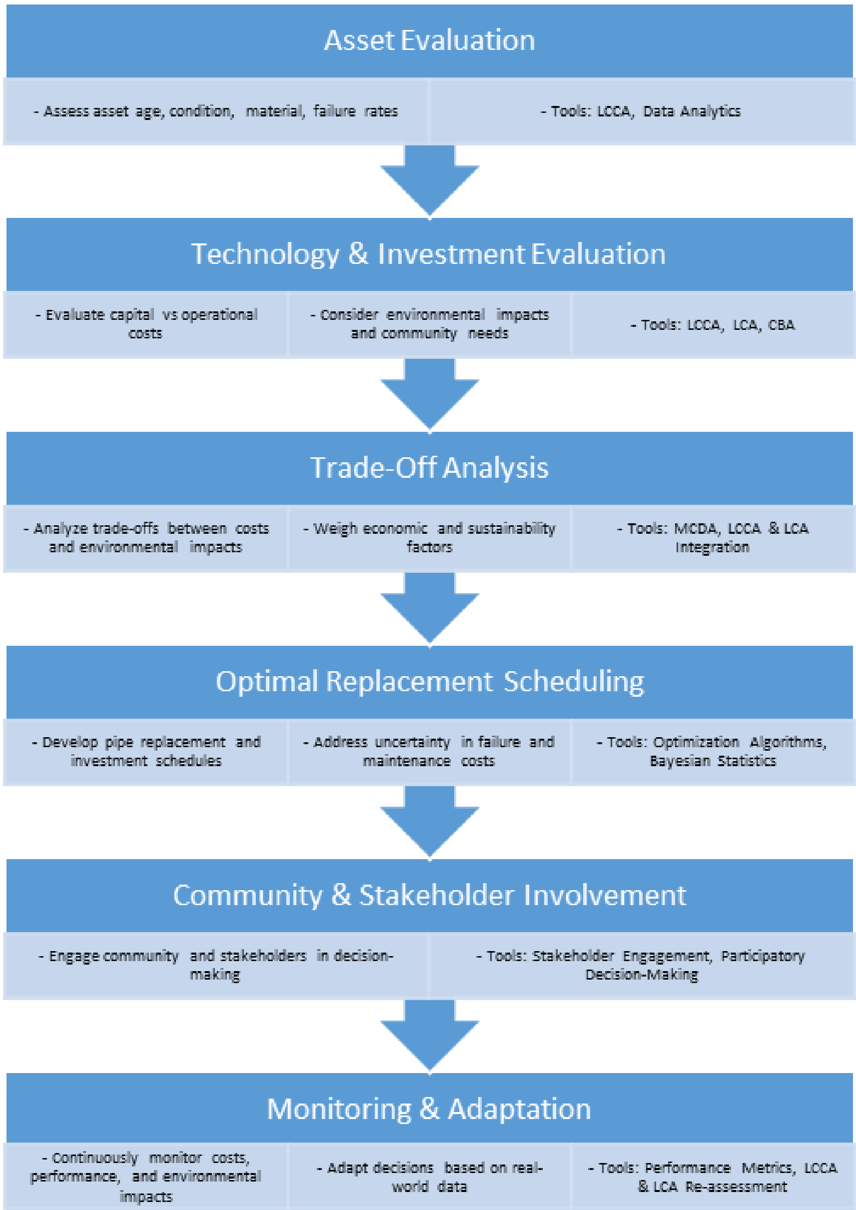

Figure 5. The framework for life-cycle-based decision-making in water supply utility management

This life-cycle-based paradigm provides a systematic approach to managing water utilities by integrating operational, financial, and environmental factors. By reconciling immediate expenses with enduring advantages, decision-makers can establish robust, reliable, and environmentally sustainable water delivery systems through the integration of LCCA, LCA, and CBA. This strategy enables infrastructure systems to adjust to evolving conditions by prioritizing stakeholder involvement, routine inspections, and adaptive management. The research determined that piped water systems are more cost-effective than point sources when including capital expenditures and emergency water supply expenses in a life cycle cost analysis.

The framework is a representation of the relationships described in the bibliometric network, with processes that serve as practical implementations of the identified concepts. The goal of asset evaluation, which stems from resource cost and water scarcity, is to comprehend the state of resources and their infrastructure. This evaluation emphasizes the importance of considering resource costs and the impact of water scarcity in asset management. Subsequently, technology and investment evaluation, rooted in affordable technology and sustainability, focuses on selecting cost-efficient and environmentally friendly technologies while ensuring that investments support long-term sustainability.

Trade-off analysis, as a derivative of political economy, water pricing, and resource cost, involves analyzing the balance between costs, benefits, and sustainability. This process helps determine socially, economically, and environmentally optimal solutions, including those related to fair water pricing. Water Markets and Decision-Making inform Optimal Replacement Scheduling, which employs data to efficiently schedule asset replacements. We also leverage water markets to enhance optimal resource allocation.

Political Economy and Decision-Making's reflection of community and stakeholder involvement emphasizes the significance of social and political factors in decision-making. This ensures that decisions meet multiple parties' needs. Finally, Monitoring and Adaptation, stemming from the concept of Sustainability, underscores the need for ongoing monitoring and adaptation to changing conditions. This process ensures that the framework remains dynamic and relevant in addressing evolving challenges. Thus, this framework maps the implementation of concepts from the network visualization into practical steps aimed at achieving efficient, sustainable, and inclusive water resource management.

3.3.4 Risk-based research

The bibliometric network in the image highlights interconnected themes such as sustainability, water scarcity, resource costs, water pricing, and water markets, all of which align with the principles of risk-based research in water management. Risk-based research focuses on identifying, assessing, and mitigating uncertainties and vulnerabilities across these thematic areas to enhance resilience and ensure sustainable water utilities. In the sustainability cluster, risk-based approaches inform decision-making processes by evaluating the potential risks and benefits of adopting affordable technologies and greywater reuse systems, ensuring that innovations are both cost-effective and reliable under varying conditions. The water scarcity and resource cost cluster reflects the importance of probabilistic simulations and accounting provisions, showcasing how risk assessments help predict water deficits, resource depletion, and the impacts of climate variability. Similarly, the water pricing cluster emphasizes how externality costing and single-block pricing can mitigate financial risks by incorporating environmental and social costs, promoting equitable access while preventing overuse or depletion. The cost recovery and environmental cost cluster highlights how risk-based frameworks ensure that pricing structures cover operational and maintenance costs, safeguarding long-term service delivery. In the water markets and political economy cluster, risk assessments help shape policies that balance market efficiency with equity, minimizing the risks of resource monopolization or political interference. By integrating risk-based research across these clusters, water utilities can proactively address uncertainties, ensuring more adaptive, equitable, and sustainable management strategies.

Within the realm of risk-based research, numerous scholars have employed a trade-off methodology to analyze the relationship between costs and risks. In their study, Tran et al. [22] took into account the planning period and projects for 2020–2040, the future supply and demand for water, and the total expenses (capital costs) needed to meet this need in Florida, USA. The use of a probabilistic-based approach to evaluate the uncertainty of the investment costs needed to fulfill future water demand makes this study unique when compared to earlier research. To meet the state's future water needs, this study emphasizes the need for more cost-effective combinations of demand management techniques and alternative water supply options, as well as the development of more flexible funding strategies at the local, regional, and state levels. Previous researchers have developed a risk-based approach for evaluating cost designs. Haider et al. [23] examined failure and risk in their study by using MCDA within a fuzzy-AHP framework. Their suggestion was to employ non-metallic materials in order to reduce failure costs and losses. This study illustrates how risk-based analysis may affect the choice of materials. Raspati et al. [24] employed probabilistic statistical methods for risk level analysis as a foundation for decision-making, establishing a risk-based rehabilitation priority plan for a water utility. They consider data from physical, operational, environmental, and failure history. The analysis's conclusions offer suggestions for how to prioritize the water supply system's rehabilitation zoning. This study used probabilistic statistical approaches to create a rehabilitation priority plan based on risk assessment. When making decisions about restoration, the strategy emphasizes the importance of operational, failure history, physical, and environmental data.

Researchers in the past have studied the concept of cost-risk trade-off. Berglund et al. [25] investigated the COVID-19 risks to water utility operations and vulnerabilities based on a review of the literature and an observation of the financial standing of water utilities in North America. Their findings show that COVID-19 caused losses for the majority of water companies (51.8%). This explanation illustrates how to assess the costs of WDS using a risk-based methodology. The results showed that most utilities suffered financial losses as a consequence of the pandemic. These results highlight the importance of risk analysis in managing uncertainty and international crises. The goal of the risk-based strategy presented in this paper is, in short, to include risk in the planning and decision-making process so that water supply systems can be managed more adaptably and responsively in the face of changing and unpredictable circumstances. Yao [26] investigated the resilience of water and electric power utilities to fluctuations in income due to water resource uncertainty by applying revenue analysis and uncertainty simulations in multiple scenarios. When utilities achieve two-thirds of their water service responsibilities, they are the most resilient to losses, according to a dataset that includes information on water availability in reservoirs, pumping capacity, hydropower capacity, water balance statistics, water pricing, and electricity tariffs. Furthermore, some researchers have developed risk-derived cost design assessments. Yao [26] used uncertainty models to investigate how resilient utilities are to revenue swings brought on by unpredictability in the water supply. According to the research, utilities that fulfill two-thirds of their water supply responsibilities show the best degree of resilience to losses. Shin et al. [27] used an optimal rehabilitation model that included genetic algorithms and cost analysis to create a risk-based water utility renewal plan. Variables like vulnerability indices and failure statistics were considered in this approach. To evaluate the reduction of microbiological risks in a drinking water treatment system, Bergion et al. [28] used a risk-based cost-benefit analysis approach. They applied methodologies from water quality modeling and cost-benefit analysis (CBA). A unique decision model for reducing microbiological risk was created using information from the examination of the quality of the raw water, investment costs, yearly operating costs, advantages, and technical specifications of the water treatment system.

Table 3 displays the content analysis and theoretical mapping of risk-based research.

Table 3. Content analysis of risk based research

Authors	Main Concept	Research Objective
[22-24]	Risk based cost assesment	Probabilistic water balance [22], risk-based rehabilitation and inspection plan [23], risk-based rehabilitation zoning [24]
[25-28]	Cost-risk trade-off	Water utility COVID-19 risk assessment [25], water utility uncertainty resilience [26], risk-based water utility renewal plan [27], mitigation plan evaluation [28]

Figure 6 illustrates the design of the Risk-Based Cost Analysis Framework for Water Utility Management, which integrates various risk-based methodologies to enhance decision-making throughout the water utility's life cycle. These methodologies include MCDA, fuzzy Analytic Hierarchy Process (fuzzy-AHP), probabilistic models, and optimization algorithms. The framework's primary goal is to align investment decisions, rehabilitation strategies, and cost evaluations with comprehensive risk assessments, thereby improving the resilience of water supply systems while minimizing costs associated with failures. The initial phase centers on risk assessment, evaluating risk levels through the analysis of physical attributes, operational data, and historical failure records. This involves conducting failure analysis to identify high-risk zones within the water supply system, utilizing both physical and operational data, as highlighted by Haider et al. [23]. The integration of MCDA with fuzzy-AHP helps quantify risks through risk scores, and probabilistic statistical techniques are employed to assess the likelihood of failures over time. Following the risk assessment, the framework emphasizes risk-based rehabilitation and material selection. This stage prioritizes rehabilitation actions and material replacements based on the identified risks. We use probabilistic risk analysis to recommend priority areas for rehabilitation, and suggest non-metallic materials to reduce long-term failure rates and costs. We further support decision-making by developing a risk-based priority plan and conducting CBA, which evaluates the financial implications of material choices.

The framework also addresses resilience and uncertainty management, focusing on enhancing the ability of water utilities to withstand financial losses stemming from unpredictable conditions, such as variations in water availability or global crises like the COVID-19 pandemic. We analyze revenue resilience to manage fluctuations due to supply uncertainties, and we use simulations of revenue and water availability to predict financial resilience under various scenarios. We also integrate risk-based cost models into the cost structures for water delivery and revenue management. The subsequent phase focuses on the optimization of rehabilitation and renewal plans, aiming to develop optimal schedules for rehabilitation and renewal activities through risk and cost analysis. We utilize failure statistics and vulnerability indices to optimize rehabilitation actions, and employ genetic algorithms to formulate an optimal renewal plan that balances costs and failure risks. The optimization process guarantees the efficient allocation of resources.

Another critical aspect of the framework is risk-based investment and cost evaluation. This stage assesses investment strategies and operational costs with a focus on risk analysis and cost-benefit assessments. We analyze the costs and benefits of mitigating microbiological risks within drinking water systems, seeking a balance between operational costs and the advantages of reducing these risks. We employ tools like CBA and water quality modeling to develop investment models that minimize microbiological risks, and we guide investments in advanced water treatment technologies using risk-based approaches.

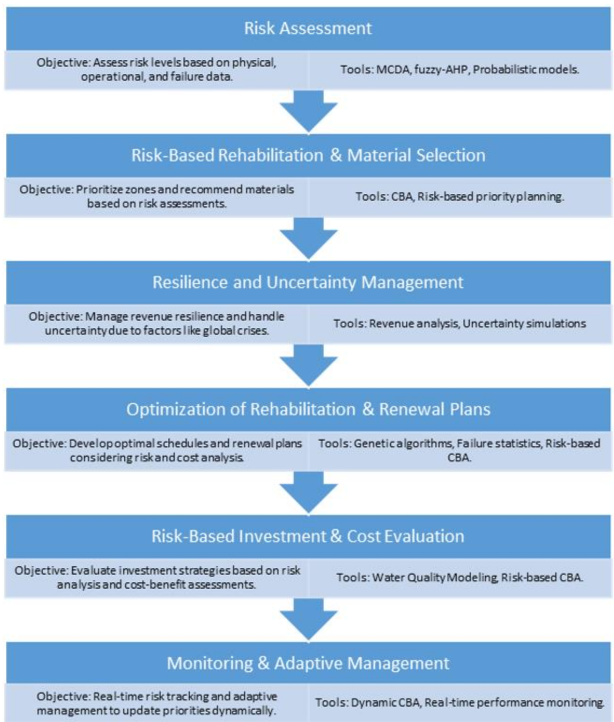

Figure 6. The risk-based framework for water utility management

Finally, the framework emphasizes continuous monitoring and adaptive management. This involves real-time risk monitoring systems to track the health of the infrastructure, allowing for dynamic adjustments in rehabilitation priorities. Adaptive management practices enable modifications to investment and operational strategies based on evolving risk profiles and cost-benefit analyses. We develop key performance indicators that reflect both risk levels and financial outcomes, and utilize dynamic CBA to reassess costs and benefits in real time, ensuring an agile decision-making process that can adapt to changing conditions. In conclusion, this risk-based cost framework highlights the significance of integrating risk assessments at each stage of water utility management. By focusing on rehabilitation prioritization, material selection, financial resilience, and adaptive management, the framework effectively employs MCDA, probabilistic models, optimization techniques, and cost-benefit analysis. This comprehensive approach ensures that decision-making processes account for both risks and costs, leading to the development of more resilient, flexible, and cost-effective water supply systems. By embedding risk considerations into the management of water infrastructure, utilities can enhance their operational efficiency and service delivery, ultimately benefiting both the utility and the communities they serve.

In the bibliometric network, water pricing encompasses elements such as the cost recovery principle, environmental cost, and externality costing. These concepts form the basis for managing water resources in a fair, efficient, and sustainable manner. These ideas are put into practice by the framework's risk-based investment and cost evaluation. It uses the cost recovery principle and externality cost assessment to judge investments based on risk and cost analysis. Additionally, optimization of rehabilitation and renewal plans minimizes environmental and economic costs, aligning with the environmental cost approach.

The concept of water scarcity in the bibliometric network focuses on aspects such as stochastic simulation and the probability of water shortages, emphasizing the need to understand risks and uncertainties in water management. This is put into action by the framework's risk assessment, which uses simulations and probabilistic methods to figure out the risks of physical, operational, and failure scenarios. This helps to figure out the effects of not having enough water. Similarly, resilience and uncertainty management address uncertainties related to revenue and global impacts, reflecting the risks associated with water scarcity.

The bibliometric network's resource cost incorporates the principles of cost recovery and environmental cost assessment, guaranteeing the appropriate valuation of water resources. The framework reflects this through risk-based rehabilitation and material selection, where risk analysis informs material selection and prioritization, taking into account cost efficiency and environmental impacts. Additionally, risk-based investment and cost evaluation incorporates risk into cost evaluation to optimize resource utilization.

The bibliometric network links sustainability to decision-making based on affordable technology and sustainability principles. The framework implements this through monitoring and adaptive management, ensuring long-term sustainability by enabling real-time monitoring and adaptive management to dynamically adjust plans. The optimization of rehabilitation and renewal plans further supports this, taking into account the long-term environmental and societal impacts of water management strategies.

The bibliometric network introduces the concept of political economy. It highlights its role in relation to water markets, which require evidence-based policies and strategic decision-making. The framework translates this into risk assessment, which incorporates policy and operational data in risk analysis to help decision-makers understand the economic and political implications of their actions. Furthermore, resilience and uncertainty management focuses on managing political and market uncertainties that can affect water availability and pricing.

Overall, the framework integrates theoretical concepts from the bibliometric network into practical, solution-oriented steps. It adopts a holistic approach by encompassing interconnected elements such as water scarcity, sustainability, and resource cost. At its core, the framework emphasizes risk and cost analysis as essential components of decision-making, bridging the gap between theoretical insights and actionable water resource management strategies.

3.3.5 Cost-benefit and investment research

The bibliometric network highlights five interconnected clusters in water management research, offering a comprehensive perspective on cost-benefit analysis (CBA) and investment strategies. Clusters such as sustainability, water pricing, and cost recovery principles demonstrate the critical role of economic frameworks in shaping policies that ensure long-term water security. The decision-making process within the sustainability cluster relies heavily on CBA to assess affordable technologies and the environmental impact of greywater reuse. Simultaneously, the water scarcity and resource cost clusters focus on forecasting risks through stochastic simulations and probabilistic models, addressing challenges posed by climate change and resource depletion. The water markets and political economy cluster underscores the influence of regulatory frameworks and market-based approaches in resource allocation, directly affecting investment flows and pricing strategies. By linking economic principles with environmental sustainability, this interconnected analysis highlights the necessity for integrated investment models that align with equitable access, resource conservation, and resilient water infrastructure development.

Several researchers have studied research topics using the concept of Investment and development assessment. Mcharo and Maghenda [29] employed the CBA and NPV approaches to evaluate land conservation and water management programs in upstream watersheds. They considered initial cost variables, annual maintenance costs, and conservation technology costs. Their findings indicated that the NPV remained positive despite an 80% reduction in income. Saboori [30] devised a water treatment facility that utilized renewable energy sources. The objective was to minimize the levelized cost of water (LCOW) by employing simulation techniques and a mathematical model. The factors provided include investment costs, operating expenses, energy costs, and maintenance costs of the water treatment unit. The objective is to optimize the use of electricity and water storage in order to reach the minimal low coefficient of variation (LCOW) condition. Research in the field of cost and investment studies also explores the trade-off concept approach between cost variables and asset reliability. Ahopelto and Vahala [31] conducted a cost-benefit analysis of three investment-based leakage control techniques: district metering, pressure reduction, and pipe upgrades. To find the most pertinent information for leakage analysis and national policymaking, we also performed sensitivity and uncertainty analyses. The findings suggest that utilities with moderate leakage levels may not directly benefit financially from water loss management. To establish leakage targets for the Finnish utility, neither the leakage percentage nor the Infrastructure Leakage Index (ILI) was appropriate. The most significant influencing elements in the sensitivity study were the costs of renovating or purchasing district metering; the findings demonstrated that the predicted values were accurate enough to evaluate leakage regulations. Ratnaweera et al. [32] identified financial valuation gaps in the regional and worldwide CBA standards supporting investment cases in an article. Analyses of assessment reports from Scandinavia, prepared in compliance with these principles, reveal a concerning lack of financial valuation for the social and environmental effects of water sector initiatives. The results indicated that more comprehensive and approachable recommendations for valuation techniques tailored to the water sector were required. Theoretically, it explains how water utility project managers might benefit from a more user-friendly CBA framework, with a focus on secondary source data and monetary valuation techniques. This study finds that the guidelines' partial discussion of valuation techniques should be modified and applied to water utility projects in a timely and economical manner. Nafi and Brans [33] used CBA and artificial neural network (ANN) approaches to investigate the expected costs and benefits of asset management operations on a Water Distribution Network (WDN). They created an optimization strategy that considers the budget and water efficiency ratio using data from water utility, construction expenditures, and operating expenses. Skourtos et al. [34] have developed a probabilistic framework to aid in the appraisal of investments in water treatment projects that utilize desalination technologies. The levelized cost of energy (LCOE), levelized cost of water (LCOW), and probability analysis are used in this framework to take into account variables including investment costs, operating expenses, initial costs, heat rate, treatment unit capacity, and facility life. With reference to project finance (PF) and public-private partnerships (P3s), Gonzalez-Ruiz et al. [35] created an investment valuation model based on blue bonds and the mezzanine debt mechanism. This study applies the financial captured value (FCV) theory to measure the potential financial value that lenders could gain from financing sustainable infrastructure systems (SIS). The empirical findings demonstrate that lenders can profit financially from the conversion of outstanding debt into equity shares at the stage of operation and maintenance. Results from case studies also shed new light on how the debt-to-equity conversion ratio affects the correlation between the sponsors' IRR and the FCV. Martinez-Dalmau et al. [36] examined the implications of irrigation water prices in various regions. They used a hydro-economic model that takes a basic cost analysis method and uses hydrological and socioeconomic aspects to calculate water pricing. They also considered other pertinent factors, such as data on water availability and water demand. According to the current study, cropping patterns are impacted by irrigation water costs, which in turn affect agricultural profitability.

Numerous scholars have investigated the notion of water commodity pricing. Thomas et al. [37] examined the application of the Full Cost Recovery (FCR) strategy in urban water management. They use a water pricing strategy and take into account several important variables, such as the number of customers, capital and operating expenses, energy costs, and opportunity costs. The current research proves that the least water price may be achieved and the return on investment can be maximized by using a multi-block pricing strategy. Zetland [38] examined the role that pricing plays in managing water shortages by doing a thorough literature review and data analysis on water prices, revenues, supply, and demand in the Netherlands. It is advised that prices that take into account both water demand and income high enough to pay for the costs of maintaining a continuously dependable supply of water be the foundation for efficient management of water shortage. Sanabria and Torres [39] used probabilistic statistics in conjunction with the water pricing approach to establish a water price that took resource conservation and environmental costs into account. Costs associated with conservation, water production, and consumption were the variables taken into account. The researchers came to the conclusion that production and conservation objectives should be balanced in the optimal water pricing. The impact of water prices on the differences in water usage between different regions of Spain was examined in the study by García-López et al. [40]. After analyzing customer, water use, and water utility data, the researchers came to the conclusion that geographical features should not be taken into account when setting water rates, since this will not encourage efficient use and adequate funding of water services. Expósito [41] examined the application of the cost recovery principle in irrigation water service units using the cost recovery rate and water price analysis approach. The analysis took into account a number of variables, including revenue, tariffs on irrigation water, pricing, and environmental and financial consequences. Lee et al. [42] conducted a thorough analysis of the quantitative sustainability metrics suggested for WDS and their sustainable development. The reviews led to two main recommendations: instead of concentrating on impacts, consider balancing utilization (cost) and gain (benefit); additionally, consider indirect (cascading/consequential) interactions. Overall, to support a focus on restorative systems, optimize benefits, and allow for multidisciplinary and larger assessments, current sustainability metrics and sustainable development techniques in WDS must be expanded. In 2020, García-López and Montano [43] investigated the water tariff that Spanish families paid to assess the suitability of the river-basin method that was set forth by the water framework directive. The analysis focuses in particular on the interregional variations in water prices in Spain and identifies the key determinants of household water consumption. The outcomes obtained via minimal ordinary squares and 2-stage least squares demonstrate the significant impact of pertinent variables, such as household composition, since the rate structure penalizes the most populous households.

Research on the cost-reliability trade-off explores the balance between maintaining high system reliability and managing costs, a critical aspect in fields like water utility management, manufacturing, and operations. This trade-off is essential because achieving higher reliability often requires additional resources, such as improved materials, more frequent maintenance, or redundancy, which can significantly increase costs. Conversely, cutting costs can result in lower reliability and increased risks of system failures. Zangenehmadar et al. [44] used genetic algorithms and economic analysis to develop a pipe repair plan for a WDN. To establish the best repair timetable that maximizes resource efficiency, the plan combined physical pipe data, damage categories, historical damage numbers, mobilization costs, repair costs, and replacement costs. The explanation given provides a comprehensive overview of the risk- and cost-based research methodology used in water supply system management. The presented studies demonstrate the application of technologies such as genetic algorithms and CBA in the evaluation and strategic planning of improvements and investments in water utilities. Kim et al. [45] used a risk-based economic approach to calculate the pipe failure rate and water pipe renewal period. They applied probabilistic statistical analysis techniques, NPV, and CBA. To create the optimal pipe renewal period plan that takes the benefit-cost ratio into account, this study makes use of physical pipe data, failure rate, repair costs, replacement costs, and damage costs. D'Ercole et al. [46] proposed a modeling approach that provides a robust tool for intervention action planning, enhancing the efficiency of a water supply system while considering energy consumption and environmental impacts. Because of limited funds, this study shows how to use the suggested method to plan pipe rehabilitation or replacement while maximizing network mechanical dependability, lowering the risk of unmet water demand, and checking the pressure deficit at the node level. Mazumder et al. [47] observed US water utilities and examined the literature to evaluate the management and performance of assets in WDS. Many research studies that examine the price of water also employ a methodology that takes into account cost restrictions and environmental effects. The purpose of this research is to determine whether adding cost, risk, and pricing mechanisms to the management of water resources could improve sustainability and efficiency. These research findings provide important insights for better decision-making. This study develops a repair cost scheme that integrates many performance evaluation methodologies using data on various asset failure categories and estimated repair expenditures.

As indicated in Table 4, content analysis and theoretical mapping of investment and cost-benefit studies.

Table 4. Content analysis of cost-benefit and investment research

Authors	Main Concept	Research Objectives
[29-35]	Investment and development assessment	Water conservation plan [29], infrastructure design [30], pipe network investment plan [31], infrastructure costing framework [32], cost optimization [33], facility investment framework [34, 35]
[36-43]	Water pricing and cost recovery assesment	Water price assessment [36, 42], cost recovery policy [37], water tariff structure [38], resource based water tariff [39], regional water price assessment [40], cost recovery assessment [41]
[44-47]	Cost-reliability trade-off	Infrastructure renewal optimization [44], economic-based rehabilitation plan [45], future rehabilitation strategy [46], facility maintenance scheme [47]

Figure 7 illustrates the Framework for Cost-Benefit and Investment Evaluation in Water Utility Management, which integrates several investment evaluation methodologies to optimize water utility. Evaluation of the projects and technology related to the water utility's financial feasibility is the main goal of the first stage. Using techniques like Artificial Neural Networks (ANN), NPV, and CBA, the goal is to assess how well costs and anticipated gains are balanced. To assess watershed-wide water management and conservation initiatives, Mcharo and Maghenda [29] utilized NPV and CBA methodologies. Despite an 80% drop in income, their research showed a positive NPV. Nafi and Brans [33] evaluated asset management practices in water distribution by maximizing budget allocation and raising water efficiency ratios through the application of CBA and ANN. With an emphasis on factors like LCOE and investment costs, Skourtos et al. [34] developed a probabilistic methodology for investment evaluations in desalination plants.

The second stage aims to develop pricing mechanisms that facilitate cost recovery, resource conservation, and effective demand management. This involves considering socio-economic and environmental factors and employing tools like hydro-economic models, multi-block pricing, and probabilistic statistics. By using multi-block pricing techniques, Thomas et al. [37] investigated the FCR strategy in urban water management, resulting in reduced water prices and increased returns on investment. Zetland [38] further explored water scarcity management by utilizing pricing mechanisms that balance supply and demand. Additionally, Sanabria and Torres [39] applied probabilistic statistics to create water pricing strategies that effectively balance environmental and conservation costs.

The objective of the next stage is to optimize utility renewal and rehabilitation schedules while minimizing operational costs. Tools such as simulation techniques, genetic algorithms, and cost-benefit analysis are employed here. For instance, Saboori [30] focused on optimizing water treatment facilities by utilizing renewable energy and simulation techniques, aiming to reduce the LCOW. Similarly, Zangenehmadar et al. [44] devised a pipe repair strategy for water distribution networks using genetic algorithms to determine optimal repair schedules that maximize resource utilization.

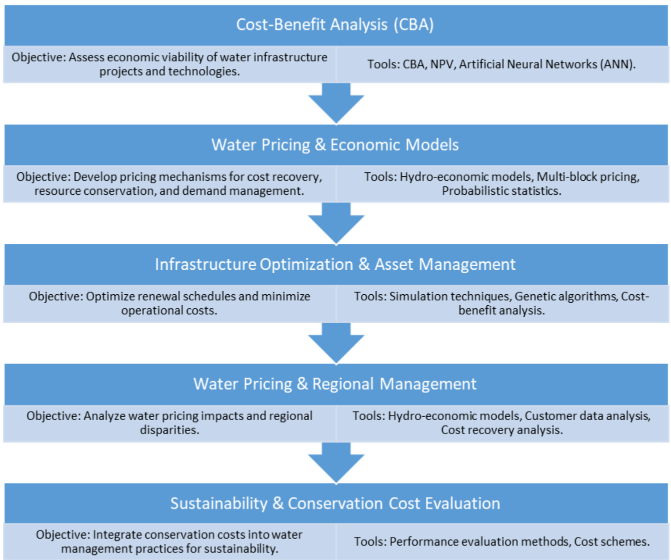

Figure 7. The framework for cost-benefit and investment evaluation in water utility management

Another stage analyzes the impact of water pricing on agriculture, irrigation, and regional disparities, ensuring sustainable water use and agricultural profitability. Tools used include hydro-economic models, customer data analysis, and cost recovery analysis. Martínez-Dalmau et al. [36] employed hydro-economic models to assess irrigation water pricing, linking it to socio-economic and hydrological factors, while García-López et al. [40] analyzed water tariffs to understand regional disparities in consumption. Expósito [41] examined cost recovery principles applied to irrigation water services.

The final stage integrates conservation costs into water management practices to promote sustainability. Performance evaluation methods and cost schemes are utilized for this purpose. Mazumder et al. [47] focused on asset management and repair cost schemes for WDS, while Sanabria and Torres [39] developed water pricing methods that incorporate environmental and resource conservation costs to achieve sustainability. Overall, this framework emphasizes the importance of balancing costs, optimizing utility, and incorporating sustainability principles to ensure efficient resource utilization and promote long-term sustainability in water system management.

The framework transforms the conceptual relationships in the bibliometric network into structured and actionable steps for implementation. Each stage in the framework reflects specific elements from the bibliometric network concept map. For example, cost-benefit analysis (CBA), which stems from concepts such as resource cost and environmental cost in the bibliometric network, is translated into the initial stage of economic feasibility analysis. This ensures that decisions are based on a comprehensive understanding of both economic and environmental impacts. Similarly, Water Pricing and Economic Models explores the connection between water pricing, recovery principles, and political economy in the bibliometric network. It provides a framework for developing pricing mechanisms that are grounded in sound economic models, thereby fostering fairness and efficiency in the management of water resources.

The framework also operationalizes Infrastructure Optimization and Asset Management by building on the bibliometric network concepts of water scarcity and financial responsibilities. We transform these ideas into actionable strategies to optimize resource utilization and manage infrastructure effectively, ensuring long-term sustainability. Additionally, Water Pricing and Regional Management addresses regional disparities highlighted in the bibliometric network, such as water markets and inequities across regions, by incorporating steps to analyze and address pricing differences, thereby promoting equitable access to water resources.

The framework finally adopts Sustainability and Conservation Cost Evaluation, a central theme in the bibliometric network, as the concluding stage. This stage focuses on evaluating conservation costs and environmental impacts to ensure that all actions align with long-term sustainability goals, balancing economic, social, and environmental considerations. By translating theoretical insights from the bibliometric network into practical steps, the framework provides a structured and holistic approach to effective and sustainable water resource management.

3.4 Discussions

This study identified and integrated economic, environmental, and technological factors into a comprehensive cost framework for sustainable water supply utility. This approach emphasizes the importance of considering various cost components to achieve the long-term sustainability of water supply utility systems. The analysis of theme occurrences highlights the importance of a comprehensive and balanced strategy for managing water supply utilities, which takes into account technological, economic, environmental, and political factors to ensure sustainable and equitable water management for all stakeholders.

From 2018 to 2023, research on water supply utilities experienced significant growth, with the focus evolving over time. In early 2018, research focused on resource costs, particularly related to the water supply life cycle, such as procurement, treatment, and distribution. The goal was to understand the factors that influence the efficiency and cost of water supply systems in order to reduce operational costs. In 2020, the focus shifted significantly to water scarcity and pricing. This research highlights how water prices can encourage conservation and influence user behavior and how water scarcity influences resource management policies and strategies. In 2021, research becomes more complex, focusing on the political economy and water markets. This research examines the mechanisms of trade and resource allocation in market systems and the impact of political policies and authorities on water distribution and access. Social and sustainability aspects are also of major interest. From 2022 to 2023, the main research theme is sustainability, with an emphasis on applying sustainability principles to all aspects of water resources management. This research highlights the importance of ensuring that water supply systems meet the needs of the present without compromising the ability of future generations to meet their own. Overall, the evolution of this research theme reflects a changing perspective on water management. The focus has shifted from simply efficiency and cost to broader considerations including prices, scarcity, markets, politics, and sustainability. This shift highlights the growing need for more comprehensive and sustainable solutions to the increasingly complex challenges of water management.

To enhance the sustainability of water supply utilities, it is essential to establish and validate a comprehensive cost framework that integrates economic, environmental, and technological factors. Such a framework ensures that all relevant costs are aligned with desired objectives, facilitating informed decision-making and ultimately leading to improved societal outcomes. This approach enables the design of water supply utilities that not only meet current demands but also remain sustainable and resilient in the face of future challenges. Future research should focus on developing more flexible and effective methods for the widespread implementation of this framework to address evolving needs and challenges.

A review of previous studies highlights three foundational approaches to cost management in water resource utility assets: life-cycle analysis, risk-based analysis, and cost-benefit and investment analysis. Life-cycle cost analysis evaluates the total expenses of an asset throughout its lifespan, including planning, construction, operation, maintenance, and disposal or replacement. This approach is often used to select design alternatives, develop technologies, and create operational and maintenance plans to optimize long-term expenditures. Cost-benefit and investment analysis focuses on initial investments and operational expenses, emphasizing cost recovery and appropriate water pricing to ensure the recoupment of project costs through revenue. Risk-based analysis assesses potential risks and uncertainties that may affect costs and asset performance, such as environmental changes, price fluctuations of raw materials, or unforeseen damage. By integrating these approaches, decision-makers can create a robust and adaptable cost framework that supports the sustainable management of water supply utilities.

The empirical and theoretical foundations of these three concepts provide a basis for future research and development. Integrating existing approaches allows for the creation of a more comprehensive and adaptive cost management model. Future research should focus on the impact of asset reliability, particularly its role in achieving full cost recovery by accounting for repair costs often excluded from traditional life cycle analyses. Evaluating and improving asset reliability is essential for optimizing system performance. Additionally, advancements in technologies and methodologies can further enhance the efficiency and resilience of water resource utilities. However, further research is needed to assess and validate the effectiveness of these innovations across diverse contexts. By adopting this approach, future studies can contribute to the development of a more robust and adaptive framework for managing water utility costs while promoting sustainable and efficient management practices, as illustrated in Figure 8.

Future research opportunities can be explored by creating or integrating concepts that focus on recent developments in the field. Previous studies have primarily concentrated on determining water pricing and achieving cost recovery through investment analysis. Additionally, life-cycle cost analysis has been widely employed to select alternative designs, develop technologies, and formulate operational and maintenance plans. Future research could integrate the trade-off between life-cycle costs and asset reliability with the concepts of water pricing and cost recovery. Asset reliability often presents challenges to achieving full cost recovery (FCR) due to unanticipated expenses, such as repair costs, that are not typically accounted for in life-cycle analyses. Addressing these empirical issues will further support the development of a more robust and comprehensive framework for managing water utilities.

Figure 8. Future research based on main concept

4. CONCLUSIONS

This study contributes to the field of sustainable water supply management by proposing a comprehensive cost framework that integrates economic, environmental, and technological factors. The framework highlights the importance of balancing multiple dimensions—such as life-cycle costs, water pricing, and asset reliability—to achieve long-term sustainability and resilience in water supply utilities. By addressing key themes such as resource efficiency, environmental impact, and socio-economic considerations, this research underscores the need for a holistic approach to managing water systems that can adapt to evolving challenges.

This study's bibliometric analysis reveals the dynamic evolution of research on water supply utilities from 2018 to 2023. Early research primarily focused on operational efficiency and resource costs, but recent studies have expanded to include critical topics such as water scarcity, pricing mechanisms, political economy, and sustainability principles. This shift reflects a growing recognition of the complex, interconnected nature of water management challenges and the need for solutions that address both immediate demands and long-term goals. The analysis also highlights significant contributions from diverse disciplines, such as civil engineering, environmental science, and geographic planning, emphasizing the interdisciplinary nature of sustainable water resource management.

A key insight from this study is the role of geographic and urban planning in shaping water management strategies. Research on cost assessment in water supply has moved beyond technical and engineering aspects to incorporate spatial and developmental considerations. This indicates the importance of tailoring water supply systems to specific geographic and socio-economic contexts to maximize their impact and sustainability.

The study identifies three primary analytical approaches—life-cycle analysis, cost-benefit and investment analysis, and risk-based analysis—as critical tools for cost management in water utilities. Life-cycle analysis offers a comprehensive understanding of costs across an asset's entire lifespan, enabling the optimization of design, technology, and maintenance schedules. Cost-benefit and investment analysis focuses on initial investments, water pricing, and cost recovery mechanisms, ensuring financial sustainability. Meanwhile, risk-based analysis addresses uncertainties such as environmental changes and unanticipated costs, ensuring robust and adaptable management strategies.

The Life-Cycle-Based Decision-Making Framework translates bibliometric network insights into actionable strategies for efficient, sustainable, and inclusive water resource management. Resource costs and water scarcity drive the integration of asset evaluation, ensuring optimal infrastructure performance. Technology and investment choices prioritize cost-effective, sustainable solutions. Trade-off analysis balances economic, social, and environmental goals, promoting equitable water pricing and resource distribution. Data-driven optimal replacement scheduling enhances resource allocation, while community involvement in decision-making ensures transparency and stakeholder alignment. Continuous monitoring and adaptation maintain the framework's relevance, fostering resilience against evolving challenges.

The Risk-Based Framework operationalizes theoretical principles through risk-based investment and cost evaluation, optimizing rehabilitation and renewal plans to minimize economic and environmental costs. Addressing water scarcity through stochastic simulations and probabilistic modeling, it evaluates risks and uncertainties to mitigate the effects of shortages, enhancing resilience and uncertainty management in response to revenue fluctuations and global challenges. The bibliometric network also emphasizes the importance of proper resource valuation through cost recovery and environmental assessments, informing risk-based material selection and resource allocation. Adaptive management and real-time monitoring ensure sustainability and long-term environmental and societal benefits. Additionally, the framework recognizes the influence of political economy, incorporating policy and operational data to guide evidence-based governance and address market uncertainties affecting water availability and pricing. Ultimately, this integrated approach bridges theoretical insights with actionable strategies, reinforcing risk and cost analysis as fundamental pillars of resilient and adaptive water management.

The Cost-Benefit and Investment Evaluation Framework integrates economic, environmental, and social considerations by translating conceptual insights from the bibliometric network into structured, actionable steps for water resource management. The framework initiates with a cost-benefit analysis based on resource and environmental cost concepts, which guides the assessment of economic feasibility. Water pricing models address fairness and efficiency by linking pricing, recovery, and political economy principles. Infrastructure optimization strategies draw from concepts of water scarcity and financial responsibility to enhance resource use and long-term sustainability. Targeted pricing analysis addresses regional disparities in water access, promoting equity. The final stage evaluates conservation costs and environmental impacts, reinforcing sustainability as a core objective. This comprehensive approach transforms theoretical ideas into practical strategies for sustainable water management.

To advance the field, future research should focus on integrating these approaches into a unified, flexible framework that accommodates diverse geographic and climatic settings. The trade-offs between asset reliability and life-cycle costs, alongside water pricing and cost recovery, require deeper exploration to develop more effective management strategies. We should rigorously evaluate emerging technologies and methodologies to enhance system efficiency, resilience, and sustainability.

This research offers a foundation for future studies to refine and expand the proposed framework, focusing on interdisciplinary approaches and innovative solutions to the increasingly complex challenges of water resource management. By bridging gaps between economic, environmental, and technological considerations, future research can contribute to the development of sustainable water supply utilities that ensure equitable access to clean water for generations to come.

ACKNOWLEDGMENT

The Ministry of Education, Culture, Research, and Technology of Indonesia provided funding and support for this project through Research Grant Program Number 018.04/II.3.AU/14.00/C/PER/VI/2024, which the authors gratefully acknowledge. The authors would also like to express their sincere gratitude to the faculty and staff of Universitas Muhammadiyah Sidoarjo (UMSIDA), whose unwavering support and guidance have been invaluable.

REFERENCES

[1] Adil, S., Nadeem, M., Malik, I. (2021). Exploring the important determinants of access to safe drinking water and improved sanitation in Punjab, Pakistan. Water Policy, 23(4): 970-984. https://doi.org/10.2166/wp.2021.001

[2] Nugroho, W., Iriawan, N. (2019). Effect of the leakage location pattern on the speed of recovery in water supply networks. Journal of Physics, 1402(2): 022023. https://doi.org/10.1088/1742-6596/1402/2/022023

[3] Nugroho, W., Iriawan, N., Utomo, C. (2021). Determining physical and operational factors influencing pipeline leakage location pattern in water distribution networks using spatial poisson point process. Materials Science and Engineering, 1098(2): 022051. https://doi.org/10.1088/1757-899x/1098/2/022051
[4] Sihombing, N.H., Utomo, C., Nurcahyo, C.B., Nugroho, W., Astarini, S.D. (2023). The cost assessment in water infrastructure within the framework of circular economy: A bibliometric analysis. In International Conference on Architecture and Civil Engineering Conference, Putrajaya, Malaysia, pp. 325-333. https://doi.org/10.1007/978-981-97-0751-5_32
[5] Zhang, C.Y., Oki, T. (2023). Water pricing reform for sustainable water resources management in China's agricultural sector. Agricultural Water Management, 275: 108045. https://doi.org/10.1016/j.agwat.2022.108045
[6] Nugroho, W., Utomo, C., Iriawan, N. (2023). A spatial data-driven decision analysis of pipe failure management in water supply system. In AIP Conference Proceedings, Bandung, Indonesia, p. 050029. https://doi.org/10.1063/5.0139420
[7] Aivazidou, E., Banias, G., Lampridi, M., Vasileiadis, G., Anagnostis, A., Papageorgiou, E., Bochtis, D. (2021). Smart technologies for sustainable water management: An urban analysis. Sustainability, 13(24): 13940. https://doi.org/10.3390/su132413940
[8] Sarkar, D. (2023). Life cycle costing analysis of grey water recycling systems for commercial and residential projects of Ahmedabad, India. Materials Today: Proceedings, 77: 254-259. https://doi.org/10.1016/j.matpr.2022.11.298
[9] Koseoglu, N.M., Ellis, R., Biswas, D. (2021). Scenario-based life-cycle cost assessment to support sustainable investment in rural communal sanitation facilities: Application to a school-based sanitation facility. Journal of Water, Sanitation and Hygiene for Development, 11(5): 771-784. https://doi.org/10.2166/washdev.2021.230
[10] Pryce, D., Alsharrah, F., Khalil, A.M., Kapelan, Z., Memon, F.A. (2022). Comparative life-cycle cost analysis of alternative technologies for the removal of emerging contaminants from urban wastewater. Water, 14(12): 1919. https://doi.org/10.3390/w14121919
[11] López-Serrano, M.J., Lakho, F.H., Van Hulle, S.W., Batlles-delaFuente, A. (2023). Life cycle cost assessment and economic analysis of a decentralized wastewater treatment to achieve water sustainability within the framework of circular economy. Oeconomia Copernicana, 14(1): 103-133. https://doi.org/10.24136/oc.2023.003
[12] Godfrey, S., Hailemichael, G. (2017). Life cycle cost analysis of water supply infrastructure affected by low rainfall in Ethiopia. Journal of Water, Sanitation and Hygiene for Development, 7(4): 601-610. https://doi.org/10.2166/washdev.2017.026
[13] Lee, H., Shin, H., Rasheed, U., Kong, M. (2017). Establishment of an inventory for the Life Cycle Cost (LCC) analysis of a water supply system. Water, 9(8): 592. https://doi.org/10.3390/w9080592
[14] Mo, W., Cornejo, P.K., Malley, J.P., Kane, T.E., Collins, M.R. (2018). Life cycle environmental and economic implications of small drinking water system upgrades to reduce disinfection byproducts. Water Research, 143: 155-164. https://doi.org/10.1016/j.watres.2018.06.047
[15] Harris, S., Tsalidis, G., Corbera, J.B., Gallart, J.J.E., Tegstedt, F. (2021). Application of LCA and LCC in the early stages of wastewater treatment design: A multiple case study of brine effluents. Journal of Cleaner Production, 307: 127298. https://doi.org/10.1016/j.jclepro.2021.127298
[16] Peña, A., Rovira-Val, M.R. (2020). A longitudinal literature review of life cycle costing applied to urban agriculture. The International Journal of Life Cycle Assessment, 25: 1418-1435. https://doi.org/10.1007/s11367-020-01768-y
[17] Ilyas, M., Kassa, F.M., Darun, M.R. (2021). Life cycle cost analysis of wastewater treatment: A systematic review of literature. Journal of Cleaner Production, 310: 127549. https://doi.org/10.1016/j.jclepro.2021.127549
[18] Jocanovic, M., Agarski, B., Karanovic, V., Orosnjak, M., Ilic Micunovic, M., Ostojic, G., Stankovski, S. (2019). LCA/LCC model for evaluation of pump units in water distribution systems. Symmetry, 11(9): 1181. https://doi.org/10.3390/sym11091181
[19] Ghobadi, F., Jeong, G., Kang, D. (2021). Water pipe replacement scheduling based on life cycle cost assessment and optimization algorithm. Water, 13(5): 605. https://doi.org/10.3390/w13050605
[20] Nugroho, W., Utomo, C., Iriawan, N. (2022). A Bayesian pipe failure prediction for optimizing pipe renewal time in water distribution networks. Infrastructures, 7(10): 136. https://doi.org/10.3390/infrastructures7100136
[21] Elsebaie, I.H., Al-Khomairi, A. (2022). Optimization of pipeline lifecycle cost using alternatives with different life spans. Water Supply, 22(2): 1835-1847. https://doi.org/10.2166/ws.2021.305
[22] Tran, D., Borisova, T., Beggs, K. (2023). The cost of alternative water supply and efficiency options under uncertainty: An application of modern portfolio theory and Chebyshev's inequality. Earth, 4(1): 40-65. https://doi.org/10.3390/earth4010003
[23] Haider, H., Almutlaq, M.A., Alodah, A., Ghumman, A.R., AlSalamah, I.S., Ghazaw, Y.M., Shafiquzzaman, M. (2022). Risk-based inspection and rehabilitation planning of service connections in intermittent water supply systems for leakage management in arid regions. Water, 14(24): 3994. https://doi.org/10.3390/w14243994
[24] Raspati, G.S., Bruaset, S., Bosco, C., Mushom, L., Johannessen, B., Ugarelli, R. (2022). A risk-based approach in rehabilitation of water distribution networks. International Journal of Environmental Research and Public Health, 19(3): 1594. https://doi.org/10.3390/ijerph19031594
[25] Berglund, E.Z., Buchberger, S., Cunha, M., Faust, K.M., Giacomoni, M., Goharian, E., Ethan Yang, Y.C. (2022). Effects of the COVID-19 pandemic on water utility operations and vulnerability. Journal of Water Resources Planning and Management, 148(6): 04022027. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001560
[26] Yao, J. (2022). Quantifying the resilience of the water-energy nexus for a reservoir-pump station system. Water Supply, 22(4): 4278-4295. https://doi.org/10.2166/ws.2022.050
[27] Shin, H., Joo, C., Koo, J. (2016). Optimal rehabilitation model for water pipeline systems with genetic algorithm. Procedia Engineering, 154: 384-390.

https://doi.org/10.1016/j.proeng.2016.07.497
[28] Bergion, V., Lindhe, A., Sokolova, E., Rosén, L. (2018). Risk-based cost-benefit analysis for evaluating microbial risk mitigation in a drinking water system. Water Research, 132: 111-123. https://doi.org/10.1016/j.watres.2017.12.054
[29] Mcharo, M., Maghenda, M. (2021). Cost-benefit analysis of sustainable land and water management practices in selected highland water catchments of Kenya. Scientific African, 12: e00779. https://doi.org/10.1016/j.sciaf.2021.e00779
[30] Saboori, H. (2023). Hybrid renewable energy powered reverse osmosis desalination–minimization and comprehensive analysis of levelized cost of water. Sustainable Energy Technologies and Assessments, 56: 103065. https://doi.org/10.1016/j.seta.2023.103065
[31] Ahopelto, S., Vahala, R. (2020). Cost–benefit analysis of leakage reduction methods in water supply networks. Water, 12(1): 195. https://doi.org/10.3390/w12010195
[32] Ratnaweera, D., Heistad, A., Navrud, S. (2021). The current use and potential of cost benefit analysis in water sector projects. Water Supply, 21(4): 1438-1449. https://doi.org/10.2166/ws.2020.364
[33] Nafi, A., Brans, J. (2019). Cost–benefit prediction of asset management actions on water distribution networks. Water, 11(8): 1542. https://doi.org/10.3390/w11081542
[34] Skourtos, M., Damigos, D., Kontogianni, A., Tourkolias, C., Marafie, A., Zainal, M. (2021). A combined probabilistic framework to support investment appraisal under uncertainty in desalination projects: An application to Kuwait's water/energy nexus. Water Supply, 21(1): 276-288. https://doi.org/10.2166/ws.2020.278
[35] Gonzalez-Ruiz, J.D., Arboleda, A., Botero, S., Rojo, J. (2019). Investment valuation model for sustainable infrastructure systems: Mezzanine debt for water projects. Engineering, Construction and Architectural Management, 26(5): 850-884. https://doi.org/10.1108/ECAM-03-2018-0095
[36] Martínez-Dalmau, J., Gutiérrez-Martín, C., Expósito, A., Berbel, J. (2023). Analysis of water pricing policy effects in a Mediterranean basin through a hydroeconomic model. Water Resources Management, 37(4): 1599-1618. https://doi.org/10.1007/s11269-023-03446-8
[37] Thomas, S.J., Haribhau Bade, M., Sahoo, S.S., Thomas, S., Kumar, A., Awad, M.M. (2022). Urban water management with a full cost recovery policy: The impact of externalities on pricing. Sustainability, 14(21): 14495. https://doi.org/10.3390/su142114495
[38] Zetland, D. (2021). The role of prices in managing water scarcity. Water Security, 12: 100081. https://doi.org/10.1016/j.wasec.2020.100081
[39] Sanabria, S., Torres, J. (2020). Water price: Environment sustainability and resource cost. Water, 12(11): 3176. https://doi.org/10.3390/w12113176
[40] García-López, M., Montano, B., Melgarejo, J. (2022). Alternative tariff structures and household composition: Evidence from Spain's Valencia region. Utilities Policy, 79: 101433. https://doi.org/10.1016/j.jup.2022.101433
[41] Expósito, A. (2018). Irrigated agriculture and the cost recovery principle of water services: Assessment and discussion of the case of the Guadalquivir River Basin (Spain). Water, 10(10): 1338. https://doi.org/10.3390/w10101338
[42] Lee, S., Pomeroy, C., Burian, S. (2021). Setting future water rates for sustainability of a water distribution system. Journal of Water Resources Planning and Management, 147(2): 04020108. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001313
[43] García-López, M., Montano, B. (2020). Water price effects on consumption and territorial imbalances in Spain in the context of the water framework directive. Water, 12(6): 1604. https://doi.org/10.3390/w12061604
[44] Zangenehmadar, Z., Moselhi, O., Golnaraghi, S. (2020). Optimized planning of repair works for pipelines in water distribution networks using genetic algorithm. Engineering Reports, 2(6): e12179. https://doi.org/10.1002/eng2.12179
[45] Kim, K., Seo, J., Hyung, J., Kim, T., Kim, J., Koo, J. (2019). Economic-based approach for predicting optimal water pipe renewal period based on risk and failure rate. Environmental Engineering Research, 24(1): 63-73. https://doi.org/10.4491/eer.2017.188
[46] D'Ercole, M., Righetti, M., Raspati, G.S., Bertola, P., Maria Ugarelli, R. (2018). Rehabilitation planning of water distribution network through a reliability—based risk assessment. Water, 10(3): 277. https://doi.org/10.3390/w10030277
[47] Mazumder, R.K., Salman, A.M., Li, Y., Yu, X. (2018). Performance evaluation of water distribution systems and asset management. Journal of Infrastructure Systems, 24(3): 03118001. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000426