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Research paper

FLOOD AND DROUGHT RISK MANAGEMENT SOLUTIONS IN SMART CITIES

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Abstract

The frequency and intensity of floods and droughts are projected to rise under future climatic conditions. Urban areas, with their increasing populations and expanding built environments, are expected to face these challenges more acutely. In response, smart cities that leverage digital technologies for data collection and service delivery are well-positioned to address these risks more effectively than traditional cities. This study reviews, analyzes, and discusses how digital technologies are applied in managing urban flood and drought risks. Smart cities integrate information and communication technology alongside Internet of Things devices to optimize public services and foster citizen engagement. A literature review of smart city solutions across Europe highlights the application of risk assessment tools, decision support systems, and early warning mechanisms, in flood- and drought-related climate adaptation strategies, and overall city resilience. The findings underscore the urgent need for an integrated approach to managing these escalating risks, including shared technological solutions that address both hazards simultaneously.

Key words: *Urban Floods, Urban Droughts, Risk Management, Technological Solutions, Smart City*

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1. INTRODUCTION

Driven by rising global temperatures, altered precipitation patterns, and more extreme weather events, the frequency and intensity of both floods and droughts are projected to increase under future climate scenarios [1]. These hydrometeorological hazards significantly threaten human well-being, ecosystems, and economic stability. With climate change continuing to accelerate, the need for proactive and adaptive water risk management strategies becomes increasingly urgent [2].

Urban areas are particularly vulnerable to these growing risks due to their dense populations, high concentration of infrastructure, and often aging water management systems [3]. As cities expand, impervious surfaces multiply, disrupting the natural hydrological cycle, intensifying surface runoff during floods, and reducing groundwater recharge, leading to droughts. Additionally, the socio-economic diversity within urban populations often leads to unequal exposure and sensitivity to water-related hazards, complicating effective risk mitigation [4].

In this context, smart cities offer a promising approach to enhance resilience [5]. Smart cities are urban areas that embrace digital technologies and data-driven solutions. By integrating real-time monitoring, predictive analytics, and automated response systems, smart cities can more efficiently manage water resources, detect and respond to extreme events, and support informed decision-making [5]. Unlike traditional urban environments, smart cities are better equipped to anticipate hydrological hazards and implement targeted, adaptive measures that protect both infrastructure and vulnerable populations [6].

The number of smart cities has been steadily increasing since the 1960s, when Milton Keynes in the UK was established as one of the earliest examples of a smart city [7]. In 2025, the International Institute for Management Development (IMD) ranked 146 smart cities worldwide according to its Smart City Index [8]. This index evaluates residents' perceptions of the infrastructure and technological applications available in their cities. Of the ranked cities, 58 are located in Europe, 47 in Asia, 16 in North America, 10 in South America, 9 in Africa, and 6 in Australia. Similarly, the Smart Cities World platform [9] profiles 108 cities, with European cities making up the largest group, 37 in total.

This paper aims to analyze urban flood and urban drought-related solutions in selected European smart cities, with a focus on digital technologies, data, and system-based solutions. The structure of the paper is as follows: the methodology section outlines the criteria for city selection, as well as the review and analysis approach. The results section presents smart city solutions addressing the topics of interest. The discussion explores cross-cutting themes, and the conclusion highlights common technological approaches and shared solutions.

2. METHODOLOGY

The research was conducted through the following sequential steps: 1) Identification of a comprehensive list of smart cities; 2) Initial selection of candidate cities; 3) Literature review; 4) Organization of relevant references by city; 5) Final selection of smart cities based on literature availability and relevance; 6) In-depth study of selected literature for each city; 7) Thematic grouping of references based on the topics of interest; 8) Synthesis of findings by topic and identification of cross-topic linkages.

The Smart Cities World platform [9] was identified as the most appropriate source for generating the initial list of smart cities. From this platform, 37 European smart cities were identified for a preliminary review. The UK had the highest representation with 15 cities, followed by Spain, Germany, and Finland with three cities each. Sweden contributed two cities, while the Netherlands, Belgium, Ireland, Italy, Russia, France, Latvia, Poland, Estonia, Norway, and Austria each had one city.

The literature review was conducted using a targeted text mining approach, focusing on three main themes: 1) Connectivity and Data (C&D), 2) Urban Flood Risk Management (UFRM), and 3) Urban Drought Risk Management (UDRM).

Based on earlier work on water management solutions in smart cities [10], the C&D component of the review encompassed not only digital technologies for data collection and service delivery but also public engagement and education as key elements of effective implementation. Figure 1 illustrates the scope of this study, with blue boxes highlighting the primary research focus areas.

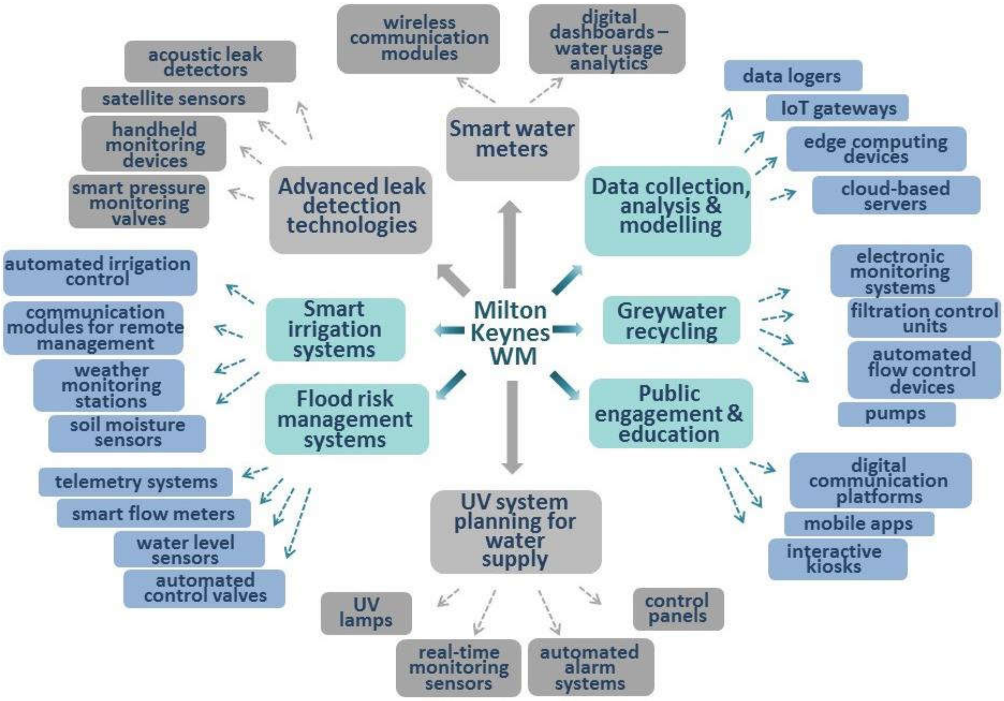

Figure 1. Blue boxes showing areas of research for this study within innovative solution elements and applied devices for water management (WM) in the smart city of Milton Keynes (Modified from: [10])

For UFRM, the literature search focused on identifying risk assessment tools, decision support systems, early warning mechanisms, and other flood-related climate adaptation strategies that contribute to overall city resilience. The primary interest was in pluvial floods, as these are typically managed at the municipal/city level, unlike fluvial, coastal, or flash floods, which generally fall under higher administrative jurisdictions.

The UDRM review followed a similar focus, targeting literature on tools, systems, and strategies used for drought risk assessment and response in urban environments. An alternative was placed on water scarcity and urban irrigation solutions, which are critical under changing climatic conditions.

3. RESULTS

The most abundant literature was found in the area of Connectivity and Data, followed by UFRM. The least represented theme in the literature was UDRM. Therefore, the final selection of cities included in this study was determined based on the availability and quality of sources related to UDRM, ensuring a balanced review of all three research themes.

The following cities are selected for this paper: Amsterdam (the Netherlands), Barcelona (Spain), Dortmund (Germany), Paris (France), and Vienna (Austria).

3.1. Amsterdam

The city of Amsterdam is the capital and largest city of the Netherlands, with a population of around 900,000. The Amsterdam Metropolitan Region is characterized by an integrated landscape of urban areas, water bodies, and green infrastructure. The prevailing land use in the Amsterdam region is agricultural land (56% primarily pasture and arable land) followed by about 25% urbanized space, of which over one third is impervious surface, and approximately 11% forest and nature areas [11].

Amsterdam is situated below sea level and has a historically developed water management system of canals, dikes, and pumping stations, making it particularly vulnerable to both pluvial and fluvial floods as well as sea-level rise. Green space per capita in central Amsterdam is limited, with spatial pressure from urbanization remaining a concern, although strong planning policies have preserved surrounding green belts and polder landscapes. The municipality has invested in expanding green-blue infrastructure, promoting climate-adaptive urban design, and implementing Nature-Based Solutions (NBS) to enhance both urban livability and flood resilience [12].

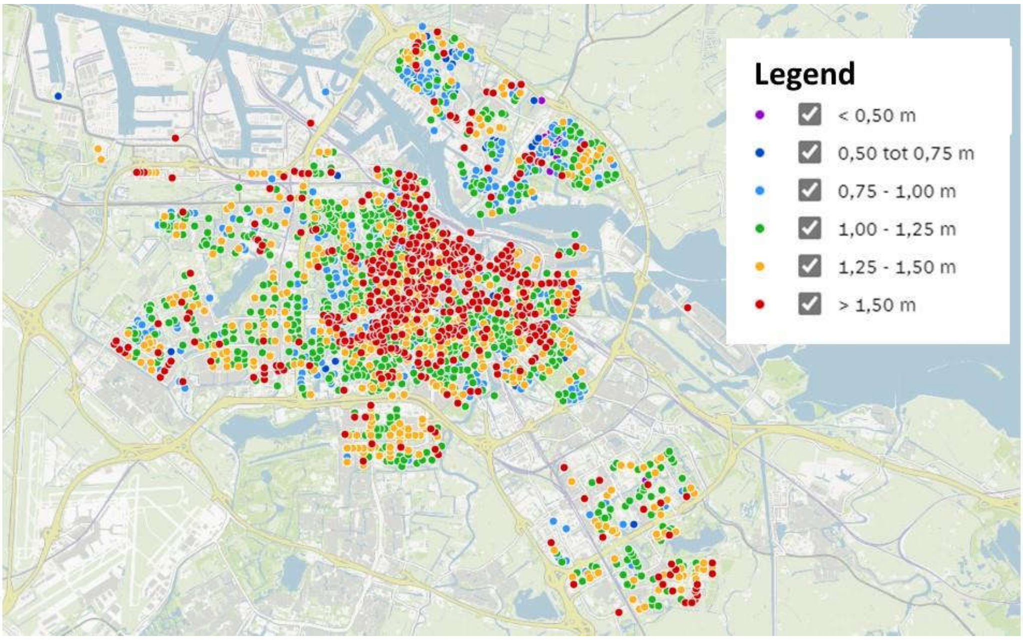

Figure 2. Groundwater table depth on the online map (Source: [13])

The “Rainproof Amsterdam” program launched in 2014, specifically addresses pluvial floods within the UFRM, and encourages decentralized rainwater management through green roofs, permeable pavements, and urban water buffers. The city also promotes multi-functional land use, where public spaces serve both recreational and water retention functions [12].

The UDRM is considered under the climate adaptation plan. Drought-prone locations are shown on the interactive online maps through groundwater table levels (Figure 2).

The Amsterdam University of Applied Sciences, together with 6 universities, 4 water boards and district water boards, 8 municipalities, and other partners, has just begun a five-year project (2025-2030) Thirsty Cities: Towards drought resilient cities. The project will explore how cities can cope with increasing drought [14].

Within the RESILIO project (2018-2021) [15], the 10,000m^2 area of new smart blue green roofs helps the city adapts to climate change by reducing impacts of heavy rain, urban heat island effect, and drought. These smart roofs have been created by repurposing the rooftops of climate-vulnerable neighbourhoods of Amsterdam. The roofs have been designed to capture and store rainwater, thereby mitigating flood risks and conserving water for use during droughts. They are equipped with smart valves and sensors that manage water levels by releasing stored water before storms, enhancing their capacity to absorb rainfall. Additionally, during dry periods, these systems retain water to support rooftop vegetation, contributing to urban cooling and biodiversity [15].

3.2. Barcelona

The Barcelona Metropolitan Area, home to over 5 million people, represents one of the most densely populated urban regions in Spain, with the city of Barcelona itself having a density of over 16,000 inhabitants/km^2. Land cover in the metropolitan area includes approximately 25% forest, 45% agricultural or semi-natural areas, and around 30% urbanized land, with a high share of impervious surfaces contributing to urban heat and flood risks [3]. Despite significant green infrastructure initiatives, green space per capita remains unevenly distributed, especially in older, densely built districts, prompting ongoing efforts to green streets, rooftops, and courtyards as climate adaptation measures.

Barcelona participated in the RESCCUE (Resilience to Climate Change in Urban Areas) project, which developed sectorial and integrated models to assess the resilience of critical urban services under current and future pluvial flood scenarios. These models analyze the behavior of urban services during heavy storm events (Figure 3), considering cascading effects due to infrastructure failures. The project aims to inform decision-making and enhance urban resilience strategies [16].

An alternative within NBS as measures in both UFRM and UDRM is studied in Barcelona for two floodable areas [17]. A more notable disaster is extreme drought, for which urgent water supply restrictions have been implemented. The findings for different scenarios and common parameters in calculations of water harvesting and rainwater infiltration could support the decisions to implement either green or blue NBS, depending on the hydrological balance in the study area [17].

Barcelona is recognized as a leader in smart water management, leveraging the Internet of Things (IoT) to optimize water usage. The city has deployed a network of sensors to monitor water consumption, detect leaks in real-time, and manage irrigation systems efficiently. This approach has led to significant water savings and improved resource management [7].

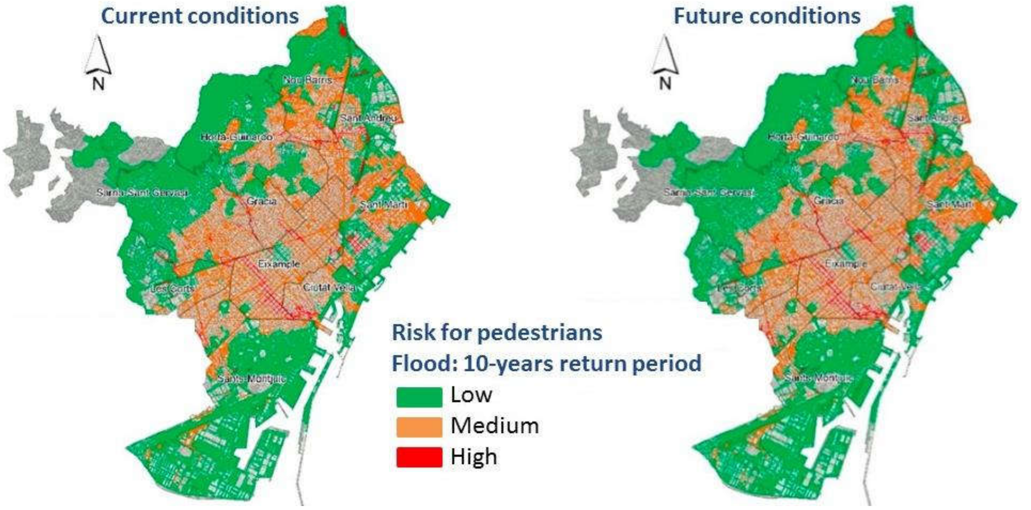

Figure 3. Flood risk maps for pedestrians for a 10-year return period design storms related to: Left- baseline and Right - business as usual (BAU) scenarios (Source: [16])

3.3. Dortmund

The city of Dortmund, located in the federal state of North Rhine-Westphalia, Germany, is the largest city in the historically industrial Ruhr area, with a population exceeding 600,000 residents. Despite its industrial legacy, nearly half of Dortmund's municipal territory comprises green spaces, including forests, agricultural land, parks, gardens, and natural reserves. The city has actively pursued the transformation of former industrial zones into green areas as part of its broader sustainability goals [18]. In line with climate change adaptation strategies, the City Council has developed a range of recommendations and measures aimed at mitigating the urban impacts of extreme heat, air pollution, heavy rainfall, and prolonged summer droughts [19].

Following a severe pluvial flooding event in July 2008, which resulted in significant damage despite the full functionality of the sewer system, the city initiated several key actions to improve its flood resilience [20]: 1) Formation of a flood protection working group; 2) Development of a civil protection emergency plan in collaboration with the Fire Department and the Federal Agency for Technical Relief; 3) Publication of a flood prevention information flyer; 4) Implementation of a hydrodynamic sewer network analysis to evaluate urban flood risks; 5) Appointment of a municipal flood prevention officer; 6) Formulation of a comprehensive flood prevention plan for both water and sewage systems; 7) Procurement of advanced technical equipment, including mobile high-capacity flood pumps.

Today, Dortmund employs a comprehensive, multifaceted approach to managing pluvial floods, combining infrastructure improvements, institutional planning, and advanced modeling techniques.

The city's local climate strategy, outlined in The Development Concept for Dortmund City Centre [19], advocates moving away from conventional stormwater drainage systems. Instead, it promotes the use of narrow surface channels, ditches, and vegetated areas to direct runoff, providing the dual benefit of urban cooling and stormwater management. Stored water in cisterns, pools, and green spaces is also integrated into this system to manage overflow and mitigate extreme rainfall effects. Green roofs on underutilized buildings in the city center are also being promoted as part of this strategy. With plans to establish a green roof registry and develop regulations for both flat and slightly inclined roofs, the city is clearly prioritizing NBS for improved environmental sustainability, contributing simultaneously to UFRM and UDRM.

Innovative technologies have also been piloted in Dortmund. Stavroulakis et al. [21] propose a novel system architecture for augmented reality (AR) flood visualization, currently being tested in the city. This AR system enables rescuers equipped with wearable devices to access real-time visualizations of floodwater levels and optimal evacuation routes, based on large-scale data analytics from open data sources on weather and critical infrastructure (Figure 4).

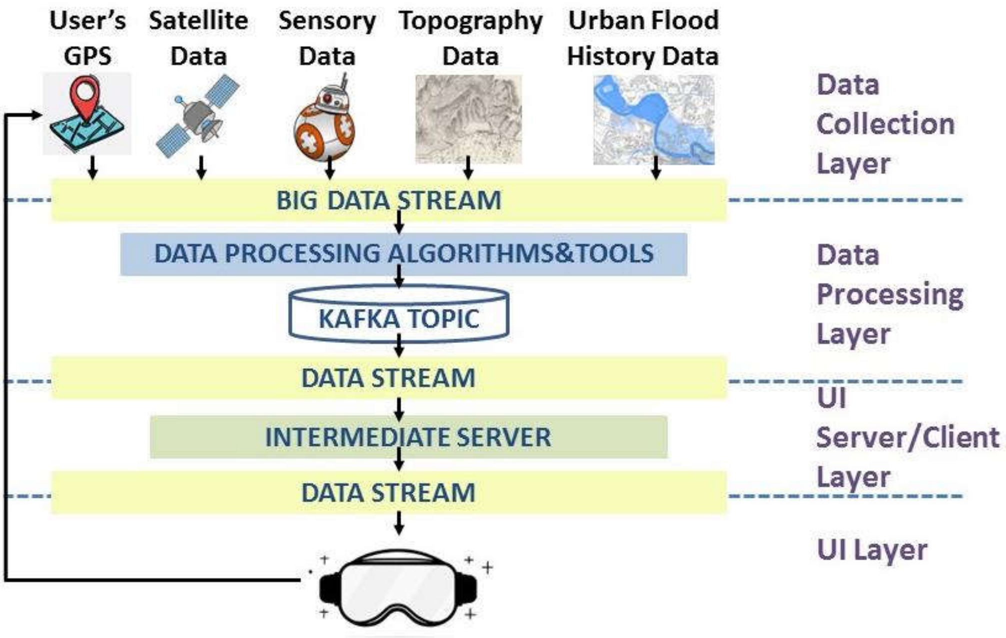

Figure 4. Augmented Reality flood visualisation system architecture and layers (Source: [21])

Furthermore, the city is supporting the deployment of a cutting-edge biometeorological sensor network, alongside a nowcasting service, to monitor outdoor thermal comfort [22]. While primarily intended to support Dortmund's forthcoming Heat Action Plan, this smart-city initiative uses in-situ and remotely sensed data to generate near real-time assessments of urban thermal conditions. The potential application of this system for UDRM highlights Dortmund's commitment to integrating digital innovation into climate adaptation and resilience planning.

3.4. Paris

The Paris Region, home to approximately 12 million inhabitants, nearly one-fifth of France's population, includes the city of Paris, the most densely populated capital in Europe. Land cover in the region comprises 23% forest, 47% cultivated land (primarily intensive openfield crops), and 21% urbanized area, of which 16% is fully impervious [23]. Green space per capita is especially limited within the inner ring of the Paris Region, which continues to experience significant land take, with over 900 hectares of rural land lost to urbanization each year. This situation presents a considerable challenge for managing pluvial floods. However, the City of Paris is actively pursuing greening strategies, including the creation of 100 hectares of green roofs and public squares, along with an additional 30 hectares allocated for urban agriculture. These efforts, aligned with the Paris Climate Action Plan and the "Soil & Rainwater Plan," aim to enhance the city's capacity to manage stormwater and adapt to future climate conditions [23, 24].

The city has also sought to institutionalize green infrastructure by making it a legal requirement in new developments, thereby promoting NBS and integrating biodiversity considerations, primarily to mitigate urban heat island effects and restore local biodiversity [25]. A key concern among stakeholders implementing these urban flood solutions is the quality of stormwater runoff. Through its Rain Management Plan, Paris is in the process of deploying NBS capable of managing rainfall events that exceed rain depth of 16 mm, the threshold of the sewer system's capacity [25].

While the expansion of green spaces offers benefits for mitigating urban heat and managing stormwater, it may also increase water demand, raising concerns from an UDRM perspective. A severe drought could significantly disrupt economic activity in the Paris Region, which generates one-third of France's GDP. Although agriculture and manufacturing are the most vulnerable sectors, urban expansion could also intensify drought risks, particularly through structural damage caused by clay shrinkage [26]. To prepare for a water-scarce future, three climate adaptation scenarios have been developed for the Paris Metropolitan Area, with water reuse (recycling) identified as a key strategy [26] (Table 1).

Table 1. Examples of annual water volumes saved under different adaptation measures in the Paris region (Source: [26])

Objective	Reduction potential (millions of m^3)	Contribution to the target of a 10% reduction in abstraction	Contribution to per-user target
Reuse of 1% of treated wastewater	57.5	44.2%	100%
Reduction in leakage	20	15.3%	26%
Reuse of rainwater in 20% of buildings	28.6	22%	37.1%
Reuse of rainwater for irrigation	4.1	3.1%	16%
Reuse of greywater in 20% of buildings	52-139	40%	67.4-100%

Paris employs a comprehensive, data-driven approach to both flood and drought risk management that integrates advanced modeling, smart infrastructure, and sustainable planning. However, these systems are primarily designed for managing fluvial flood risks and water resources. A noted challenge remains the fragmented nature of governance: different public and private sector stakeholders often work in silos, hindering the implementation of integrated strategies necessary to build systemic urban resilience [27].

3.5. Vienna

The City of Vienna, Austria's capital and largest city, is home to nearly 2 million inhabitants and is one of the fastest-growing urban areas in Central Europe. Land cover within Vienna's municipal boundaries includes approximately 20% forest, 15% agricultural land, and nearly 40% built-up areas, with about 27% of the city covered by green spaces such as parks, gardens, and recreational areas [3]. With its long-standing focus on sustainable urban development, Vienna implements extensive green infrastructure policies including the Urban Heat Island Strategy Plan and Smart City Wien Framework Strategy to increase resilience to climate-related risks such as pluvial flooding and heatwaves, while maintaining a high quality of life for its residents [28]. Vienna's UFRM strategies aimed at pluvial flooding rely upon the Dual Infiltration System (a dual infiltration model that differentiates between contaminated and clean rainwater), and the Green Infrastructure and Sponge City Concept. The latter implies the measures aiming to make urban areas more resilient to flooding by absorbing and retaining rainwater. The most notable example of strategy implementation is a completely new suburb area "Seestadt Aspern" [29].

Vienna is implementing wireless ad-hoc sensor networks to monitor drought stress in specific crops and urban greenery. These networks allow for long-term observation of environmental parameters, providing valuable data to inform water resource management and drought mitigation strategies [30].

4. DISCUSSION

The analysed cities are ranked according to its Smart City Index [8] among 146 cities, while Dortmund is not measured. Besides, each city is assigned to one of four groups, based upon its Human Development Index (HDI) values. The cities are distributed into four groups based on the Global Data Lab's Subnational Human Development Index (SHDI) score of the city they are part of. Within each SHDI group, cities are assigned a 'rating scale' (AAA to D) based on the perceptions-score of a given city compared to the scores of all other cities within the same group (Table 2). In the case of studied cities, groups 1 and 2 are important. For group 1 (highest HDI quartile), scale is AAA–AA–A–BBB– BB, and for group 2 (second HDI quartile), scale is A–BBB– BB–B– CCC [8]. There are two pillars for which perceptions from residents are solicited: The Structures pillar referring to the existing infrastructure of the cities, and the Technology pillar describing the technological provisions and services available to the inhabitants.

Table 2. Studied smart cities ranking and rating for 2024 (Source: [8])

Smart city	Ranking (out of 146)	Rating	Factor rating		Group
			Structures	Technologies	
Amsterdam	17	A	AA	AA	1
Barcelona	92	CCC	B	BB	2
Paris	71	BB	BB	A	1
Vienna	26	A	A	A	1

Although the topics of UFRM and UDRM are not included in the survey, the general impression about individual studied smart cities is in an agreement with our results.

Amsterdam combines decentralized green infrastructure and smart technologies, such as blue-green roofs and smart valves, to manage both flood and drought risks. The city's ongoing "Thirsty Cities" project and Rainproof initiative demonstrate a proactive, cross-sectoral approach to climate resilience.

Barcelona applies advanced modeling and IoT systems to address urban flood and drought risks, integrating NBS strategies tailored to hydrological conditions. Its smart water management and participation in RESCCUE position it as a leader in adaptive urban planning.

Dortmund has implemented a comprehensive flood resilience strategy combining traditional infrastructure, NBS, and cutting-edge technologies like AR flood visualization and thermal monitoring. The city's regulatory and planning frameworks strongly support long-term integration of green infrastructure.

Paris promotes extensive greening through legal mandates and data-driven stormwater strategies, aiming to enhance flood resilience and urban biodiversity. However, increasing drought risk and fragmented governance present challenges to fully integrated water management.

Vienna applies sponge city concepts and smart monitoring systems to manage both urban flooding and drought stress. The city's systemic approach combines policy, infrastructure, and digital tools for high-quality, climate-resilient urban development.

5. CONCLUSION

Smart cities are committed to enhancing urban livability through the integration of modern technologies. Based on the review and analysis of five European smart cities—Amsterdam, Barcelona, Dortmund, Paris, and Vienna—in the context of urban flood risk management (UFRM) and urban drought risk management (UDRM), the following conclusions can be drawn:

1. Climate adaptation measures targeting heatwaves and urban heat islands have indirectly supported urban drought risk management, primarily through greening initiatives. However, concerns have been raised regarding the availability of water for maintaining such green infrastructure during periods of water scarcity.
2. All five cities are actively advancing the implementation of nature-based solutions (NBS) to address both flood and drought risks, highlighting a shared strategic approach toward sustainable and resilient urban development.
3. Technological innovation in support of climate resilience is highly developed, with some cities piloting advanced tools—such as virtual reality (VR) and augmented reality (AR)—for infrastructure monitoring, risk visualization, and public engagement, although these technologies are currently in experimental stages.

Future research should focus on developing integrated frameworks that combine NBS with digital twin technologies, allowing cities to model, predict, and respond to both floods and droughts in a unified system. Comparative studies across cities should investigate the long-term performance and co-benefits of different NBS types under varied climatic, hydrological, and socio-political conditions. Further, governance research is needed to understand how institutional structures either enable or inhibit systemic adaptation across sectors. Co-creation processes that include vulnerable communities, interdisciplinary experts, and utility providers should be strengthened to ensure that innovation is inclusive, scalable, and context-sensitive. The next phase of urban water resilience lies in the fusion of nature, data, and design into dynamic, adaptive systems.

ACKNOWLEDGMENTS

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