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Review

Resilience Assessment in Urban Water Infrastructure: A Critical Review of Approaches, Strategies and Applications

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Abstract: Urban water infrastructure (UWI) comprises the main systems, including water supply systems (WSS), urban drainage/stormwater systems (UDS) and wastewater systems (WWS). The UWI needs to be resilient to a wide range of shocks and stresses, including structural failures such as pipe breakage and pump breakdown and functional failures such as unmet water demand/quality, flooding and combined sewer overflows. However, there is no general consensus about the resilience assessment of these systems widely presented by various research works. This study aims to critically review the approaches, strategies and applications of the resilience assessment for the complex systems in UWI. This review includes examining bibliometric analysis, developed frameworks related to resilience assessment to help comprehend resilience concepts for the specified UWI systems in urban settings, strategies for improving resilience, resilience indicators and common tools used for modelling resilience assessment in UWI. The results indicate that resilience assessment has primarily been conducted in developed countries, underscoring the macroeconomic significance of UWI. Three key areas have been identified for analysing resilience in UWI: system design, development of resilience concepts and implementation of green infrastructure. Moreover, it has been discovered that although resilience is commonly defined using technical approaches, a more comprehensive understanding of resilience can be gained through a holistic approach. Furthermore, while strategies such as system upgrades, decentralisation, digitalisation and nature-based solutions can enhance UWI resilience, they may be insufficient to fulfil all resilience indicators. To address the challenge of effectively comparing different resilience options, it is crucial to extensively examine comprehensive and sustainability-based indicators in future research.

Keywords: resilience assessment; resilience strategies; urban stormwater and wastewater; urban water infrastructure; water supply systems

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1. Introduction

Urban water infrastructure (UWI) comprises three primary systems, i.e., water supply systems (WSS), urban drainage/stormwater systems (UDS) and wastewater systems (WWS). These components are essential for delivering clean water to customers and collecting surface runoff from urban areas and sanitary sewage from households in cities. While providing these essential services, these systems also offer opportunities to implement strategies that can enhance urban resilience. However, these systems face various challenges and stresses that can result in technical failures or performance losses, leading to exorbitant costs [1]. Some of these challenges include ageing infrastructure and insufficient investment in infrastructure rehabilitation, which can reduce system capacity, population growth and rapid urbanisation that increase system loads, inadequate water infrastructure maintenance, climate change and extreme weather events such as flooding and drought. Addressing these challenges is crucial for maintaining the functionality of UWI and avoiding costly disruptions [2].

To address the challenges and stresses faced by UWI, it is crucial to establish a robust and resilient system that can withstand significant disruptions, dynamically reorganise itself and continue to perform essential functions without any interruptions [3]. This resilience can be achieved through various measures such as incorporating redundant capacity in the infrastructure, adopting flexible design principles, implementing advanced monitoring and control systems and promoting community engagement and awareness. By constructing a more resilient UWI and ensuring that residents have access to clean water, cities can better withstand the challenges and stresses they face [4].

Resilience in urban infrastructure is defined by its ability to maintain essential functions while adapting to external changes, promoting sustainability. Extensive research has been conducted in recent years to understand, analyse and enhance resilience in urban infrastructure, including the development of resilient systems and the measurement of experimental resilience, and improvements to various resilience infrastructures to overcome uncertainty related to future drivers [5].

However, measuring global resilience is challenging and requires the use of multiple indicators and metrics. Some common metrics used to measure resilience in UWI include the availability of clean and safe drinking water, the efficiency and reliability of sewage collection systems and the implementation of United Nations safety management facilities [6], as shown in Figure 1. There are significant differences in the level of investment given to the main UWI components across the world. Although access to drinking water has improved in the Middle East, water recycling in UWI requires more investment. African countries suffer greatly from a lack of investment in both access to drinking water and proper collection of stormwater and wastewater. Furthermore, unequal investments in UWI components can have severe consequences, not only for UWI resilience but also for the health and well-being of society. In addition, the currently employed indicators to measure resilience may not accurately reflect the intricacies and complexities of UWI services and performance. This is partly due to the absence of globally recognised standards, clear methodologies, and consistent metrics for assessing resilience, which can make it challenging to compare different regions and systems [7].

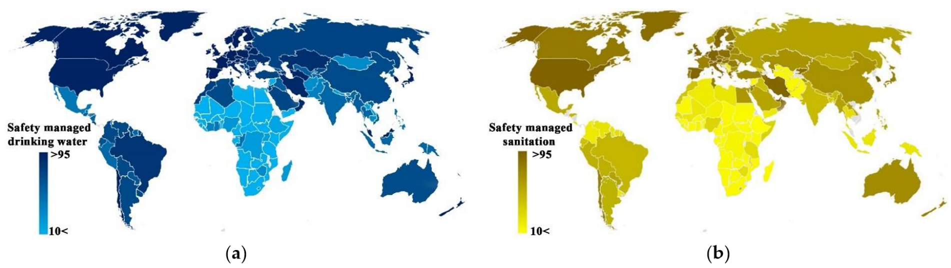


Figure 1. Percentage of people with access to safely managed (**a**) drinking water facilities and (**b**) sanitation facilities.

While the literature offers several perspectives and frameworks for understanding, evaluating and improving UWI resilience, there is no general consensus for using resilience in these complex systems, and hence, there is a need for further critical analysis and methodological classification of these approaches and assessments. Some research works have attempted to provide the resilience assessment for various parts of water infrastructure. For example, Juan-García et al. (2017) [5] developed a quantitative resilience theory that incorporates the benefits of green infrastructure. Fu et al. (2020) [8] and Fu and Butler (2020) [9] evaluated the resilience of green infrastructures in terms of integrated flood risk and resilience management, climate change and water management and sustainable pathways. Juan-García et al. (2017) [5] and Fu and Butler (2020) [9] reviewed both quantitative and qualitative aspects of decentralised systems in the context of UWI resilience. Mehvar et al. (2021) [10] presented various challenges and adaption strategies. To the best of the authors' knowledge, there is no previous literature that comprehensively reviews these approaches with relevant tools and strategies critically, and therefore, additional research is needed to further evaluate and classify these different resilience perspectives and frameworks.

Although many studies have looked at different aspects and strategies for promoting resilience in UWI, there are gaps in the areas, such as comprehensive comparisons and documenting approaches and strategies, software applications and metrics. Therefore, additional research and analysis are needed to fully understand the developed framework of resilience concepts in UWI, as well as develop a comprehensive and unified understanding of UWI resilience. This would involve blending frameworks and perspectives and developing tools and methods for measuring and assessing resilience in every aspect of the system. Hence, this study aims to critically review frameworks and concepts of resilience assessment in various UWI components by analysing four main steps: (1) bibliometric analysis to highlight hot topics and main drivers; (2) describing various developed frameworks and associated approaches and characteristics; (3) identifying main strategies designed to make the frameworks effective; and (4) listing evaluation metrics and software used for developing resilience frameworks.

2. Research Design and Bibliometric Analysis

The UWI components consist of various components, as shown in Figure 2, ranging from water abstraction to wastewater treatment and more. These components are categorised into three groups: abstraction (parts 1 and 9 in Figure 2), water/wastewater treatment and water storage (parts 2, 3 and 7) and distribution of water supply or stormwater/wastewater collection (parts 4, 5, 6 and 8). Water abstraction is often evaluated at the watershed or basin level [11], while resilience assessment in treatment and storage sections focuses on failure events [12]. This study concentrates on the distribution of water supply systems or stormwater/wastewater collection systems (i.e., resilience assessment of WSS, WWS and UDS), which is referred to as UWI hereafter. These components are grouped together as they share similarities and, in some cases, complement each other.

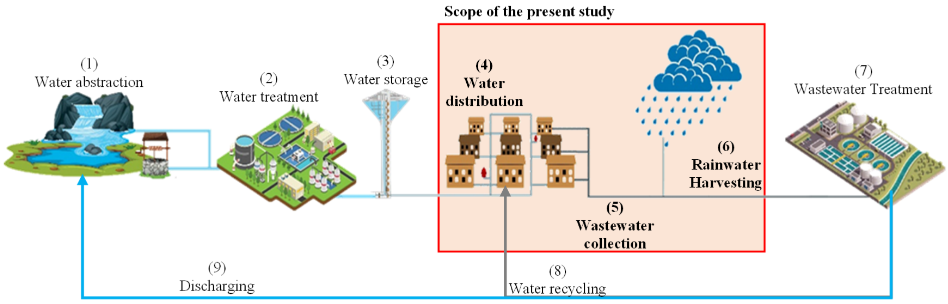
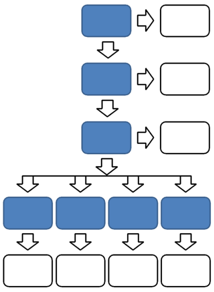


Figure 2. Illustration of different UWI components and focus area of this study.

The research database of this study was gathered from the Scopus search engine using the recommended method of searching in titles, abstracts and keywords. A set of seven search and screening strategies (S_1–S_7), as shown in Table 1, were used to narrow down the search results. In total, 76 relevant studies were found and classified into four categories. The search began with 871 publications in the first stage (S_1), which were gradually narrowed down in steps S_2 and S_3. Due to the limited scope of this study, research on wastewater abstraction, water/wastewater treatment, storage consumption and wastewater treatment were excluded in these stages. Ultimately, 76 studies were selected and classified into four groups: 37 studies for applied analytical approaches for resilience in UWI (S_4), 68 studies for new resilience strategies (S_5), 28 studies for software tools assessing resilience (S_6) and 13 studies for proposed existing resilience metrics (S_7).

Table 1. Flowchart of research strategies in this study.



Code	Search and Screen Strategy	Keywords
S_1	Finding publications studying resilience in urban water infrastructures	(Resilience OR Resilient) AND (water OR wastewater OR sewer OR sewage) OR (Rain OR Storm) AND (Urban OR Domestic OR Municipal)
S_2	Results were limited to the last decade, English language papers and journal papers; Searching is also limited to titles, keywords and abstracts	-
S_3	Results were screened for case studies or reviews focusing on urban water distribution systems	(Distribution) OR (Collection) OR (Harvesting)
S_4	Results were divided and screened to find relevant approaches	(Holistic OR Technical)
S_5	Results were divided and screened to find relevant introduced strategies	-
S_6	Results were divided and screened to find relevant applied tools	(Software OR Platform OR Tool)
S_7	Results were divided and screened to find relevant metrics	(Metric) OR (Indicator) OR (Parameter) OR (Key AND Performance)

This study began by examining the retrieved publications, which included an evaluation of the geographical distribution of resilience studies. Figure 3a–c illustrates that the majority of relevant studies (33.6%) are from Europe, and there is a clear correlation between the number of publications and the level of economic development of the countries. The top three countries in terms of the number of publications are the USA (31.5%), China (12%) and the UK (10.4%), all of which have some of the world's largest economies. This trend highlights the importance of resilience studies in regions with high economies, both currently and in the future. As urbanisation continues to increase and climate change poses new challenges, the need for financial support for a resilient UWI will become even more critical.

Figure 3b focuses on the accessibility of national research works and highlights a significant challenge faced by African, South American and Oceania countries, where only a small percentage of studies (less than 20% overall) are documented. This finding underscores the need for more efforts, particularly from low- and middle-income countries, to support research and inform decision-making on UWI resilience. International collaboration is also an important factor in advancing research and promoting knowledge and expertise exchange, as evidenced by the fact that 20% of the selected articles (see Figure 3c) are the result of such collaboration, which is a positive sign that researchers have international cooperation to address the challenges of resilience in UWI.

However, as previously stated, more research is required in countries where the concept of resilience has yet to be localised. This highlights the significance of promoting capacity-building and knowledge-sharing initiatives in these regions to foster the development of research and expertise on UWI resilience. Such initiatives would ensure that the benefits of resilience are available to all communities, regardless of their geographic location or level of development.

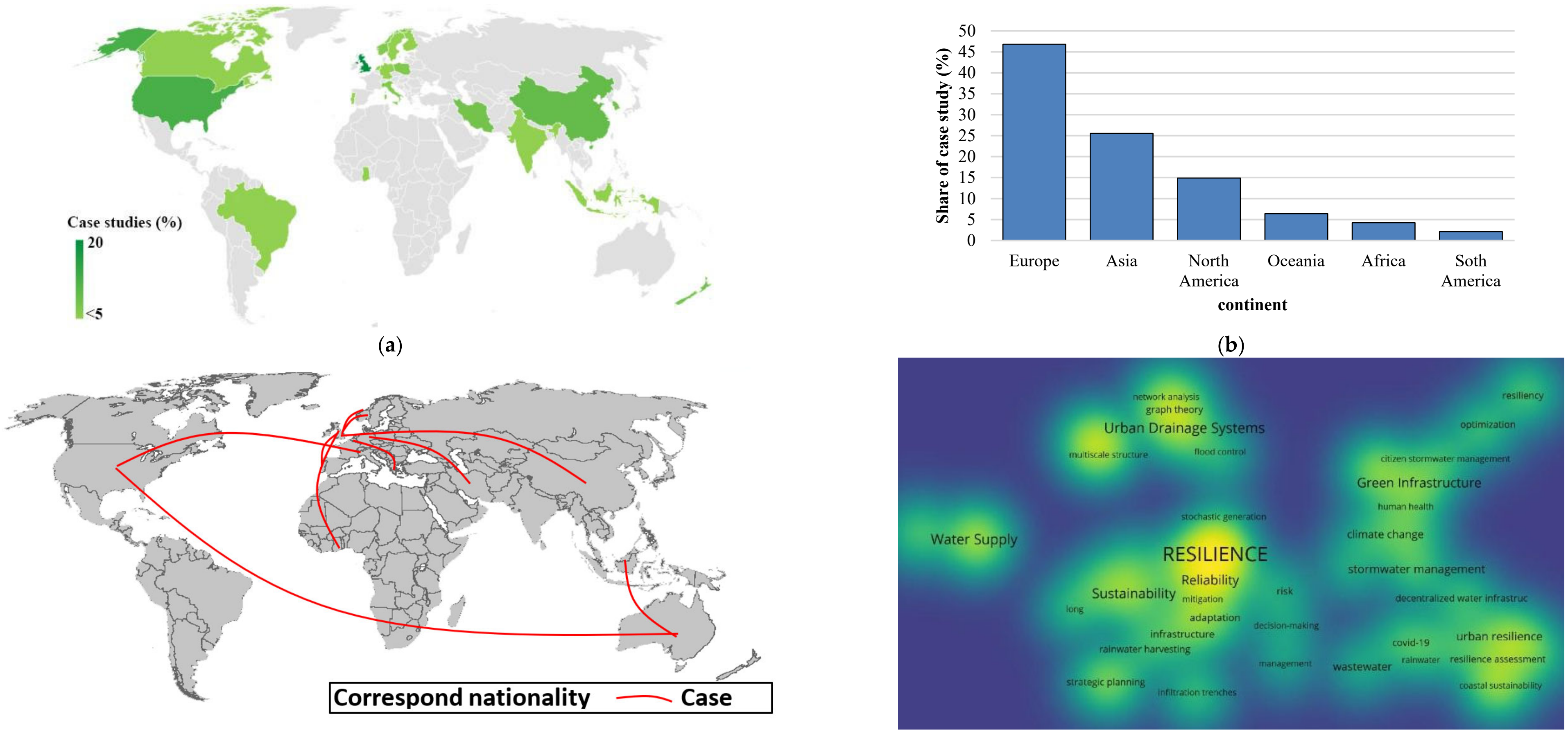
VOS viewer software was also used to analyse the knowledge domain bibliometric track based on the co-occurrence of key terms for a specific unit of analysis (keywords, titles, and abstracts), type of analysis (co-occurrence) and counting method (full counting). Figure 4d–f shows the results of this analysis. Figure 3d highlights the close relationship between the concepts of "reliability" and "sustainability" with "resilience" while also revealing the clear distinctions between "water supply", "urban drainage systems", "green infrastructure", and "resilience" indicating that these components are well-defined individually.

Based on the content of the selected studies, Figure 3e identifies three major clusters: the red cluster focuses on green infrastructure, the green cluster on physical components such as the distribution system, and the blue cluster on sustainability and reliability. The green cluster is dominated by research on water system design, such as risk assessment and systems optimisation. The blue cluster connects resilience to other concepts, such as sustainability and reliability, and focuses on key performance indicators, adaptive plans and failure analysis of various strategies, such as rainwater harvesting. The timeline flow shown in Figure 3f demonstrates how the research topics have evolved over time, with an initial emphasis on the interaction of sustainability, reliability and resilience, shifting towards more practical and functional concepts, such as evaluating the performance of water system management or urban resilience. This suggests that the research community is moving towards more action-oriented approaches to resilience evaluation, which can have a greater impact on field applications. The findings of this analysis can provide insights into the current state of research on this as well as inform future research and policymaking.

The holistic approach involves integrating resilience as a fundamental design feature of the system, considering socio-ecological-technical factors to address chronic stressors. It evaluates the system's capacity to withstand, adapt to and recover from shocks and stresses. This approach can be used to identify the potential risks and vulnerabilities in the system, prioritise investments in resilience-enhancing measures and evaluate the effectiveness of interventions [13].

The holistic approach involves examining the physical, social and environmental dimensions of UWI and their interactions. The physical infrastructure, which includes the design, construction, and maintenance of water distribution, urban drainage systems, and wastewater collection, as well as the condition and durability of pipelines, pumps, and other components, is a critical aspect of resilience assessment since it forms the backbone of water infrastructure systems [14]. The assessment should take into account the physical infrastructure's ability to withstand various hazards. It is important to understand the vulnerability of the infrastructure to these hazards and how they might impact the system's functionality [15]. Note that any type of stress caused by a hazard can have an impact on the physical infrastructure's functionality in UWI.

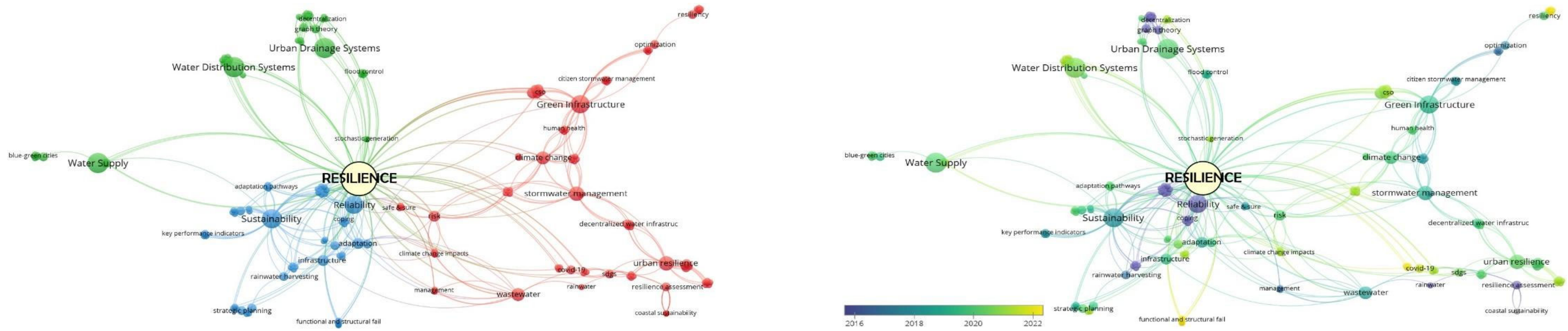
In addition to physical infrastructure, the assessment should also focus on social and institutional systems, which involves examining policies, regulations and governance structures that govern water management, as well as the roles and responsibilities of stakeholders, including water utilities, government agencies and community organisations [16]. Social and institutional systems are an essential aspect of resilience assessment since they influence the system's ability to respond to and recover from shocks and stresses. The assessment should evaluate the effectiveness of the social and institutional systems in terms of coordination, communication and collaboration among stakeholders. It should also examine the system's capacity to mobilise resources and implement interventions to enhance resilience [17]. Additionally, the natural environment's focus should be on the ecological processes that support water infrastructure systems, such as the availability of required urban water and the impacts of climate change on these systems. The natural environment influences the system's ability to adapt and respond to changing conditions, especially droughts, floods, and sea-level rise [18].



(**a**) (**b**)

(**c**) (**d**)

Figure 3. *Cont*.



(**e**) (**f**)

Figure 3. Bibliometric analysis for the selected papers based on (**a**) geographical distribution, (**b**) continental share, (**c**) international cooperation, (**d**) density of keywords, (**e**) cluster of keywords, and (**f**) timeline of keywords. Resilience assessment approaches: resilience approaches are frameworks that help identify chronic or acute stressors, their link to different factors and other aspects of resilience [9]. Table 2 summarises the two main approaches to resilience: holistic and technical. The holistic approach emphasises the social, economic and environmental factors that impact resilience, while the technical approach focuses on the physical and technological components of resilience. Both approaches are crucial in addressing different aspects of resilience, and the choice depends on the specific context and goals of the study.

Table 2. Applied resilience assessment approaches in UWI.

Approach/Frameworks	Description	Major Used Application	Reference
Holistic Approaches			
Safe & Sure	Assessing measures of mitigation, adaptation, coping and learning and exploring organisational and operational responses.	Intermittent water supply utilities	[19]
S-FRESI [1]	Specifying major potential investment and greatest positive effect area	Drainage systems	[20]
PESTEL [2]	Evaluating based on different political, economic, social, technical, legal and environmental aspects	Drainage systems	[21]
RAF [3]	Following the resilience of the city from the perspective of urban stormwater control through NBS solutions. In this framework, three degrees (essential, complementary and comprehensive) are defined for resilience.	City resilience	[22]
Technical approaches			
SAF [4]	Systematically identifying flood impact and flood source areas along with opportunity areas for integration of different infrastructure systems to manage surface water	Urban drainage system	[23]
GRA [5]	Assessing potential failure, regardless of the threats, without the need to develop a scenario or identify the root of all fractures	Infrastructure system	[24]
Smart city framework	The Internet of Things concept as part of smart cities assists in the development of communicating 'items' integrated into the overall system. This development enables new possibilities for the management of UWI in a smart city framework	City resilience	[25]

[1]: Spatialised Urban Flood Resilience Index; [2]: Political, Economic, Social, Technological, Environmental and Legal; [3]: Resilience Assessment Framework; [4]: Spatial Analysis Framework; [5]: Global Resistance Analysis.

The technical approach focuses on improving the engineering and technical aspects of the system to increase its capacity and resilience to acute stressors or shocks [26]. Technical resilience approaches typically aim to increase the capacity and robustness of specific system components or infrastructure to withstand and recover quickly from acute stressors such as natural disasters or system failures through targeted engineering solutions such as reinforcing pipes and are more concerned with the physical aspects of the system rather than the social or ecological components [8]. A technical framework for resilience assessment typically includes several elements [27,28]. The first step is to identify critical infrastructure, mapping out the infrastructure and assets to understand how they are interconnected and dependent on one another. Next, risk assessment is conducted using scenario planning and modelling to better understand the potential impacts of different hazards. A vulnerability assessment is then conducted at different levels of the system, such as the individual assets, the subsystems and the overall system. Capacity assessment is conducted under different scenarios and stressors to better understand the system's capacity for resilience. Performance evaluation involves using performance indicators to measure the effectiveness of different resilience strategies. Based on the results of the risk, vulnerability and capacity assessments, risk management strategies are prioritised. Finally, a process for continual improvement is established, involving regular monitoring, evaluation and review of the system's resilience to identify areas for improvement and implement changes accordingly.

Figure 4 shows that resilience studies in the technical part are five times more common than in the holistic part. The Safe & Sure framework is the most widely used holistic framework because it assesses risk and reliability, calculates resilience and promotes system resilience towards urban sustainability through a circular economy-based management perspective [8]. Physically based modelling is widely used as a part of the technical approach, particularly in urban drainage and stormwater management, because of its ability to simulate various hydraulic processes and support decision-making in the design and operation of drainage systems. It can also consider various types of disturbances and elementary failures that can cause system failure, including both natural and man-made hazards [28].

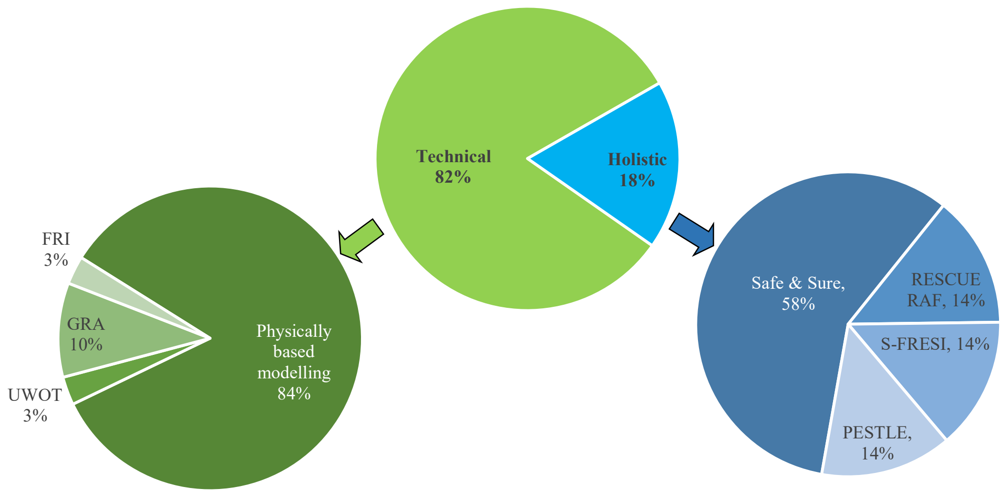


Figure 4. Dashboard of technics and frameworks used for resilience assessment of urban water systems.

The "S-FRESI" framework employs indices to assess urban flood resilience before, during and after a flood. The framework is composed of three main components: exposure, sensitivity and adaptive capacity. Exposure refers to the likelihood and severity of flooding, sensitivity measures the degree of susceptibility of urban systems and populations to flooding, and adaptive capacity assesses the ability of cities to recover from floods and build resilience for the future [29]. The sensitivity component is focused on identifying areas of risk and vulnerability in urban systems and populations to flooding. It helps to identify populations and infrastructure that may be particularly susceptible to flooding. The adaptive capacity component is used to assess the ability of cities to prepare for and recover from floods. It helps to identify areas where improvements could lead to increased resilience in the face of flooding [30]. The accuracy and reliability of the S-FRESI depend on the availability and quality of data used. The index requires detailed information on the physical, social, and environmental characteristics of urban areas, as well as historical flood events and their impacts.

However, the availability and reliability of data required for the S-FRESI framework may be limited, especially in low- and middle-income countries where data collection and management systems may be weak or non-existent [31]. In addition, the accuracy and relevance of the assessment results can be impacted by the spatial scale and resolution of the assessment, which may not provide enough detail for local-level decision-making [32]. Moreover, the subjective judgments and weighting of indicators based on expert opinions and stakeholder inputs can lead to inconsistencies in results across different locations and times. This weighting of indicators may also vary depending on the context and objectives of the assessment. Furthermore, stakeholder engagement (e.g., community members, local governments and other relevant actors) may not always be adequate, which can result in a limited understanding of local needs and priorities, as well as a lack of ownership and commitment to the assessment outcomes and recommendations [33].

RAF is an extension of the S-FRESI approach and concentrates on nature-based solutions for managing and controlling stormwater. It has several critical components, such as economic sustainability, environmental factors, spatial planning, involvedness, system robustness and level of service management. These components are then assessed and validated by external factors such as contributions and stakeholders [34]. However, similar to S-FRESI, RAF is subject to the subjective nature of the evaluation process, and the weighting of indicators may vary depending on the context and goals of the assessment. This subjectivity may lead to inconsistencies and variations in results across different locations and times. Furthermore, involving different stakeholders can make it challenging to reach a consensus on the indicators to be included and their relative importance [35]. Although designed to assess the resilience of nature-based solutions, it may not be suitable for evaluating other water infrastructure components [36].

The PESTEL framework takes a broader view in comparison to the other two frameworks by adding policy and law factors to the assessment factors. This helps identify potential risks and opportunities that may be missed by a narrower focus. PESTEL analysis is a flexible tool that can be adjusted to different contexts and applied at different scales, from individual projects to entire cities. The insights obtained from a PESTEL analysis can inform strategic planning for urban water management by identifying priorities and focusing resources where they are most needed [37]. However, PESTEL analysis focuses on external factors, such as political and economic conditions, which may limit its usefulness in identifying internal factors that may be contributing to resilience challenges. Furthermore, PESTEL analysis may result in inconsistencies and variations in results across different contexts and stakeholders. The external factors that impact urban water resilience are constantly changing, which can make it difficult to keep the analysis up-to-date and relevant over time [38].

The “Safe & Sure” framework measures the resilience of UWI using three risk-based parameters, i.e., risk assessment, risk management and recovery assessment. Risk assessment involves identifying potential hazards and assessing their likelihood and consequences. The risk management component focuses on developing and implementing strategies to reduce the likelihood and consequences of hazards, while the recovery assessment component evaluates the effectiveness of risk management strategies and measures the overall system resilience [19]. The Safe & Sure framework emphasises stakeholder engagement and collaboration in the resilience assessment process, which includes involving system operators, regulators, customers and other stakeholders in the development and implementation of risk management strategies. One of the strengths of the Safe & Sure framework is its flexibility and adaptability to different types of critical infrastructure systems and contexts. However, like other holistic resilience assessment frameworks, the Safe & Sure framework is subject to the involvement of stakeholders and the need for comprehensive and accurate data, which may be difficult to obtain, particularly for complex and interconnected systems [32].

“SAF” is a robust methodology designed to assess the resilience of urban areas to natural disasters. Its objective is to promote and facilitate interoperability by systematically identifying flood impact and flood source areas and identifying opportunities for the integration of different infrastructure systems to manage surface water [23]. SAF relies heavily on the data collected and prepared for analysis using geographic information systems (GIS). It uses spatial analysis to identify areas of high and low resilience based on the spatial distribution of various factors. The results of the analysis are then integrated and interpreted to identify the factors that contribute most strongly to resilience, as well as areas where interventions may be needed to improve resilience [39].

The smart city framework for resilience assessment is a robust methodology designed to evaluate the resilience of cities to various shocks and stresses, including critical UWI. The framework considers the complex and interconnected nature of urban systems and aims to provide a holistic approach to resilience assessment [25]. It incorporates a range of tools and techniques to facilitate the resilience assessment process, such as GIS mapping, stakeholder engagement, scenario planning and risk assessments. The framework emphasises the importance of collaboration and communication between stakeholders and the need for adaptive and flexible strategies to address the changing nature of urban risks and uncertainties. However, while the framework is comprehensive, it primarily focuses on the resilience assessment of the entire city rather than specifically on UWI [40].

Overall, technical approaches offer targeted solutions to identified problems, providing a clear focus for addressing specific issues. They often rely on data and quantitative analysis, which can lead to more objective and reliable decision-making [41]. Additionally, they can be efficient in terms of time and resources since they are narrowly focused on specific issues rather than the entire system [42]. However, technical approaches can be narrow in their scope, potentially overlooking important interconnections and interdependencies within the system. Their reductionist approach may break down complex systems into their constituent parts, missing the broader picture [43]. Additionally, they may not fully engage stakeholders or consider their perspectives and needs, leading to solutions that are not sustainable in the long run [44]. In contrast, holistic approaches consider the system as a whole, considering interconnections and interdependencies between its different parts. This can lead to more comprehensive solutions that address multiple issues and are more resilient to unexpected shocks and stresses [45]. Holistic approaches also prioritise stakeholder engagement, considering their perspectives and needs in the decision-making process [46]. However, holistic approaches can be time-consuming and resource-intensive, requiring a broad and detailed understanding of the system. They may also rely on subjective assessments and qualitative analysis, potentially leading to biased or incomplete decision-making [18]. Additionally, the complexity of holistic approaches may make it difficult to communicate findings to stakeholders who may not have a technical background [47].

3. Resilience-Enhancing Strategies

Figure 5 depicts the four main strategies proposed to improve UWI resilience. These strategies include the following: (1) system upgrade involving a wide range of installation and configuration, improving and constructing the physical infrastructure of the UWI, such as pipe strengthening, increasing channel banks, creating auxiliary tunnels or constructing detention ponds; (2) decentralisation where possible by introducing small-scale water related facilities or community-managed water system;, (3) nature-based solutions (NBS) integrating natural elements, such as wetlands or open green spaces into the urban water system; and (4) smart network using digital technologies, such as sensors, computational devices and big data analytics to improve the monitoring, control and management of UWI.

System upgrade is a strategy for improving the robustness and redundancy of water infrastructure to increase its resilience. While investing in physical structures, this strategy is still widely regarded as a primary solution for increasing resilience, owing to the high investment and long-term performance that water infrastructure is expected to provide [28]. For example, long-term optimal rehabilitation strategies in WSS can be obtained by using sequential multi-objective optimisation models [48]. The majority of system upgrades involve centralised systems, which are criticised for their high energy requirements, changes to the natural hydrological system and long-term costs associated with their maintenance and operation [49]. Decentralisation is another strategy proposed to improve UWI's resilience. The system becomes more flexible and reduces water loss due to cutting leakage in long-distance piping networks by distributing the water and wastewater distribution network across the city [50]. Furthermore, decentralised water systems can facilitate the circular economy of water and resources by allowing treated wastewater to be reused [51]. Nutrients in wastewater, for example, can be recycled and used as fertiliser in agriculture, and biogas produced from organic matter can be used as a renewable energy source [38]. This can help to reduce freshwater and energy demand, as well as waste and pollution in the environment. Decentralised systems, on the other hand, may necessitate more complex management and maintenance because they involve a greater number of smaller systems distributed throughout a city rather than a single centralised system [4]. This may necessitate additional resources for operation and maintenance, as well as specialised expertise.

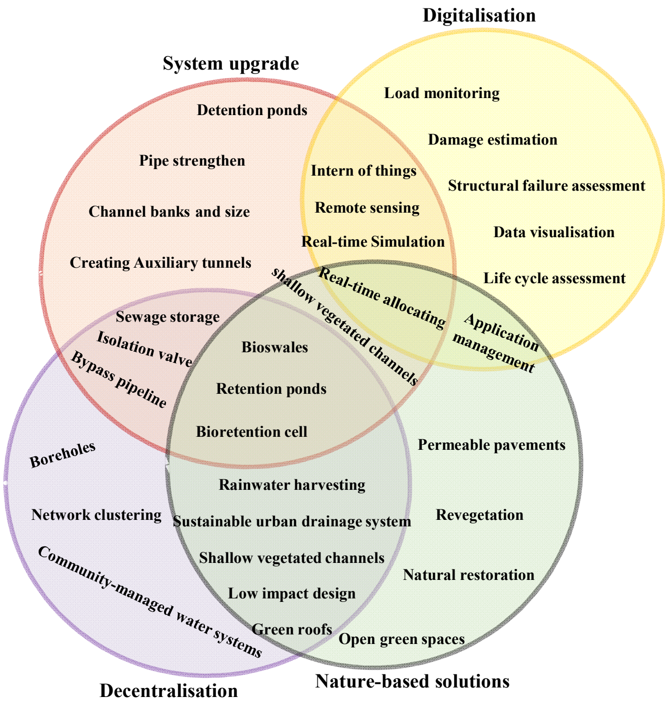


Figure 5. Main resilience strategies applied to UWI.

NBS are yet another type of resilience that combines natural elements and ecosystem services to provide cost-effective solutions such as increased infiltration, evapotranspiration, and stormwater runoff storage [52]. They have gained traction as an alternative or supplement to traditional UWI [53]. NBS is also known by the terms Low Impact Development (LID) and Sustainable Urban Drainage Systems (SuDS) (See Figure 5). This strategy can be combined with other traditional approaches, particularly flood management, to form a comprehensive strategy for long-term sustainable urban drainage [8]. Multi-criteria optimal planning of a variety of SuDS options can also be highly beneficial for enhancing UDS resilience and hence urban flood management [54]. Sponge City, for example, combines LID techniques with other measures such as permeable pavements, green roofs and rain gardens to manage stormwater and improve urban resilience [55]. However, the installation and maintenance of NBS can be more expensive and take up more space than traditional solutions [56]. Furthermore, professional education and training may be required for their successful implementation [57]. Furthermore, more research is needed to determine the efficacy of these strategies, particularly for unpredictable extreme weather events, and limitations in the availability of suitable green spaces and land for implementation may also pose a challenge [58].

Recent advances in smart network modelling have played an important and expanding role in addressing the challenges. The use of real-time data, advanced analytics, and modelling techniques to improve the management and operation of urban drainage networks is referred to as smart network modelling. It can assist decision-makers and engineers in identifying potential issues before they become major issues, optimising system performance, and making more informed infrastructure investment decisions [59]. For example, real-time flood forecasting in UDS can help decision-makers make informed decisions well in advance of the imminent flood in urban areas [60]. Smart network modelling can also help improve urban drainage network resilience by providing better insights into the impact of extreme weather events and other potential disruptions [61]. The integration of IoT devices, wireless sensors and remote sensing applications with existing systems (See Figure 5) can allow for the development of smart systems that use forecasting models. Smart rainwater harvesting systems, for example, can release stored stormwater automatically before rainy events to provide additional enclosed volumes and reduce the risk of flooding. Such approaches can also be used to monitor and manage water quality, detect leaks and blockages in near real-time, and provide operators with the information needed to take appropriate actions [25]. This can aid in the prevention and resolution of issues, lowering the risk of water contamination, flooding and other UWI-related issues [62]. Furthermore, developing smart frameworks based on artificial intelligence for fast evaluation of flood risk can accelerate the flood risk assessment to make informed decisions and hence enhance community resilience [63].

As illustrated in Figure 5, while each of these strategies provides valuable information on its own, these strategies can be interrelated. Integrating various strategies can result in more effective and long-lasting UWI. Also, this would improve their ability to provide excellent customer service in the event of unanticipated system failures [64]. Within this context, creating an emergency response plan and setting up backup water distribution systems can help with swift action in the event of water-related disasters, thus increasing UWI resilience-based resistance. Alternatively, upgraded systems can combine digital technology like smart sensors and monitoring systems to aid in the detection of leaks and faults, resulting in a smarter regime and faster system repairs and maintenance [25]. Moreover, neighbourhood water recycling facilities and rainwater harvesting systems can be integrated with digital technology, and decentralised systems can become flexible and adaptable to changing water demands, assisting in water rationing during disruptions and thus increasing resilience in situations where UWI systems resistance fail [28]. Digitalisation and nature-based solutions can also be coupled to increase UWI resilience. For instance, digital technologies and nature-based solutions can be integrated to strengthen UWI resilience through smart green roofs [65]. These systems use sensors to track weather conditions, soil moisture levels and plant water requirements to optimise irrigation schedules. Flood monitoring and warning systems can also be combined with green infrastructure to serve as a preparedness and emergency response mechanism, increasing UWI's resilience. These alert systems or device sensors keep track of rainfall patterns and water levels to provide early flood warnings [66]. Additionally, decision-makers can gain a better understanding of the water system by combining data from various sources such as sensors, weather forecasts and water quality monitoring systems. It can also reduce unnecessary infrastructure and costs by providing real-time data that allow for more efficient and targeted system maintenance and operation [24].

Figure 5 also shows the integration of decentralisation, and NBS can bring several benefits, including surface runoff control in decentralised distribution network settings, thus reducing the load on centralised systems. For example, during high precipitation, integrating rain gardens, wetlands, rainwater harvesting and permeable pavements near the decentralised network system can improve biodiversity and urban cooling, hence boosting UWI resilience [67]. Furthermore, adding permeable pavement to a decentralisation network can allow precipitation to sink into the ground through its porous materials, improving stormwater management in decentralised network settings. Using this integration strategy in the parking lot or pathways of decentralised distribution system surroundings will reduce surface water runoff and improve water quality in and around decentralised network infrastructure [68]. Moreover, the risk of flooding in decentralised distribution network settings can be reduced by employing wetlands, which aid with stormwater management and reduce the risk of flooding in UWI facilities. Further to this, green roofs can also be employed to treat and filter water, lessening the pressure on decentralisation facilities [69] as well as energy conservation and thermal comfort of buildings [70].

Another integrated strategy is to advance the upgraded systems by NBS and decentral systems. This strategy has experienced development constraints due to a lack of tools and collated information to determine or uncover its long-term value. However, the method of combining NBS solutions with system upgrades has the potential to increase and contribute to UWI resilience in urbanised areas from the perspectives of resource efficiency and societal, economic and environmental gains [22]. In UWI settings, the integration of system upgrades and infiltration trenches, vegetative swales and rain gardens would help to regulate stormwater runoff, alleviating demand on UWI and, as a result, pressure on urban drainage assets in urbanised areas. Replacing old drainage network pipes with newer ones can be an expensive upgrade work that many communities cannot afford, so integrating NBS techniques will assist communities that cannot afford such expensive UWI improvement or upgrade works to have a more affordable and resilient UWI. Another efficient strategy to enhance system resilience is to integrate combined sewer networks or UDS with detention ponds to relieve stress on the piped network in the case of failure [71]. The location and size of these detention ponds can be optimised by using multi-criteria decision-making frameworks [72].

The advantages of combining a decentralised distribution network and a system upgrade also include increased system efficacy, persistency, adaptability, transformability and sustainability of service provision, demonstrating UWI resilience by proactively providing new infrastructure to the decentralised system at a lower cost [73]. For example, replacing old pipes in a decentralised system may be less expensive than making the same improvement works to modernise a centralised distribution system. Additionally, such improvement works in a decentralised system will necessitate shorter-length pipes. In this context, system upgrades and decentralisation would more effectively manage water loss owing to leaks in long pipe networks and other wastage, strengthening the efficacy and resilience of UWI [74]. In addition to resilience enhancement through developing decentralised water reuse strategies, several other performance indicators, such as water conservation and environmental aspects, such as greenhouse gas emissions, can also be improved in UWI [75].

However, cooperation and coordination among the numerous stakeholders is required for the successful implementation of such integrated UWI resilience strategies. Different objectives and priorities, for instance, can make it challenging to align their efforts towards the common goal of the resilience strategy. Power imbalances between stakeholders can also lead to conflicts and hinder cooperation and coordination. Furthermore, a lack of trust between stakeholders can be challenging to share information and resources, and conflicts may arise. Although effective communication is crucial for successful cooperation and coordination, communication barriers such as language differences, cultural differences and technical jargon can make it difficult for stakeholders to understand each other. Finally, implementing an integrated UWI resilience strategy may require significant financial and human resources, which may not be available to all stakeholders [10,20].

4. Resilience Indicators

Measuring and assessing system resiliency is critical for effective decision-making and sustainable management. While holistic approaches evaluate resilience using quantitative or descriptive indicators, technical approaches use quantitative metrics. Figure 6 depicts the various aspects and indicators defined for each framework of the holistic approach. S-FRESI, which focuses on measuring resilience in the face of flood occurrence, demonstrates resilience based on hazard level, population potentially exposed to flooding, density of residential building and duration of water exposure with the population [21]. The exposure component is determined by a range of factors, including the frequency and magnitude of flooding events, the spatial distribution of flood risk across the urban area and the potential consequences of flooding for people and infrastructure. The sensitivity component evaluates factors such as the density and demographics of the population, the quality and age of infrastructure and the availability of emergency response resources.

Adaptive capacity, including susceptibility, material recovery and duration effect, involves evaluating factors such as the availability and quality of emergency management plans and resources, the effectiveness of disaster response systems and the capacity of local government and civil society to coordinate and respond effectively to flood events [29,30].

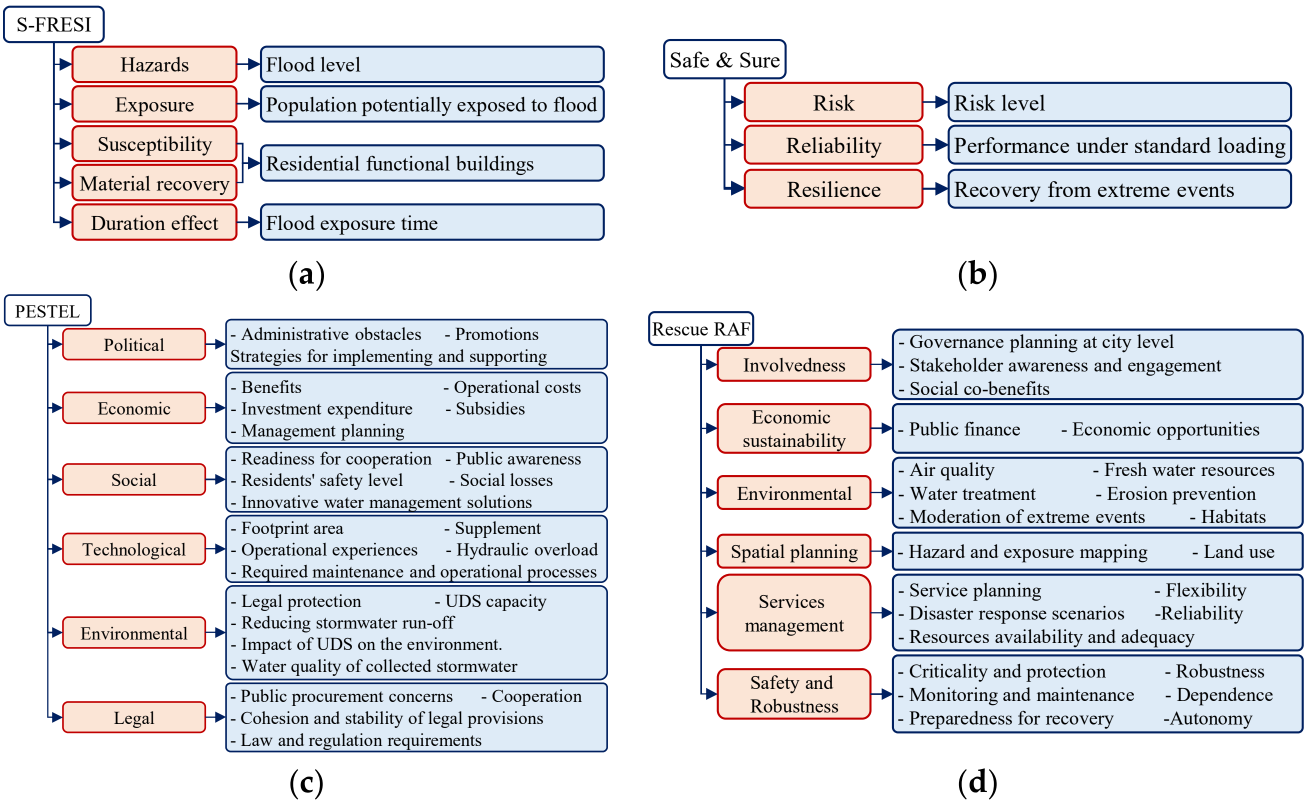


Figure 6. Different aspects and indicators used for various holistic frameworks used for resilience assessment of UWI: (**a**) S-FRESI, (**b**) Safe & Sure, (**c**) PESTEL, (**d**) RAF.

The framework includes two stages, where the first stage focuses on measuring the nature-based solution at the planning level, stakeholder awareness, public finance, economic opportunities, citizens' engagement and accessibility, social co-benefits, freshwater provision, water treatment, erosion prevention and maintenance of soil fertility, and habitats for species promotion. The second stage evaluates the role of selected nature-based solutions at the city level by measuring hazard and exposure mapping, land use and inclusion, service management and planning, resource availability and adequacy, flexible service, scenarios relevance for disaster response, infrastructure assets criticality and protection, infrastructure assets robustness, infrastructure monitoring and maintenance, infrastructure preparedness for recovery and build back, infrastructure dependence, and infrastructure autonomy [34]. The RAF framework emphasises the involvement of stakeholders in UWI's resilience, measuring their awareness and participation and social co-benefits. However, the subjectivity of the assessment process and the involvement of different stakeholders can lead to divergent views and objectives, making it challenging to reach a consensus on the indicators to be included and their relative importance [35].

Alternatively, the PESTEL method measures a variety of indicators, as shown in Figure 6c, ranging from the level of administrative obstacles and the degree of promotion of a sustainable solution to the readiness of various stakeholders and the potential for using innovative solutions. Political factors refer to the influence of government policies and regulations on the urban water system. This includes issues such as water governance, water pricing policies, and regulations related to water safety. Economic factors refer to the impact of economic conditions on the urban water system. This includes issues such as funding for water infrastructure, the cost of water treatment and distribution, and the impact of economic shocks such as recessions on the system. Sociocultural factors refer to the influence of social and cultural factors on the UWI. This includes issues such as public attitudes, the impact of demographic changes, and the influence of social norms and values [76]. Technological factors refer to the impact of technological innovations and developments on the UWI. This includes issues such as the use of smart technologies for water management, the development of new technologies and the impact of climate change on the technological infrastructure of the system. Environmental factors refer to the impact of natural and environmental factors on the UWI. This includes issues such as the impact of climate change on water availability and quality, the impact of natural disasters such as floods and droughts on the system and the impact of environmental degradation on the resilience of the system. Legal factors refer to the impact of laws and regulations on UWI. This includes issues such as water rights, water allocation policies and regulations related to water quality and safety [77].

The “Safe & Sure” approaches to assessing UWI’s resilience employs three key indicators: risk level, reliability degree and recovery rate from extreme events. Risk assessment involves analysing the physical, technological and operational vulnerabilities of the system, as well as its dependencies on other systems and stakeholders. The risk management component includes measures such as redundancy, diversity and robustness, as well as plans for emergency response and recovery. The recovery assessment involves evaluating the system’s ability to absorb and recover from disruptions, adapt to changing conditions and maintain essential services and functions.

Table 3 includes a list of the most used metrics for assessing the effectiveness of technical frameworks. Most of the introduced metrics are applicable to flood evaluation in conjunction with nature-based solutions. Flood volume reduction is often considered in these models. Other models concentrate on disruption and recovery time. For example, robustness, pipe failure and floods are all measured as part of the resilience index based on the duration of disruption or recovery. However, one of the most difficult aspects of using these metrics is determining whether metrics are appropriate for a given system or application, as different metrics may be relevant depending on the context. Another challenge is ensuring that the data used to calculate the metrics are accurate and up to date, which may necessitate significant data collection and analysis resources. Finally, some metrics may be difficult to measure directly, necessitating the use of proxies or estimates, adding uncertainty to the analysis.

As a result, it appears that measuring and quantifying resilience can be difficult, with no single universally accepted method. There are numerous frameworks and models that attempt to capture the various dimensions of resilience, but each has limitations and potential biases. Furthermore, because resilience is a complex and dynamic concept, developing metrics and models that accurately capture all the relevant factors and interactions can be difficult. Nonetheless, efforts to measure and evaluate resilience are critical for better understanding the concept and guiding decision-making in areas such as urban water management.

“FRI” is another technical approach that investigates resilience in two stages: response and recovery time. In the response phase, water depth and flood duration are measured, and in the recovery phase, flood severity, total water depth and total flood are measured. Furthermore, the rate of affected elderly population, women households, and children in collaboration with household income will also be measured.

Table 3. Main resilience metrics used in UWI studies.

Number	Formula	Parameters	UWI Component (WSS, UDS, WWS)	Description	References
1	$1 - \frac{V_{TF}}{V_{TI}} \times \frac{t_f}{t_n}$	V_{TF}: Total flood volume V_{TI}: Total inflow t_f: Mean duration of flooding t_n: Total simulation time	UDS	Measuring system residual functionality	[64]
2	$\frac{\sum_j \left(Ti_j + F_j \Delta Tf_j + R_j \Delta Rf_j\right)}{L_s}$	Ti: Incident time F: Failure profile ΔTf: Failure duration R: Recovery profile ΔRf: Recovery duration L_s: Lifespan of the system	UDS	Calculating occurrence of multiple challenges in different events	[78]
3	$1 - \sum_{k=0}^{1} \frac{\sum_{i=1}^{N}(T_i - E_i)}{\sum_{i=1}^{N} T_i}$	T_i: Threshold at time step i E_i: exceeded Threshold at time step i N: Number of time steps K: Normalised disturbance magnitude	WSS	Expressing performance definition under a wide range of perturbation magnitudes	[5]
4	$\frac{F_r \times F_d}{{F_o}^2} \times \{ \left(\frac{t_\delta}{t_r^*}\right) e^{-a(t_r - t_r^*)} \text{ if } t_r \geq t_r^* \left(\frac{t_\delta}{t_r^*}\right) \quad \text{if } t_r < t_r^*$	F_o: Initial system performance F_r: System performance after recovery F_d: System performance after failure t_δ: Maximum time after demolition t_r: Final recovery time	UDS/WWS	Defining a resilience metric based on pre- and post-disruption performance and reliability and recovery	[79]
5	$\int_{t_2}^{t_2} \frac{[100 - HPC_i(t)]}{D} dt$	HPC: Hydraulic performance capacity t_1: Start time of rainfall event t_2: Recovery time D: The pipe diameter	WSS	Calculating the total area under the hydraulic performance capacity curve from the onset of a severe event to the point of system recovery	[27]
6	$100 \times \left(1 - \frac{A_{cum,i}}{A_{total}}\right)$	$A_{cumi,i}$: Accumulated impervious area A_{total}: Total impervious areas	UDS	Measuring frequency and magnitude of failure due to structural problems	[80]

Table 3. *Cont.*

Number	Formula	Parameters	UWI Component (WSS, UDS, WWS)	Description	References
7	$Res_f = 1 - \left(\frac{V_{flooding}}{V_{runoff}} \times \frac{T_{flooding}}{T_{simulation}}\right)$ $Res_s = \frac{\sum_{i=1}^{NP} 100\left(1 - \left(\frac{A_i}{A_T}\right)\right)}{NP}$	$V_{flooding}$: Total overflowed water V_{runoff}: Total runoff volume $T_{flooding}$: Average flood duration $T_{Simulation}$: Total simulation time A_i: Area connected to pipe i A_T: Total area Res_s: Structural resilience index Res_f: Functional resilience index	UDS/WWS	Stating the magnitude and duration of failure when extreme loading conditions occur	[80]
8	N/A	N/A	UWS	A time-varying is developed to quantify the resilience level of households ranging from 0 to 1 as the minimum and maximum values, respectively. This framework not only considers withstanding the capacity of adverse effects but also the ability to recover quickly.	[81]

5. Resilience-Simulating Tools

Several technical frameworks used to assess the resilience of UWI are provided in Table 2 and Figure 4. Physically based modelling is an effective tool that can predict how UWI behaves under different stressors and scenarios. It can simulate the impacts of natural disasters, such as floods, hurricanes and earthquakes, on UWI and assess the effectiveness of various resilience measures. For example, it can predict the behaviour of water distribution networks under different scenarios, such as power outages, pipe failures and extreme weather events, and identify areas that require resilience measures [82]. Furthermore, physically based modelling can evaluate the effectiveness of different adaptation strategies, such as green infrastructure, in reducing the vulnerability of UWI to natural disasters. This approach is linked to global resilience analysis (GRA), which assesses the resilience of systems and communities at a global level [83]. GRA involves identifying the key drivers and indicators of resilience, analysing their interconnections and assessing the resilience of systems and communities based on their ability to adapt and respond to shocks and stresses [26].

The software tools for modelling the UWI that are commonly used in the research work for simulating the resilience performance in UWI are listed in Table 4 as (1) EPANET, (2) Stormwater Management Model (SWMM), (3) MIKE URBAN, (4) Urban Water Optioneering tool (UWOT) (5) WaterMet^2 and (6) System for Infrastructure Modelling and Assessment (SIMBA). The first three tools (EPANET, SWMM and MIKE URBAN) are physically based models that are typically data demanding and hence their applications are limited to those components that access to all physical data is available. EPANET is a simulation model for water distribution systems and is typically coupled with optimisation models to obtain optimal rehabilitation strategies and operation [84,85], while it has also been applied for resilience assessment of system failure [26]. However, the other three (UWOT, WaterMet^2 and SIMBA) are conceptually based models that are less data demanding with simplified system components used for modelling purposes. Although MIKE URBAN allows the integration of real-time data, such as weather forecasts and sensor measurements, to provide more accurate modelling and predictions, SWMM is more popular due to its free availability and greater capabilities in simulating single flood events or long-term runoff [28,86]. WaterMet^2 is a software tool used for both technical and holistic approaches in an integrated UWI. It can also combine hydrological, hydraulic and water quality models to simulate and optimise UWI performance [87]. SIMBA is a comprehensive tool that models various UWI components and uses a simulation-based holistic approach to assess the performance of UWI under various scenarios, such as changing populations or climate conditions [88]. This tool supports decision-making in the planning, design and operation of UWI. UWOT is a conceptually based modelling tool for performance assessment of UWS and can be efficiently used to estimate resilience indicators of various water management options (e.g., household appliances and fittings or rainwater harvesting schemes) under various scenarios/stressors. UWOT also estimates the energy required by water appliances and evaluates water and wastewater reuse and other green technologies [89].

Table 4. Tools used for simulating resilience and measuring resilience in research works.

Tool	Modelling Type	UWI Component	Reference
EPANET	Physically based	WSS	[26]
SWMM	Physically based	UDS	[64]
MIKE URBAN	Physically based	UDS	[27]
UWOT	Conceptually based	WSS/WWS/UDS	[88]
WaterMet^2	Conceptually based	WSS/WWS/UDS	
SIMBA (simulink)	Conceptually based	WSS/WWS/UDS	[88]

Despite the usefulness of resilience assessment methods, it is important to acknowledge some limitations of these methods as follows: (1) resilience assessment involves dealing with uncertain future events, which can make it challenging to accurately predict and plan for all possible scenarios; (2) adequate data on historical events, infrastructure characteristics and system performance may not always be readily available, making it difficult to conduct comprehensive assessments; and (3) UWI is often interconnected with other critical systems, such as energy and transportation. Assessing resilience solely within the water sector may overlook the interdependencies and cascading effects during disruptive events.

To address these limitations and improve the resilience of UWI, those in charge of UWI can take concrete actions, such as the following: (1) conducting routine inspections and maintenance of water infrastructure to identify vulnerabilities and address potential issues before they escalate; (2) foster collaboration among relevant stakeholders, including water utility operators, local authorities, emergency management agencies and community representatives, to enhance coordination and information sharing during emergencies; and (3) exploring alternative water sources, such as rainwater harvesting, recycled water or groundwater, to ensure a diversified supply and reduce dependence on a single source. For example, groundwater contamination due to pipe infiltration in urban areas can be a common concern that requires attention and can pose risks of contaminant infiltration into the groundwater. To mitigate this risk, proactive measures should be taken, such as (1) pipe maintenance and rehabilitation, (2) monitoring and testing and (3) source protection.

6. Conclusions

In the current scope, this study aimed to map recent attempts at resilience assessment of urban water systems (i.e., urban water distribution and urban drainage and wastewater systems). The study included a brief bibliometric and scientometric analysis, as well as a discussion of major approaches, applied strategies and associated relevant indicators and metrics. The current study highlights the following research findings:

- Most of the research in this area has been conducted in developed countries with strong economics, highlighting the importance of these systems from a macroeconomic perspective and highlighting the need for in-depth localised research in many parts of the world;
- The study's findings reveal three major research areas: (1) system design, which includes risk assessment and system optimisation; (2) resilience in relation to other concepts, such as sustainability and reliability; and (3) green infrastructure implementation;
- Although the concepts of "reliability" and "sustainability" are closely related to the concept of resilience, there are clear boundaries between "water supply", "urban drainage systems", "green infrastructure" and "resilience". This finding suggests that in the future, more emphasis should be placed on integrating these systems as comprehensive approaches;
- This study identified two major approaches to assessing the resilience of urban water systems: a (1) holistic approach and (2) technical approach. Approximately 80% of the research was conducted using technical approaches, the majority of which involved physically based modelling of the UWI. The Safe & Sure framework was applied by half of the papers that used the holistic approach because of its high ability to assess resilience based on system responsiveness, as well as its ability to assess risk and reliability;
- While the identified strategies of (1) system upgrade, (2) decentralisation, (3) digitalisation and (4) nature-based solutions may contribute to promoting resilience in urban water systems, they may not be sufficient to achieve all resilience goals on their own. As a result, multifaceted and integrated solutions that combine digital technologies and nature-based options, for instance, should be tested to upgrade current systems while focusing on decentralisation. This comprehensive and integrated concept appears to be required for further investigation;

- While each holistic approach introduces some aspects of UWI resilience assessment, there is no significant correlation between these indicators. When various metrics are introduced into technical frameworks, the same problem arises. This problem results in an inability to properly compare different implemented resilience options in different case studies, which can lead to a lack of relatively universal solutions. As a result, introducing comprehensive and qualified indicators (for the holistic approach) or quantified metrics (for technical approaches) can help effectively address this problem.

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References

1. World Bank. *Resilient Water Infrastructure Design Brief*; World Bank: Washington, DC, USA, 2020. [CrossRef]
2. Pamidimukkala, A.; Kermanshachi, S.; Adepu, N.; Safapour, E. Resilience in Water Infrastructures: A Review of Challenges and Adoption Strategies. *Sustainability* **2021**, *13*, 12986. [CrossRef]
3. Van Duin, B.; Zhu, D.Z.; Zhang, W.; Muir, R.J.; Johnston, C.; Kipkie, C.; Rivard, G. Toward More Resilient Urban Stormwater Management Systems—Bridging the Gap from Theory to Implementation. *Front. Water* **2021**, *3*, 62. [CrossRef]
4. Leigh, N.G.; Lee, H. Sustainable and Resilient Urban Water Systems: The Role of Decentralization and Planning. *Sustainability* **2019**, *11*, 918. [CrossRef]
5. Juan-García, P.; Butler, D.; Comas, J.; Darch, G.; Sweetapple, C.; Thornton, A.; Corominas, L. Resilience Theory Incorporated into Urban Wastewater Systems Management. State of the Art. *Water Res.* **2017**, *115*, 149–161. [CrossRef]
6. World Health Organization. *Strong Systems and Sound Investments Evidence on and Key Insights into Accelerating Progress on Sanitation, Drinking-Water and Hygiene*; World Health Organization: Geneva, Switzerland, 2022.
7. Donnell, E.O.; Thorne, C.; Ahilan, S.; Arthur, S.; Dawson, D.; Everett, G.; Birkinshaw, S.; Butler, D.; Fenner, R.; Glenis, V.; et al. The Blue-Green Path to Urban Fl Ood Resilience. *Blue-Green Syst.* **2020**, *2*, 28–45. [CrossRef]
8. Fu, G.; Meng, F.; Casado, M.R.; Kalawsky, R.S. Towards Integrated Flood Risk and Resilience Management. *Water* **2020**, *12*, 1789. [CrossRef]
9. Fu, G.; Butler, D. Pathways towards Sustainable and Resilient Urban Water Systems. In *Water-Wise Cities Sustainable Water Systems; Concepts, Technologies and Applications*; IWA Publishing: London, UK, 2021; pp. 3–24. [CrossRef]
10. Mehvar, S.; Wijnberg, K.; Borsje, B.; Kerle, N.; Maarten Schraagen, J.; Vinke-De Kruijf, J.; Geurs, K.; Hartmann, A.; Hogeboom, R.; Hulscher, S. Review Article: Towards Resilient Vital Infrastructure Systems-Challenges, Opportunities, and Future Research Agenda. *Nat. Hazards Earth Syst. Sci.* **2021**, *21*, 1383–1407. [CrossRef]
11. Zhang, Q.; Zheng, F.; Kapelan, Z.; Savic, D.; He, G.; Ma, Y. Assessing the Global Resilience of Water Quality Sensor Placement Strategies within Water Distribution Systems Water Research Assessing the Global Resilience of Water Quality Sensor Placement Strategies within Water Distribution Systems. *Water Res.* **2020**, *172*, 115527. [CrossRef]
12. Piadeh, F.; Ahmadi, M.; Behzadian, K. Reliability Assessment for Hybrid Systems of Advanced Treatment Units of Industrial Wastewater Reuse Using Combined Event Tree and Fuzzy Fault Tree Analyses. *J. Clean. Prod.* **2018**, *201*, 958–973. [CrossRef]
13. Rahimi-golkhandan, A.; Aslani, B.; Mohebbi, S. Socio-Economic Planning Sciences Predictive Resilience of Interdependent Water and Transportation Infrastructures: A Sociotechnical Approach. *Socioecon. Plan. Sci.* **2022**, *80*, 101166. [CrossRef]
14. Zuloaga, S. Quantifying Power System Operational and Infrastructural Resilience under Extreme Conditions within a Water-Energy. *IEEE Open Access J. Power Energy* **2021**, *8*, 229–238. [CrossRef]
15. Pokhrel, S.R.; Chhipi-Shrestha, G.; Mian, H.R.; Hewage, K.; Sadiq, R. Integrated Performance Assessment of Urban Water Systems: Identification and Prioritization of One Water Approach Indicators. *Sustain. Prod. Consum.* **2023**, *36*, 62–74. [CrossRef]
16. Poch, M.; Aldao, C.; Godo-Pla, L.; Monclús, H.; Popartan, L.A.; Comas, J.; Cermerón-Romero, M.; Puig, S.; Molinos-Senante, M. Increasing Resilience through Nudges in the Urban Water Cycle: An Integrative Conceptual Framework to Support Policy Decision-Making. *Chemosphere* **2023**, *317*, 137850. [CrossRef]

17. Ma, Y.; Jiang, Y.; Swallow, S. China's Sponge City Development for Urban Water Resilience and Sustainability: A Policy Discussion. *Sci. Total Environ.* **2020**, *729*, 139078. [CrossRef] [PubMed]
18. Quitana, G.; Molinos-Senante, M.; Chamorro, A. Resilience of Critical Infrastructure to Natural Hazards: A Review Focused on Drinking Water Systems. *Int. J. Disaster Risk Reduct.* **2020**, *48*, 101575. [CrossRef]
19. Butler, D.; Farmani, R.; Fu, G.; Ward, S.; Diao, K.; Astaraie-Imani, M. A New Approach to Urban Water Management: Safe and Sure. *Procedia Eng.* **2014**, *89*, 347–354. [CrossRef]
20. Patra, D.; Chanse, V.; Rockler, A.; Wilson, S.; Montas, H.; Shirmohammadi, A.; Leisnham, P.T. Towards Attaining Green Sustainability Goals of Cities through Social Transitions: Comparing Stakeholders' Knowledge and Perceptions between Two Chesapeake Bay Watersheds, USA. *Sustain. Cities Soc.* **2021**, *75*, 103318. [CrossRef]
21. Bertilsson, L.; Wiklund, K.; de Moura Tebaldi, I.; Rezende, O.M.; Veról, A.P.; Miguez, M.G. Urban Flood Resilience—A Multi-Criteria Index to Integrate Flood Resilience into Urban Planning. *J. Hydrol.* **2019**, *573*, 970–982. [CrossRef]
22. Beceiro, P.; Brito, R.S.; Galvão, A. The Contribution of NBS to Urban Resilience in Stormwater Management and Control: A Framework with Stakeholder Validation. *Sustainability* **2020**, *12*, 2537. [CrossRef]
23. Vercruysse, K.; Dawson, D.A.; Wright, N. Interoperability: A Conceptual Framework to Bridge the Gap between Multifunctional and Multisystem Urban Flood Management. *J. Flood Risk Manag.* **2019**, *12*, e12535. [CrossRef]
24. Rodriguez, M.; Fu, G.; Butler, D.; Yuan, Z.; Sharma, K. Exploring the Spatial Impact of Green Infrastructure on Urban Drainage Resilience. *Water* **2021**, *13*, 1789. [CrossRef]
25. Oberascher, M.; Rauch, W.; Sitzenfrei, R. Towards a Smart Water City: A Comprehensive Review of Applications, Data Requirements, and Communication Technologies for Integrated Management. *Sustain. Cities Soc.* **2022**, *76*, 103442. [CrossRef]
26. Diao, K.; Sweetapple, C.; Farmani, R.; Fu, G.; Ward, S.; Butler, D. Global Resilience Analysis of Water Distribution Systems. *Water Res.* **2016**, *106*, 383–393. [CrossRef]
27. Valizadeh, N.; Shamseldin, A.Y.; Wotherspoon, L. Quantification of the Hydraulic Dimension of Stormwater Management System Resilience to Flooding. *Water Resour. Manag.* **2019**, *33*, 4417–4429. [CrossRef]
28. Oberascher, M.; Dastgir, A.; Li, J.; Hesarkazzazi, S.; Hajibabaei, M.; Rauch, W.; Sitzenfrei, R. Revealing the Challenges of Smart Rainwater Harvesting for Integrated and Digital Resilience of Urban Water Infrastructure. *Water* **2021**, *13*, 1902. [CrossRef]
29. Cea, L.; Costabile, P. Flood Risk in Urban Areas: Modelling, Management and Adaptation to Climate Change: A Review. *Hydrology* **2022**, *9*, 50. [CrossRef]
30. Ji, J.; Chen, J. Urban Flood Resilience Assessment Using RAGA-PP and KL-TOPSIS Model Based on PSR Framework: A Case Study of Jiangsu Province, China. *Water Sci. Technol.* **2022**, *86*, 3264–3280. [CrossRef] [PubMed]
31. Ro, B.; Garfin, G. Building Urban Flood Resilience through Institutional Adaptive Capacity: A Case Study of Seoul, South Korea. *Int. J. Disaster Risk Reduct.* **2023**, *85*, 103474. [CrossRef]
32. Francisco, T.H.S.; Menezes, O.V.C.; Guedes, A.L.A.; Maquera, G.; Neto, D.C.V.; Longo, O.C.; Chinelli, C.K.; Soares, C.A.P. The Main Challenges for Improving Urban Drainage Systems from the Perspective of Brazilian Professionals. *Infrastructures* **2023**, *8*, 5. [CrossRef]
33. Zheng, J.; Huang, G. Towards Flood Risk Reduction: Commonalities and Differences between Urban Flood Resilience and Risk Based on a Case Study in the Pearl River Delta. *Int. J. Disaster Risk Reduct.* **2023**, *86*, 103568. [CrossRef]
34. Cardoso, M.A.; Brito, R.S.; Pereira, C.; Gonzalez, A.; Stevens, J.; Telhado, M.J. RAF Resilience Assessment Framework—A Tool to Support Cities' Action Planning. *Sustainability* **2020**, *12*, 2349. [CrossRef]
35. Cheng, Y.; Elsayed, E.A.; Huang, Z. Systems Resilience Assessments: A Review, Framework and Metrics. *Int. J. Prod. Res.* **2022**, *60*, 595–622. [CrossRef]
36. Guo, D.; Shan, M.; Owusu, E.K. Resilience Assessment Frameworks of Critical Infrastructures: State-of-the-Art Review. *Buildings* **2021**, *11*, 464. [CrossRef]
37. Fonseca, K.; Espitia, E.; Breuer, L.; Correa, A. Using Fuzzy Cognitive Maps to Promote Nature-Based Solutions for Water Quality Improvement in Developing-Country Communities. *J. Clean. Prod.* **2022**, *377*, 134246. [CrossRef]
38. Naghedi, R.; Alavi Moghaddam, M.R.; Piadeh, F. Creating Functional Group Alternatives in Integrated Industrial Wastewater Recycling System: A Case Study of Toos Industrial Park (Iran). *J. Clean. Prod.* **2020**, *257*, 120464. [CrossRef]
39. Zhou, J.; Hou, Q.; Li, W. Spatial Resilience Assessment and Optimization of Small Watershed Based on Complex Network Theory. *Ecol. Indic.* **2022**, *145*, 109730. [CrossRef]
40. Yuan, F.; Liu, R.; Mao, L.; Li, M. Internet of People Enabled Framework for Evaluating Performance Loss and Resilience of Urban Critical Infrastructures. *Saf. Sci.* **2021**, *134*, 105079. [CrossRef]
41. Büyüközkan, G.; Ilıcak, Ö.; Feyzioğlu, O. A Review of Urban Resilience Literature. *Sustain. Cities Soc.* **2022**, *77*, 103579. [CrossRef]
42. Saikia, P.; Beane, G.; Garriga, R.G.; Avello, P.; Ellis, L.; Fisher, S.; Leten, J.; Ruiz-Apilánez, I.; Shouler, M.; Ward, R.; et al. City Water Resilience Framework: A Governance Based Planning Tool to Enhance Urban Water Resilience. *Sustain. Cities Soc.* **2022**, *77*, 103497. [CrossRef]
43. Balaei, B.; Noy, I.; Wilkinson, S.; Potangaroa, R. Socio-Economic Planning Sciences Economic Factors Affecting Water Supply Resilience to Disasters. *Socioecon. Plan. Sci.* **2020**, *76*, 100961. [CrossRef]
44. Assad, A.; Bouferguene, A. Resilience Assessment of Water Distribution Networks—Bibliometric Analysis and Systematic Review. *J. Hydrol.* **2022**, *607*, 127522. [CrossRef]

45. Rasoulkhani, K.; Mostafavi, A.; Cole, J.; Sharvelle, S. Resilience-Based Infrastructure Planning and Asset Management: Study of Dual and Singular Water Distribution Infrastructure Performance Using a Simulation Approach. *Sustain. Cities Soc.* **2019**, *48*, 101577. [CrossRef]
46. Pokhrel, S.R.; Chhipi-Shrestha, G.; Hewage, K.; Sadiq, R. Sustainable, Resilient, and Reliable Urban Water Systems: Making the Case for a "One Water" Approach. *Environ. Rev.* **2022**, *30*, 10–29. [CrossRef]
47. Zeng, X.; Yu, Y.; Yang, S.; Lv, Y.; Sarker, M.N.I. Urban Resilience for Urban Sustainability: Concepts, Dimensions, and Perspectives. *Sustainability* **2022**, *14*, 2481. [CrossRef]
48. Rahmani, F.; Behzadian, K.; Ardeshir, A. Rehabilitation of a Water Distribution System Using Sequential Multiobjective Optimization Models. *J. Water Resour. Plan. Manag.* **2016**, *142*, C4015003. [CrossRef]
49. Casal-Campos, A.; Sadr, S.M.K.; Fu, G.; Butler, D. Reliable, Resilient and Sustainable Urban Drainage Systems: An Analysis of Robustness under Deep Uncertainty. *Environ. Sci. Technol.* **2018**, *52*, 9008–9021. [CrossRef]
50. Cecconet, D.; Raček, J.; Callegari, A.; Hlavínek, P. Energy Recovery from Wastewater: A Study on Heating and Cooling of a Multipurpose Building with Sewage-Reclaimed Heat Energy. *Sustainability* **2020**, *12*, 116. [CrossRef]
51. Maniam, G.; Zakaria, N.A.; Leo, C.P.; Vassilev, V.; Blay, K.B.; Behzadian, K.; Poh, P.E. An Assessment of Technological Development and Applications of Decentralized Water Reuse: A Critical Review and Conceptual Framework. *Wiley Interdiscip. Rev. Water* **2022**, *9*, e1588. [CrossRef]
52. UNESCO World Water Assessment Programme. *The United Nations World Water Development Report: Nature-Based Solutions for Water*; UNESCO World Water Assessment Programme: Paris, France, 2018; Available online: https://unesdoc.unesco.org/ark:/48223/pf0000261424 (accessed on 1 March 2023).
53. Ashley, R.; Gersonius, B.; Horton, B. Managing Flooding: From a Problem to an Opportunity. *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.* **2020**, *378*, 20190214. [CrossRef]
54. Karami, M.; Behzadian, K.; Ardeshir, A.; Hosseinzadeh, A.; Kapelan, Z. A Multi-Criteria Risk-Based Approach for Optimal Planning of SuDS Solutions in Urban Flood Management. *Urban Water J.* **2022**, *19*, 1066–1079. [CrossRef]
55. O'Donnell, E.C.; Thorne, C.R.; Yeakley, J.A.; Chan, F.K.S. Sustainable Flood Risk and Stormwater Management in Blue-Green Cities; an Interdisciplinary Case Study in Portland, Oregon. *J. Am. Water Resour. Assoc.* **2020**, *56*, 757–775. [CrossRef]
56. Rentachintala, L.R.N.P.; Reddy, M.G.M.; Mohapatra, P.K. Urban Stormwater Management for Sustainable and Resilient Measures and Practices: A Review. *Water Sci. Technol.* **2022**, *85*, 1120–1140. [CrossRef] [PubMed]
57. D'ambrosio, R.; Longobardi, A.; Balbo, A.; Rizzo, A. Hybrid Approach for Excess Stormwater Management: Combining Decentralized and Centralized Strategies for the Enhancement of Urban Flooding Resilience. *Water* **2021**, *13*, 3635. [CrossRef]
58. Jato-Espino, D.; Toro-Huertas, E.I.; Güereca, L.P. Lifecycle Sustainability Assessment for the Comparison of Traditional and Sustainable Drainage Systems. *Sci. Total Environ.* **2022**, *817*, 152959. [CrossRef]
59. Bach, P.M.; Rauch, W.; Mikkelsen, P.S.; McCarthy, D.T.; Deletic, A. A Critical Review of Integrated Urban Water Modelling—Urban Drainage and Beyond. *Environ. Model. Softw.* **2014**, *54*, 88–107. [CrossRef]
60. Piadeh, F.; Behzadian, K.; Alani, A.M. A Critical Review of Real-Time Modelling of Flood Forecasting in Urban Drainage Systems. *J. Hydrol.* **2022**, *607*, 127476. [CrossRef]
61. Boulos, P.F. Smart Water Network Modeling for Sustainable and Resilient Infrastructure. *Water Resour. Manag.* **2017**, *31*, 3177–3188. [CrossRef]
62. Tuptuk, N.; Hazell, P.; Watson, J.; Hailes, S. A Systematic Review of the State of Cyber-Security in Water Systems. *Water* **2021**, *13*, 81. [CrossRef]
63. Nakhaei, M.; Nakhaei, P.; Gheibi, M.; Chahkandi, B.; Wacławek, S.; Behzadian, K.; Chen, A.S.; Campos, L.C. Enhancing Community Resilience in Arid Regions: A Smart Framework for Flash Flood Risk Assessment. *Ecol. Indic.* **2023**, *153*, 110457.
64. Mugume, S.N.; Gomez, D.E.; Fu, G.; Farmani, R.; Butler, D. A Global Analysis Approach for Investigating Structural Resilience in Urban Drainage Systems. *Water Res.* **2015**, *81*, 15–26. [CrossRef]
65. Busker, T.; de Moel, H.; Haer, T.; Schmeits, M.; van den Hurk, B.; Myers, K.; Cirkel, D.G.; Aerts, J. Blue-Green Roofs with Forecast-Based Operation to Reduce the Impact of Weather Extremes. *J. Environ. Manag.* **2022**, *301*, 113750. [CrossRef] [PubMed]
66. Liu, W.; Engel, B.A.; Feng, Q. Modelling the Hydrological Responses of Green Roofs under Different Substrate Designs and Rainfall Characteristics Using a Simple Water Balance Model. *J. Hydrol.* **2021**, *602*, 126786. [CrossRef]
67. Futter, M. *Commentary: A (Mostly) Hydrological Commentary on the Small Retention Programs in the Polish Forests*; Springer: Berlin/Heidelberg, Germany, 2019. [CrossRef]
68. Judeh, T.; Shahrour, I.; Comair, F. Smart Rainwater Harvesting for Sustainable Potable Water Supply in Arid and Semi-Arid Areas. *Sustainability* **2022**, *14*, 9271. [CrossRef]
69. Moisès, D.J.; Kunguma, O. Strengthening Namibia's Flood Early Warning System through a Critical Gap Analysis. *Sustainability* **2023**, *15*, 524. [CrossRef]
70. Mousavi, S.; Gheibi, M.; Wacławek, S.; Behzadian, K. A Novel Smart Framework for Optimal Design of Green Roofs in Buildings Conforming with Energy Conservation and Thermal Comfort. *Energy Build.* **2023**, *291*, 113111.
71. Chakraborty, T.; Biswas, T.; Campbell, L.S.; Franklin, B.; Parker, S.S.; Tukman, M. Feasibility of Afforestation as an Equitable Nature-Based Solution in Urban Areas. *Sustain. Cities Soc.* **2022**, *81*, 103826. [CrossRef]
72. Hosseinzadeh, A.; Behzadian, K.; Rossi, P.; Karami, M.; Ardeshir, A.; Torabi Haghighi, A. A New Multi-criteria Framework to Identify Optimal Detention Ponds in Urban Drainage Systems. *J. Flood Risk Manag.* **2023**, *16*, e12890. [CrossRef]

73. Hall, J.W.; Borgomeo, E.; Bruce, A.; Di Mauro, M.; Mortazavi-Naeini, M. Resilience of Water Resource Systems: Lessons from England. *Water Secur.* **2019**, *8*, 100052. [CrossRef]
74. McClymont, K.; Morrison, D.; Beevers, L.; Carmen, E. Flood Resilience: A Systematic Review. *J. Environ. Plan. Manag.* **2020**, *63*, 1151–1176. [CrossRef]
75. Landa-Cansigno, O.; Behzadian, K.; Davila-Cano, D.I.; Campos, L.C. Performance Assessment of Water Reuse Strategies Using Integrated Framework of Urban Water Metabolism and Water-Energy-Pollution Nexus. *Environ. Sci. Pollut. Res.* **2020**, *27*, 4582–4597.
76. Kordana, S.; Słyś, D. An Analysis of Important Issues Impacting the Development of Stormwater Management Systems in Poland. *Sci. Total Environ.* **2020**, *727*, 138711. [CrossRef]
77. Lee, K.; Jepson, W. Drivers and Barriers to Urban Water Reuse: A Systematic Review. *Water Secur.* **2020**, *11*, 100073. [CrossRef]
78. Schoen, M.; Hawkins, T.; Xue, X.; Ma, C.; Garland, J.; Ashbolt, N.J. Technologic Resilience Assessment of Coastal Community Water and Wastewater Service Options. *Sustain. Water Qual. Ecol.* **2015**, *6*, 75–87. [CrossRef]
79. Joyce, J.; Chang, N.-B.; Harji, R.; Ruppert, T. Coupling Infrastructure Resilience and Flood Risk Assessment via Copulas Analyses for a Coastal Green-Grey-Blue Drainage System under Extreme Weather Events. *Environ. Model. Softw.* **2018**, *100*, 82–103. [CrossRef]
80. Bakhshipour, A.E.; Hespen, J.; Haghighi, A.; Dittmer, U.; Nowak, W. Integrating Structural Resilience in the Design of Urban Drainage Networks in Flat Areas Using a Simplified Multi-Objective Optimization Framework. *Water* **2021**, *13*, 269. [CrossRef]
81. Chen, K.; Leandro, J. A Conceptual Time-Varying Flood Resilience Index for Urban Areas: Munich City. *Water* **2019**, *11*, 830. [CrossRef]
82. Ebrahimi, A.H.; Mortaheb, M.M.; Hassani, N.; Taghizadeh-yazdi, M. A Resilience-Based Practical Platform and Novel Index for Rapid Evaluation of Urban Water Distribution Network Using Hybrid Simulation. *Sustain. Cities Soc.* **2022**, *82*, 103884. [CrossRef]
83. Hochrainer-Stigler, S.; Finn, L.; Velev, S.; Keating, A.; Mechler, R. Standardized Disaster and Climate Resilience Grading: A Global Scale Empirical Analysis of Community Flood Resilience. *J. Environ. Manag.* **2020**, *276*, 111332. [CrossRef]
84. Muhammed, K.; Farmani, R.; Behzadian, K.; Diao, K.; Butler, D. Optimal Rehabilitation of Water Distribution Systems Using a Cluster-Based Technique. *J. Water Resour. Plan. Manag.* **2017**, *143*, 04017022.
85. Rahmani, F.; Muhammed, K.; Behzadian, K.; Farmani, R. Optimal Operation of Water Distribution Systems Using a Graph Theory–Based Configuration of District Metered Areas. *J. Water Resour. Plan. Manag.* **2018**, *144*, 04018042. [CrossRef]
86. Guptha, G.C.; Swain, S.; Al-Ansari, N.; Taloor, A.K.; Dayal, D. Assessing the Role of SuDS in Resilience Enhancement of Urban Drainage System: A Case Study of Gurugram City, India. *Urban Clim.* **2022**, *41*, 101075. [CrossRef]
87. Behzadian, K.; Kapelan, Z. Modelling Metabolism Based Performance of an Urban Water System Using WaterMet2. *Resour. Conserv. Recycl.* **2015**, *99*, 84–99. [CrossRef]
88. Sweetapple, C.; Fu, G.; Farmani, R.; Butler, D. Exploring Wastewater System Performance under Future Threats: Does Enhancing Resilience Increase Sustainability? *Water Res.* **2019**, *149*, 448–459. [CrossRef] [PubMed]
89. Nikolopoulos, D.; van Alphen, H.J.; Vries, D.; Palmen, L.; Koop, S.; van Thienen, P.; Medema, G.; Makropoulos, C. Tackling the "New Normal": A Resilience Assessment Method Applied to Real-World Urban Water Systems. *Water* **2019**, *11*, 330. [CrossRef]