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Table of Contents

Smart and Resilient Infrastructure in the Wake of Climate Change

Dillip Kumar Das and Varuvel Devadas

Lessons From Climate and Pandemic-Induced Disruptions in Building Public Transport Resilience

Esperance Munezero Hirwa and Mohamed M. H. Mostafa

Resilient and Sustainable Urban Infrastructure in the Global South: Strategies to Address Climate Change-Linked Vulnerabilities

Dillip Kumar Das

Data-Driven Equitable Planning for Urban Resilience: Innovation, Risk, and Outcomes in Boston, New Orleans, and Norfolk

Kristen Hudak Rosero, Ella Howard, and Thaddeus Guldbrandsen

Enhancing Sustainable and Resilient Water Infrastructure in South Africa in the Face of Climate Change

Ayodeji Olatunji Aiyetan

Enhancing Water Infrastructure Resilience in Response to Climate Change: Evidence From South Africa

Joy Tuoyo Adu

Data-Driven Urban Digital Twins and Critical Infrastructure Under Climate Change: A Review of Frameworks and Applications

Mingyu Zhu and Jiayi Jin

Integrating Emerging Design-Build Technologies for Resilient Housing in the Navajo Nation

Sina Mostafavi, Asma Mehan, and Ali Nejat

Baltic Spas in the Face of Climate Change: In Search of Resilience

Anna Gołędzinowska and Maciej Ganczarek

Smart and Resilient Infrastructure in the Wake of Climate Change

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Abstract

Climate change and global disruptions such as pandemics are exposing critical vulnerabilities in urban infrastructure. This editorial introduces the thematic issue *Smart and Resilient Infrastructure in the Wake of Climate Change*, which explores how smart technologies, governance frameworks, and community engagement can enhance resilience. The eight contributions span multiple contexts—including transport systems, water infrastructure in South Africa, housing in the Navajo Nation, and coastal towns in the Baltic—demonstrating both the promise and limits of data-driven tools, digital twins, and IoT applications. A recurring theme across the articles is that technological innovation alone is insufficient: resilience depends equally on equity, inclusive governance, and context-sensitive strategies. Together, the studies offer empirical evidence and conceptual frameworks that bridge technical, institutional, and social perspectives. They offer actionable insights for designing infrastructures that are not only smart and adaptive but also inclusive and future-ready in an era of accelerating climate risk.

Keywords

climate change; infrastructure; resilient; smart; strategy; sustainable; technology

1. Introduction

The accelerating impacts of climate change—rising seas, recurrent flooding, extreme heat, intensifying storms, and shifting precipitation patterns—have moved from distant warnings to immediate realities that shape urban life around the globe (C40 Cities, 2020; IPCC, 2014). Cities, as hubs of human activity and economic productivity, depend heavily on infrastructure systems to maintain the functionality and livability of urban environments. However, traditional infrastructure—transport, energy, water, communications, and housing—was rarely designed to cope with the complexity and frequency of contemporary shocks.

Increasingly, urban populations face cascading risks: A single storm, heatwave, or pandemic can disrupt multiple interdependent systems simultaneously, revealing vulnerabilities that are both technical and social in nature.

The Covid-19 pandemic illustrated that infrastructure vulnerabilities are not limited to climate-related shocks. Health crises, economic disruption, and social stressors compound the challenges cities face, highlighting the urgent need for systems that are not only resilient to climate extremes but also adaptive to a wide range of shocks. As the scale and frequency of climate-related and other global disruptions increase, urban planners, policymakers, engineers, and researchers are called to envision infrastructures that are simultaneously smart, resilient, equitable, and sustainable. This thematic issue aims to contribute to this discourse by examining how infrastructure can evolve to meet these multidimensional challenges.

2. Conceptualising Resilience in Urban Infrastructure

Resilience is a concept that transcends engineering to encompass social, institutional, and ecological dimensions. Traditionally, resilience in engineering terms has been understood as the capacity of a system to absorb shocks and recover functionality. Holling (1973, 1996) broadened the notion by introducing resilience as a property of complex adaptive systems, emphasising not only the ability to resist disturbances but also to adapt and transform in the face of change. Modern urban resilience frameworks incorporate four key attributes, often referred to as the “4Rs”: robustness, the ability to withstand stress; redundancy, the existence of backup systems; resourcefulness, the capacity to mobilise resources under stress; and rapidity, the speed of response and recovery (Bruneau et al., 2003; Manyena, 2006).

Emerging smart technologies—from IoT-enabled sensors to AI for predictive modelling—offer new opportunities to enhance these dimensions of resilience. Real-time monitoring, predictive maintenance, and adaptive management can reduce system vulnerabilities and enable proactive responses to impending hazards. However, technical innovation alone is insufficient. Governance, institutional coordination, and community engagement are critical in ensuring that resilience strategies are effective and equitable. Without attention to these social and institutional dimensions, even technologically advanced systems risk reinforcing existing inequalities.

3. Influence of Smart Technologies and Data-Driven Infrastructure

The integration of smart technologies into urban infrastructure is transforming resilience thinking. AI-driven decision-support tools, digital twins, and IoT sensor networks offer the potential to anticipate failures, optimise resource allocation, and dynamically manage urban systems. For example, data-driven urban digital twins (UDTs) allow city managers to simulate infrastructure performance under various climate scenarios, providing actionable insights for planning and investment decisions. However, challenges remain. Interdependencies among infrastructure systems, chronic stresses like water scarcity or heat, and limited citizen participation can constrain the effectiveness of these technologies. Furthermore, data governance and equity concerns must be addressed to ensure that smart systems do not exacerbate disparities (Batty et al., 2012; Kitchin, 2014).

Smart technologies offer powerful tools for resilience, but their value lies in how they are applied within real-world contexts. The contributions from the thematic issue illustrate this complexity, offering insights into

the diverse ways cities and communities are navigating the challenges of climate change through innovation, governance, and equity-driven approaches.

4. Insights From the Thematic Issue Contributions

This thematic issue brings together eight contributions that collectively explore the nexus of climate change, resilience, and smart infrastructure. Each article provides novel insights into different dimensions of resilient urban systems, ranging from technical innovations to governance and equity considerations.

4.1. Public Transport Resilience

The article “Lessons From Climate and Pandemic-Induced Disruptions in Building Public Transport Resilience” by Hirwa and Mostafa (2025) applies the 4R framework to assess how transport systems respond to diverse shocks, including Storm Babet in the UK, flooding in KwaZulu-Natal, and the Covid-19 pandemic in Mexico and the US. Using comparative case studies, it shows that high-capacity systems benefited from early warning systems, institutional coordination, and smart technologies. At the same time, resource-constrained contexts struggled with infrastructural neglect and governance delays. The study’s novelty lies in its integration of climate and pandemic disruptions into a single framework, offering valuable cross-context lessons that bridge technical, institutional, and governance dimensions.

4.2. Resilience in the Global South

“Resilient and Sustainable Urban Infrastructure in the Global South: Strategies to Address Climate Change-Linked Vulnerabilities” by Das (2025) explores strategies for strengthening infrastructure in rapidly urbanising, resource-constrained regions. Combining literature synthesis with case studies, the study highlights adaptive urban planning, renewable energy integration, decentralised infrastructure, and inclusive governance as key levers for resilience. Notably, it reframes the Global South not solely as vulnerable but as a laboratory of innovation, where low-cost, community-centred solutions provide transferable insights for global urban practice.

4.3. Data-Driven Equitable Planning

The article “Data-Driven Equitable Planning for Urban Resilience: Innovation, Risk, and Outcomes in Boston, New Orleans, and Norfolk” by Rosero et al. (2025) examines the role of data in resilience planning, with a particular focus on equity. Comparative case studies show that data practices can either reinforce or mitigate existing inequities depending on governance structures and levels of community participation. By advancing critical data studies alongside urban resilience scholarship, the article emphasises that resilience planning is inseparable from ethical, governance, and accessibility considerations.

4.4. Water Infrastructure and Strategic Frameworks

Water systems are particularly vulnerable to climate stressors. In “Enhancing Sustainable and Resilient Water Infrastructure in South Africa in the Face of Climate Change,” Aiyetan (2025) identifies barriers to resilient

water infrastructure delivery and proposes a five-pronged framework addressing governance, technical capacity, maintenance, funding, and accountability. The combination of surveys, statistical modelling, and case analysis provides both empirical evidence and actionable strategies for infrastructure resilience.

Similarly, “Enhancing Water Infrastructure Resilience in Response to Climate Change: Evidence From South Africa” by Adu (2025) contributes quantitative insights by linking historical (1980–2023) climate stressors to infrastructure performance in South Africa. Using regression and ARIMA forecasting, the study demonstrates that droughts pose greater risks than floods and forecasts an increasing rate of infrastructure failures without intervention. This work underscores the importance of data-driven planning in designing robust resilience strategies.

4.5. Digital Twins and Critical Infrastructure

The review “Data-Driven Urban Digital Twins and Critical Infrastructure Under Climate Change: A Review of Frameworks and Applications” by Zhu and Jin (2025) synthesises scholarship on UDTs and identifies challenges, including system interdependencies, chronic risk factors, and limited stakeholder participation. Its conceptual framework bridges technical, social, and governance gaps, offering a roadmap for inclusive digital twin development that enhances critical infrastructure resilience.

4.6. Housing Resilience in Indigenous Communities

The article “Integrating Emerging Design-Build Technologies for Resilient Housing in the Navajo Nation” by Mostafavi et al. (2025) demonstrates how smart technologies can support culturally appropriate, resilient housing. By combining off-grid renewable energy, locally sourced materials, and participatory design with traditional Navajo values, the study presents a decolonial framework that challenges conventional planning paradigms. Its findings offer transferable insights for Indigenous and marginalised communities globally.

4.7. Coastal Resilience

Finally, Gołędzinowska and Ganczarek (2025), in “Baltic Spas in the Face of Climate Change: In Search of Resilience,” evaluate the vulnerability of Polish spa towns to sea-level rise and flooding. Integrating spatial simulations with policy reviews, the article identifies infrastructure limitations and financial constraints as key risk multipliers. Its holistic assessment, combining spatial, legal, environmental, and socio-economic dimensions, provides practical guidance for small- and medium-sized coastal towns confronting climate change.

4.8. Cross-Cutting Themes

Taken together, the eight articles advance knowledge on smart and resilient infrastructure along multiple dimensions. First, they demonstrate the potential of smart technologies—from IoT and AI to digital twins—to enhance monitoring, predictive analytics, and system optimisation. Second, they underscore the importance of context-sensitive strategies, from retrofitting and material innovations to culturally grounded housing and community engagement. Third, they reveal that governance and equity are central to resilience, showing that even the most advanced technologies risk reproducing inequalities without inclusive planning and data

justice. Finally, they contribute new empirical evidence and conceptual frameworks that bridge technical, institutional, and social perspectives.

Taken together, these eight articles illuminate several key insights:

1. *Technological Innovation*: Smart technologies, from IoT to AI and digital twins, enhance monitoring, predictive analytics, and system optimisation.
2. *Context-Sensitive Strategies*: Resilience approaches must account for local conditions, including urban density, resource availability, cultural values, and socio-economic disparities.
3. *Governance and Equity*: Effective resilience planning requires inclusive governance, data justice, and community engagement. Without these, technological interventions risk exacerbating inequalities.
4. *Empirical Evidence and Conceptual Advancement*: Combining quantitative analysis, comparative case studies, and design experimentation, the contributions offer robust, actionable frameworks for building resilient, adaptive, and sustainable infrastructure.

5. Conclusion

This thematic issue underscores that resilience in the face of climate change is both a technical and social endeavour. Smart technologies and innovative frameworks provide unprecedented opportunities, but their success depends on governance innovation, equity, and community participation. By integrating diverse methodologies—comparative case studies, quantitative analysis, design experimentation, and systematic reviews—these articles collectively chart a roadmap for infrastructures that are intelligent, adaptive, inclusive, and future-ready.

As cities confront the intensifying impacts of climate change, the insights presented here emphasise that resilience cannot be achieved through engineering alone. Instead, it requires a holistic approach that combines technological innovation, social justice, governance reform, and community empowerment. The evidence, frameworks, and case studies in this issue provide not only a state-of-the-art understanding of smart and resilient infrastructure but also practical guidance for policymakers, planners, engineers, and researchers committed to securing urban sustainability in a rapidly changing world.

Conflict of Interests

The authors declare no conflict of interests.

References

- Adu, J. T. (2025). Enhancing water infrastructure resilience in response to climate change: Evidence from South Africa. *Urban Planning*, 10, Article 10163.
- Aiyetan, A. O. (2025). Enhancing sustainable and resilient water infrastructure in South Africa in the face of climate change. *Urban Planning*, 10, Article 10096.
- Batty, M., Axhausen, K. W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., Ouzounis, G., & Portugali, Y. (2012). Smart cities of the future. *The European Physical Journal Special Topics*, 214(1), 481–518. <https://doi.org/10.1140/epjst/e2012-01703-3>
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W., & von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4), 733–752.

- C40 Cities. (2020). *Deadline 2020: How cities will meet the Paris climate agreement*.
- Das, D. K. (2025). Resilient and sustainable urban infrastructure in the Global South: Strategies to address climate change-linked vulnerabilities. *Urban Planning*, 10, Article 10037.
- Golędzinowska, A., & Ganczarek, M. (2025). Baltic spas in the face of climate change: In search of resilience. *Urban Planning*, 10, Article 10277.
- Hirwa, E. M., & Mostafa, M. M. H. (2025). Lessons from climate and pandemic-induced disruptions in building public transport resilience. *Urban Planning*, 10, Article 9943.
- Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1–23.
- Holling, C. S. (1996). Engineering resilience versus ecological resilience. In P. Schulze (Ed.), *Engineering within Ecological Constraints* (pp. 31–44). National Academies Press. <https://doi.org/10.17226/4919>
- IPCC. (2014). *Climate change 2014: Impacts, adaptation, and vulnerability*. Cambridge University Press.
- Kitchin, R. (2014). The real-time city? Big data and smart urbanism. *GeoJournal*, 79(1), 1–14.
- Manyena, S. B. (2006). The concept of resilience revisited. *Disasters*, 30(4), 433–450.
- Mostafavi, S., Mehan, A., & Nejat, A. (2025). Integrating emerging design-build technologies for resilient housing in the Navajo Nation. *Urban Planning*, 10, Article 10157.
- Rosero, K. H., Howard, E., & Guldbrandsen, T. (2025). Data-driven equitable planning for urban resilience: Innovation, risk, and outcomes in Boston, New Orleans, and Norfolk. *Urban Planning*, 10, Article 10043.
- Zhu, M., & Jin, J. (2025). Data-driven urban digital twins and critical infrastructure under climate change: A review of frameworks and applications. *Urban Planning*, 10, Article 10109.

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Lessons From Climate and Pandemic-Induced Disruptions in Building Public Transport Resilience

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Abstract

The transport system faces numerous disturbances from climate change and other events, such as the Covid-19 pandemic. This study evaluates the resilience of public transport systems by applying the qualitative 4R framework—robustness, redundancy, resourcefulness, and rapidity—to four case studies drawn from the UK, South Africa, Mexico, and the United States. The analysis demonstrates that climate-induced disruptions predominantly expose infrastructural weaknesses and strain institutional capacity, while pandemic-related disruptions challenge the adaptability and operational flexibility of transport services. Notable findings include the critical role of early warning systems, the significance of sustained investment in resilient infrastructure—as evidenced in the UK and Mexico—and the detrimental impact of inadequate infrastructure maintenance, particularly in South Africa. The study advances recommendations for enhancing resilience, emphasising the adoption of integrated, multimodal transport systems, and reinforcing institutional coordination and planning capacity.

Keywords

climate change; Covid-19; public transport; resilience

1. Introduction

Climate change-induced disturbances have increased in occurrence and intensity over the last century. According to the IPCC Assessment Report, greenhouse gas emissions have continued to rise, resulting in global warming, with many regions across the world experiencing its effects (Ruane, 2024). Extreme weather events such as floods and hurricanes affect economic development and increase the vulnerability of people and systems. Particularly, the transportation infrastructure experiences damage, resulting in travel delays and loss of accessibility due to these events (Pan et al., 2021).

Several studies have examined the impacts of climate change disruptions on public transportation. The United States Environmental Protection Agency (2025) highlights how climate change can lead to flooding and extreme heat waves, thereby causing damage to roadways and rail links. Kafalenos et al. (2008) previously indicated that approximately 50–60% of roads and 30–40% of railway lines along the Gulf Coast region of the United States are susceptible to storm surges. Similarly, extremely low temperatures in the Netherlands have damaged railway infrastructure, leading to service delays (Xia et al., 2013). The case of Hurricane Sandy in New York is an example of how extensive flooding led to disruptions, subway service cancellations, and widespread road damage (Jing, 2021).

In terms of ridership, adverse weather conditions have been found to affect public transport usage negatively (Arana et al., 2014; Bo et al., 2021; Wu & Liao, 2020), often leading to a shift towards private vehicle usage, particularly in cities without subway systems (Böcker et al., 2019). High temperatures have been associated with passenger discomfort and possible changes in modes of transportation within the London underground (Arkell & Darch, 2006). In contrast, the effects of high temperatures on the Beijing subway ridership reveal a distinct pattern underscoring the complex relationship between transit usage and extreme weather conditions (Wu & Liao, 2020). Furthermore, extreme weather events have a more significant impact on leisure trips than commuting trips (Sabir, 2011).

The Covid-19 pandemic also affected public transportation usage. Studies highlight a shift from shared to private modes of transport, such as personal vehicles, due to safety concerns and the fear of contagion (Angell & Potoglou, 2022). This increase in the number of personal vehicles has led to environmental concerns, as research studies have indicated that private cars generate higher CO₂ emissions in comparison to public transportation (Acierto et al., 2023; Burchart-Korol & Folega, 2019; Shang & Lv, 2023). Additionally, studies have highlighted a decrease in public transit ridership compared to pre-pandemic levels (Chen et al., 2024; Lee et al., 2024; Mepparambath et al., 2023; Srikanth et al., 2023; Stokenberga et al., 2023). Both climate change and the Covid-19 pandemic have had multifaceted impacts on public transportation systems, underscoring the need to strengthen the resilience of public transport.

Despite the growing body of literature examining the impacts of climate change and pandemic disruptions on public transportation, a critical gap remains concerning evaluating implemented resilience measures in response to these events. Much of the existing literature focuses on analysing the impacts of specific climate change events and travel behaviour shifts due to the Covid-19 pandemic. However, few studies, notably Amdal et al. (2017) and Fraser and Chester (2017), extend this analysis to assess actual adaptation strategies implemented to ensure resilience. Additionally, most of these studies focus on the Global North context, leaving a significant gap in understanding how these disruptions play out in the Global South context, thus limiting the ability to draw lessons from past interventions and develop context-specific resilient strategies.

This article aims to address these gaps by examining how public transportation systems have responded to challenges of climate change disruptions and the Covid-19 pandemic. Using selected case studies from both the global north and global south, the study focuses on identifying institutional and infrastructural lessons that inform resilient public transport planning and evaluating the effectiveness of these adaptive responses. A qualitative resilience framework is applied to assess how these adaptive measures enhance resilience. The article also highlights the challenges faced in implementing resilient measures and provides recommendations for creating a resilient public transportation system.

The remainder of the article follows this structure: Section 2 examines the literature on the concept of resilience, especially concerning transportation systems. Section 3 describes the methodology in detail, including the case study selection and data collection process. Section 4 presents and discusses the findings, focusing on the immediate response and long-term adaptive strategies employed during disruptions. Section 5 concludes the article by summarising key insights and offering recommendations for public transport resilience.

2. Literature Review

2.1. Defining and Assessing Resilience in Transport Systems

The concept of resilience was first introduced by Holling (1973) in ecological studies. Since then, the concept has been applied to other areas of study, such as psychology, economics, and engineering. Murray-Tuite (2006) was the first to define the resilience of transportation systems, categorising it into ten dimensions: redundancy, diversity, efficiency, adaptability, safety, mobility, autonomous components, strength, collaboration, and the ability to recover quickly. While these dimensions provide a measure of evaluating resilience, their complexity makes it difficult to establish a definite measure. Before this, Bruneau et al. (2003) proposed four dimensions of resilience: robustness, redundancy, resourcefulness, and rapidity. Tierney and Bruneau (2007) later named this the “R4 framework,” which is extensively referenced in the literature. Robustness refers to the capacity of a system or its components to withstand disruption without incurring substantial functional degradation. Redundancy refers to the degree to which elements in a system are substitutable during a shock. Resourcefulness refers to the ability to recognise emerging problems, establish priorities, and allocate resources to address those problems. Finally, rapidity refers to the system’s ability to respond promptly and efficiently to shocks, thereby minimising loss (Reggiani, 2013).

Building on these earlier definitions, the concept of resilience in transportation has been further developed and clearly defined. Based on a comprehensive literature review, Gonçalves and Ribeiro (2020, p. 3) proposed a definition of the resilience of urban transportation systems as the “ability for a system to resist, reduce, and absorb the impacts of a disturbance (shock, interruption, or disaster), maintaining an acceptable level of service (static resilience), and restoring regular and balanced operation within a reasonable period and cost (dynamic resilience).” This definition highlights two key aspects of resilience: static resilience, which pertains to the system’s ability to maintain service during disturbances, and dynamic resilience, which focuses on recovery efficiency (Sun et al., 2020). Bruneau et al. (2003) describe a resilient system as one that demonstrates lower failure probabilities, minimised impacts when failure occurs, and shorter recovery time.

In terms of assessing and measuring resilience, several methods and approaches have been studied and developed, ranging from qualitative, semi-quantitative, and quantitative methods. Qualitative approaches evaluate transport resilience using attribute-based metrics such as the 4R framework. Hughes and Healy (2014) developed a qualitative framework for the New Zealand Transport Agency, incorporating measurement categories linked to two dimensions: technical resilience—encompassing robustness, redundancy, and safe-to-fail principles—and organisational resilience—comprising change readiness, networks, and leadership and culture. The measurement categories were associated with each principle. However, this framework was not tested in real-world scenarios. Similarly, the Los Angeles County Metropolitan Transit Authority (2015) proposed a resilience indicator framework based on similar principles.

Building on these, Tonn et al. (2020) assessed the resilience of the United States passenger rail within the Northeast corridor using a framework derived from the aforementioned studies, selecting 21 metrics and rating them on a scale of low, medium, and high.

Imran et al. (2014) proposed a framework incorporating six key variables—engineering, services, ecological, social, economic, and institutional—to evaluate transport resilience from a planning perspective. The proposed framework was applied to a case study in the Manawatu-Wanganui region of New Zealand. Kermanshachi et al. (2021) also identified 21 resilience metrics but focused on infrastructure project selection, developing a decision-support model to prioritise highly resilient projects. Additionally, Leobons et al. (2019) proposed 11 indicators based on the 4R properties and suggested methods to quantify each. Beldarrain et al. (2022) employed a qualitative approach through co-creative workshops and identified key factors that contribute to the resilience of public transport systems. These factors are categorised into system organisation, information management, operating performance, and subsystem integration.

Quantitative approaches have been extensively researched. Serulle (2011) developed a method of assessing resiliency using metrics such as average delay and reduction in network speed delays. Freckleton et al. (2012) carried out similar work. Other studies use topological metrics, which focus on network efficiency. The most used metrics are the giant connected component and the average shortest path (Zhou et al., 2019). Testa et al. (2015) used a combination of topological measures such as average degree, average shortest paths, betweenness centrality, clustering coefficient, and redundancy to estimate the level of resilience of the New York Metropolitan Area transportation system in the case of an extreme climate event. Aydin et al. (2018) proposed a framework for assessing the resilience of urban road networks by using the giant connected component as an indicator of robustness and betweenness centrality as an indicator of network efficiency.

Qualitative and quantitative approaches highlight the different methodologies available for assessing transportation resilience. While qualitative frameworks emphasise technical and organisational-based metrics, quantitative frameworks rely on performance-based metrics and network topology. The literature predominantly focuses on quantitative approaches, which offer detailed insights but often require extensive data. In contrast, qualitative methods are easily applicable and require less data.

2.2. Disruption Types and Their Significance to Transportation Resilience

Various disruptions impact transportation systems. These disruptions can be categorised into several types based on their nature. Table 1 shows the different categories of disruptions and examples of those disruptions. Some of these disruptions, such as those caused by nature, extreme weather events, and health pandemics, can be unexpected and difficult to predict.

Climate-related disruptions such as floods, heatwaves and severe storms are occurring more frequently, thus highlighting a need to plan for a more resilient infrastructure (Haggag et al., 2021). These disruptions often lead to structural damage, travel delays, inaccessibility, economic loss, injuries and death (Jenelius & Mattsson, 2020), and in many cases, public transport ridership is negatively affected (Bo et al., 2021; Tao et al., 2018). These disruptions amplify the existing vulnerabilities of public transport systems, especially in urban areas (Ji et al., 2022). Studies from developed regions highlight various resilience strategies. For instance, Kim et al. (2018) identify measures such as improved infrastructure design and maintenance,

Table 1. Types of disruptions.

Type of Disruption	Examples
Natural and Weather-Induced	Flooding, repetitive freezing and thawing, hurricanes, extreme heat, tornadoes, snow and ice, earthquakes, fires, landslides and avalanches
Synthetic and People-Induced	Demand surges, dynamic supply chain needs, criminal/terrorist activities, prolonged infrastructure use, rapid demographic movement, crashes, sea-level rise, heightened public involvement, health pandemics
Institutional	Asset management, funding instability, system exceeding capacity, ageing infrastructure, antiquated design, resource limitations, political risks, prioritisation
Economic	Technology disruption, trade and commerce instability, changing market conditions, transportation and logistic costs, environmental changes, eroding ecosystem, trade disputes, recession and depression

Source: Adapted from National Academies of Sciences, Engineering, and Medicine (2024a).

technological advancements, and enhanced communication systems. Similarly, Amdal et al. (2017) reviewed case studies, offering key lessons and structural and institutional measures to mitigate the impact of natural disasters on transit systems. However, these studies focus on developed regions with more substantial resources and institutional capacities than developing countries.

Conversely, the Covid-19 pandemic caused unprecedented disruptions to transportation systems, changing travel demand and operations due to restrictions (Lee et al., 2024). Public transport operators and agencies had to implement strategies to ensure the continuity of service. These included a decrease in fleet and frequency, as well as changes in service delivery (Lima et al., 2020; Zorgati et al., 2021). These interventions were often reactive, exposing gaps in planning (Tori et al., 2023). The Covid-19 pandemic exposed the need for adaptive governance and institutional coordination in enhancing system-wide resilience.

Both climate-induced and pandemic-induced disruptions impact different dimensions of public transport resilience. Climate-induced disruptions mainly affect infrastructure resilience, while pandemic-induced disruptions mainly affect the institutional aspect of resilience. Strengthening the resilience of public transport systems is therefore essential, requiring collaboration between institutions and end-users in developing resilience strategies (National Academies of Sciences, Engineering, and Medicine, 2024a).

In summary, drawing from the literature review, key gaps remain. First, most studies focused on natural, climate-induced disruptions or pandemic impacts in isolation, often within specific regions, thus lacking an integrated, cross-disruption perspective. Second, most studies use a quantitative approach to measure resilience, with limited attention to qualitative assessments incorporating technical and organisational dimensions. Third, limited studies compare responses across developed and developing nations or explore the integration of institutional, user, and technological factors, therefore limiting the adaptability of resilience strategies to different contexts.

This study addresses these gaps by adopting a comparative qualitative framework to analyse how diverse regions, across developed and developing contexts, respond to climate and pandemic disruptions. By examining four case studies, the article aims to identify lessons, evaluate responses, and contribute to a better understanding of public transport resilience.

3. Methodology

This study employs a qualitative approach, using a combination of document analysis, online news articles, and open-access public transport ridership data to investigate the resilience of public transport systems during extreme weather events and the Covid-19 pandemic. The methodology is outlined as follows.

3.1. Data Collection

Three primary types of data were collected: academic papers and policy documents, online news articles, and open-access transport ridership datasets. These sources were selected to capture the different dimensions of resilience and to triangulate information across various data types.

The documents were accessed through academic databases such as Google Scholar, ScienceDirect, the Transport Research Board publication database, and government and international agencies' websites. These databases were chosen due to their field-related relevance and accessibility. Google Scholar was employed due to its extensive coverage of scholarly articles across diverse academic fields, thereby capturing peer-reviewed articles on both pandemic and climate-related disruptions. ScienceDirect was utilised due to its strong focus on transportation, environmental science, and urban planning, thereby presenting articles focused on resilience and transportation. The Transport Research Board database was selected for its comprehensive collection of transport-related case studies, reports, and research articles, particularly within the context of the Global North, thereby providing valuable insights into adaptive resilience strategies. The synergetic use of these databases ensured a comprehensive assessment of resilience within public transport systems across various geographical regions, aligning with the study's overarching objectives.

The literature search was conducted using keywords such as *public transportation*, *resilience*, *climate change*, *extreme weather*, *pandemic*, *Covid-19*, and *adaptation*. The initial search yielded 200 articles. Afterwards, the documents were reviewed to understand the practical aspects of public transport resilience, adaptive strategies, and policies, and 131 articles were chosen for further review. The articles and reports were screened for relevance to public transport resilience, adaptation measures and strategies, and governance responses to climate and pandemic-induced disruptions. The inclusion criteria required that the documents directly address transport-related disruptions due to extreme weather events or the Covid-19 pandemic between 2019 and 2024 and provide insights into responses and adaptation measures. The exclusion criteria ruled out sources that lacked detailed insights or generalisation without evidence. Following these criteria, a total of 95 documents were included in the study.

The online news articles were sourced from regional and national news platforms using Google News and media archives. Targeted keywords included *storm disruptions*, *climate-change events*, *public transport disruptions*, and *Covid-19*. These articles were analysed to extract real-time accounts of weather-induced disruptions, their impacts on the transport sector, and the various responses towards recovery. Articles were selected if they provided specific details of the disruptions, including their effects on public transport and communities, and immediate responses by authorities. The inclusion of these media sources provided a local perspective and details not found in the literature.

Two open-access datasets were used for the trend analysis of ridership data:

1. The first dataset was from the American Public Transportation Association (n.d.), which contains transport ridership data in the United States for different modes of transport, including heavy rail, light rail, commuter rail, trolley bus, and commuter bus. The study selected to use the data on commuter rail and commuter bus since this data provides insights into the impact of the pandemic on public transportation, especially in a Global North context.
2. The second dataset was obtained from OECD Data Explorer and included data on the total distance travelled by public transport passengers in Mexico using different modes. The data extracted was from 2019 to 2023, which helped explore the pandemic's effects on public transport in Mexico, which is considered a country in the Global South.

The selection of these two datasets aimed to represent both the Global North and Global South contexts, thereby offering comparative insight. Limitations include differences in definitions between sources, which were acknowledged in the analysis. Contextual bias was mitigated by cross-referencing findings with literature and media sources and by situating each dataset in its context.

3.2. Case Study Selection

This article examines four case studies: Storm Babet in the UK; the April 2022 floods in KwaZulu-Natal (KZN), South Africa; and two pandemic-related cases concerning public transport ridership trends in Mexico and the United States. Storm Babet was one of the most severe storms that recently affected the UK, causing significant rail and road transportation disruptions. This case study provides a perspective on resilience from a developed context. The KZN floods were among the most devastating floods in South Africa, extensively damaging transportation infrastructure. This case provides an insight into resilience from a developing context. The pandemic-related cases in Mexico and the United States focus on public transport ridership and contribute to understanding how pandemic-induced demand shocks were managed from a developing and developed context.

Collectively, these four cases align closely with the research objectives by allowing the study to compare institutional capacity, infrastructure, and governance in both developed (the UK and the United States) and developing (Mexico and South Africa) contexts. Moreover, the combination of climate and pandemic-related disruptions facilitates an examination of how various shocks influence distinct dimensions of resilience. The aim is not to generalise findings but to identify patterns of resilience strategies that may be adapted or considered in other contexts.

The case studies were selected using the following criteria:

- Data availability: Accessibility to open reports, media documentation, and operational data, enabling a robust qualitative analysis of impacts, responses, and resilience strategies;
- Comparability: Selection of case studies that represent both developed and developing contexts, allowing for institutional and infrastructural comparison;
- Disruption occurrences: Case studies focused on recent disruptions from 2019 to date.

3.3. Data Analysis

The data analysis involved multiple methods to extract key insights from the data sources. A thematic analysis approach was used to classify reports and academic articles into themes of resilience, adaptive strategies and policy frameworks. This approach allowed for identifying recurring patterns and lessons from past disruptions. Similarly, the news articles were thematically organised to identify strategies and challenges faced by public transport authorities in responding to disruptions. The themes were developed inductively from the data sources, and iterative review and cross-referencing of the articles were used for validation to ensure consistency in interpretation. While thematic and content analysis are conceptually related, content analysis was used to extract specific details and to categorise the particular strategies, impacts, and challenges incorporated in the comparative framework detailed in Table 2.

Trend analysis was applied to the study of the public transport data to compare ridership before, during, and after the pandemic. The objective was to identify ridership patterns, thus highlighting the impact of the pandemic on public transport usage. The data was analysed using descriptive statistics and was plotted over time to show peaks, troughs, and recovery trajectories. The observed trends were linked to the institutional responses identified in the literature sources.

A structured comparative analytical framework was developed based on the 4R resilience model, incorporating metrics adapted from Hughes and Healy (2014) and the Colorado Department of Transportation (n.d.). As presented in Table 2, this analytical framework was systematically applied to the selected case studies. Each case was assigned a qualitative resilience score as outlined in the clearly defined criteria below:

- Very high resilience: All requirements met (i.e robustness, redundancy, resourcefulness, rapidity, all met satisfactorily);
- High resilience: Acceptable performance, but improvements could be made;
- Moderate resilience: Less than desirable performance. Priority to be given to some improvements;
- Low resilience: Poor performance. Major improvements are required.

Table 2. Comparative analytical framework.

Resilience Principle	Qualitative Indicator: Climate-Induced Disruption	Qualitative Indicator: Pandemic-Induced Disruption
Robustness	Structural integrity of transport infrastructure, maintenance history	Physical infrastructure adaptability to reduced capacity
Redundancy	Availability of alternative routes, services or transport modes that can function during disruption	Availability of other mobility options (i.e., micro-mobility)
Resourcefulness	Institutional capacity: mobilisation of funds, emergency responses, early warnings, communication, relief	Scope of service redesigns and infrastructure development, mobilisation of funds
Rapidity	Time taken to clear and restore critical transport links, speed of response and decision making	Time taken for recovery of service (i.e., ridership recovery), speed of implementing decisions

While scoring resilience can introduce some subjectivity, the criteria were defined consistently, and each score is based on the documented data. This framework serves as a comparative lens rather than an absolute measure.

The combined use of these methods supports the study's aim of uncovering context-specific resilience strategies and institutional responses, contributing to a better understanding of how public transport systems adapt when faced with climate-related events and pandemic-induced disruptions.

4. Results and Discussion

This section presents the findings from case studies, analysing the impacts of climate-induced and pandemic-induced disruptions and discussing the resilience demonstrated in each case. The analysis incorporates the 4R framework (robustness, redundancy, resourcefulness, and rapidity) to rigorously assess the measures implemented, evaluate their effectiveness, and compare impacts across different contexts. The recurring patterns in disruptions, institutional responses, and lessons learned were discussed and summarised.

4.1. Resilience Assessment

Using the qualitative analysis framework developed, the case studies can be comparatively analysed, capturing the institutional and infrastructural dimensions of resilience across diverse contexts (see Table 3). Each case study's observed measures and outcomes were discussed and categorised below.

Table 3. Comparative analytical framework for assessing resilience.

Case Study	Robustness	Redundancy	Resourcefulness	Rapidity	Score
Storm Babet (UK)	Damage to roads and rail in some areas illustrated some vulnerability to flooding Emergency preparedness	Rail service cancellation indicates a lack of redundancy in that mode Some alternate routes were available	High resourcefulness in mobilising emergency services, funds for repairs and issuing early warnings Investment in long-term resilience shows high resourcefulness	Rapidity in issuing early warnings and responding to disruptions immediately Recovery of transportation infrastructure varied	High Resilience
KZN Floods (South Africa)	Infrastructure is highly vulnerable to flooding Poor maintenance of the drainage infrastructure contributed to a lack of robustness	Limited redundancy, as some communities became inaccessible	Resourcefulness in providing humanitarian relief Resourcefulness at the community level Limited capacity to conduct rapid damage and repairs	Slow initial response, assessment of damage and recovery Long-term plans for climate change adaptation indicate a focus on rapidity	Low Resilience

Table 3. (Cont.) Comparative analytical framework for assessing resilience.

Case Study	Robustness	Redundancy	Resourcefulness	Rapidity	Score
Covid-19 (United States)	Ridership decline indicates vulnerability, but the system can maintain some service	Service extension and micro-mobility integration ensured redundancy	Resourcefulness in implementing strategies to increase ridership	Rapid response in implementing strategies Gradual recovery of ridership	High Resilience
Covid-19 (Mexico)	Ridership decline indicates some vulnerability, but the system can maintain service	Route expansion and bus rapid transit (BRT) development increased redundancy	Resourcefulness in providing funding, subsidies and tax exemption, as well as infrastructure development	Rapid recovery of bus ridership, but rail is slowly recovering	Moderate Resilience

The following sections provide a more detailed discussion of the resilience demonstrated in each case, drawing on the 4R framework and expanding on the information provided in Table 3. The recurring patterns, like disruptions, institutional responses, and lessons learned, were discussed and summarised in Table 4.

4.2. Climate-Induced Disruptions

4.2.1. Case Study of Storm Babet in the UK

In late October 2023, Storm Babet struck the UK, causing significant disruptions, including power outages, flooding homes and roads, and travel delays due to road closures (Internet Geography, n.d.). Rail services and ferries were cancelled, and Leeds Bradford Airport was temporarily closed on 20 October (Calder, 2023). The cost of repairs in Scotland alone was estimated at £4 million (Watt, 2024). Figure 1 illustrates some of the damages to the transport infrastructure.

The initial response to Storm Babet demonstrated a degree of robustness in the form of emergency preparedness. The issuance of early weather warnings and the deployment of sandbags and pumps by the Environment Agency (2023) showcased a proactive approach to mitigating the immediate impacts. The early warning systems were effective in safeguarding public safety and facilitating evacuations (Internet



Figure 1. Damage to train lines. Sources: (a) Network Rail in Stefani (2023); (b) “Flood-hit residents ‘won’t be home for Christmas’” (2023).

Geography, n.d.) and the sandbags and pumps protected approximately 96,000 properties. The availability of such resources, as well as a flood resilience scheme for affected property owners (Engage Environment Agency, n.d.), indicated a level of resourcefulness in responding to the crisis.

The rapidity of recovery varied across transport modes. Rail service providers worked earnestly to remove debris and repair damages to resume service as quickly as possible (KITE Projects, 2023). Interim repairs were done to some affected roads, allowing for the resumption of traffic flow; though, some severely damaged roads remained closed (English, 2023; Ward, 2023), hence suggesting a need for improvement in addressing critical infrastructural failures.

In terms of long-term recovery and adaptation, infrastructure investment into drainage works, winter readiness programmes, flood risk alleviation, and integrated transport schemes has been implemented in different counties (“Nottinghamshire: Highways update shows record £66m investment,” 2025; Suffolk County Council, 2023). These efforts focus on enhancing robustness and improving the infrastructure capacity to withstand future disruptions. Additionally, the UK Government awarded £1.4 million in projects that focus on developing resilient infrastructure (UK Research and Innovation, 2023). To ensure resilience in rail services, Network Rail, which oversees rail services in the UK, planned to invest £1.274 billion in the maintenance and renewal of earthworks and drainage, intelligent infrastructure, which includes remote monitoring and sensing, and research and innovative solutions (Haines, 2021). These long-term investments further demonstrate a commitment to building long-term robustness and redundancy into the transportation system and support the “High Resilience” score in Table 3.

4.2.2. Case Study of the KZN April 2022 Floods

In April 2022, heavy rainfall in the KZN coastal region, including Durban and the South Coast, resulted in severe flooding that led to fatalities, property damage, and destruction of infrastructure, such as roads, bridges, powerlines, and pipes (Thoithi et al., 2022). Figure 2 shows some of the damage to the road infrastructure. Poor maintenance of the drainage infrastructure and inadequate regulation of informal settlements exacerbated the flood impacts (Hattingh, 2022). The cost of repair was estimated to be around



Figure 2. Damage to roads due to April 2022 floods in KZN. Source: Darren Stewart in Buthelezi (2022).

R17 billion (Monama, 2022). The damage to roads and bridges resulted in the transport infrastructure leaving 60% of communities inaccessible by roads (Magubane, 2023).

The immediate response to the flood included the establishment of shelters, the provision of humanitarian relief to the affected families, and an emergency relief fund (Mudefi, 2023). However, damage assessment and repairs were delayed due to a lack of capacity (Maluleke, 2022), thus hindering rapid recovery. This lack of capacity resulted in some residents repairing the damaged roads and bridges to restore accessibility (Enoch, 2022), demonstrating a degree of community resourcefulness in the face of institutional delayed action.

Traffic on some damaged roads was managed through deviations or reopened after risk assessments and interim repairs, with permanent repairs planned for the third quarter of 2022 (Department of Planning, Monitoring and Evaluation, 2023); however, the overall recovery process was slow. The availability of alternate routes for traffic diversion shows a level of redundancy, but this is limited since some communities were left inaccessible. Long-term adaptation efforts included promoting climate change awareness, improving access to early weather warnings, and encouraging municipalities to develop climate change response plans (Department of Economic Development, Tourism and Environmental Affairs, 2023), thereby improving the region's adaptive capacity and preparedness. Overall, the case illustrates low resilience due to infrastructural vulnerability, making it susceptible to the impacts of the disruption and institutional capacity constraints, which led to delayed response and recovery.

4.3. *Pandemic-Induced Disruptions*

4.3.1. *Case Study of Public Transport Ridership in the United States*

Figure 3 shows the commuter rail and bus ridership trends in the United States from 2014 to 2023. As indicated, ridership declined sharply during 2020 due to the Covid-19 pandemic, with a gradual recovery afterwards, though ridership levels remain lower than the pre-pandemic levels. The decline in ridership led to financial losses and a reduction in service levels (Federal Transit Administration, 2024). This decline indicates an initial lack of robustness in the face of the pandemic.

However, some service providers implemented strategies to boost ridership amidst the pandemic, which proved successful. These strategies included service extensions, new rail stations and bus services connecting to the rail stations, bus route extension and redesign, transit signal priority and bus lanes, exclusive bus-only roads, micro-mobility services, investment in new technologies such as Wi-Fi on buses and ticket vending machines, discounts for bike sharing riders and BRT, like features such as queue jumpers and enhanced stops, free fare zones, and many other interventions (Tabassum et al., 2024). These measures represent a significant adaptation of service provision in response to the disruption, illustrating resourcefulness in identifying and implementing solutions. The quick integration of micro-mobility services and extending operations enhances redundancy.

According to the American Public Transportation Association (2021), leveraging such opportunities and institutionalising the best practices from the pandemic period will ensure the resilience of public transit in the post-pandemic period alongside prioritising social equity. The free-fare strategy has been one of the interventions adapted for post-pandemic implementation, with the National Academies of Sciences,

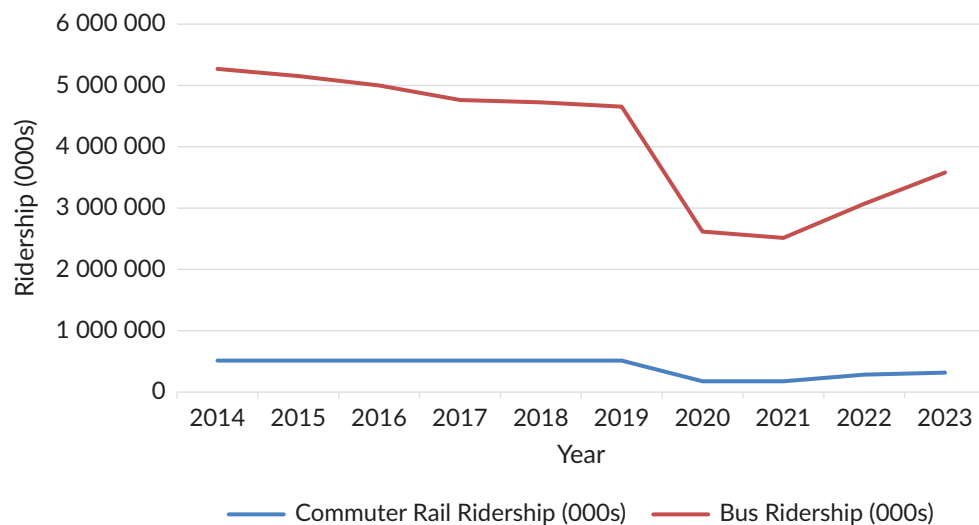


Figure 3. Year-end ridership by mode in the United States.

Engineering, and Medicine (2024b) published guidelines to support state departments of transportation and transit agencies in adopting these strategies. While ridership is recovering, it is still below pre-pandemic levels, indicating that full recovery is ongoing and that rapid return to pre-pandemic levels is variable. The prompt carrying out of recovery plans and rapid adaptability demonstrate high resilience.

4.3.2. Case Study of Public Transport Ridership in Mexico

Figure 4 shows the annual passenger kilometres by bus in Mexico from 2019 to 2023, indicating a significant decline in 2020 due to the pandemic, followed by a strong, rapid recovery in the subsequent years, suggesting a high resilience in this transport mode. In Mexico City, microbuses, which form a core part of the public transportation system, expanded their routes during the pandemic to provide services to peripheral areas (Calnek-Sugin & Heeckt, 2020), indicating resourcefulness and enhancing redundancy within the system.

The rail passenger kilometres, as shown in Figure 5, decreased during the pandemic and had a slow recovery thereafter, compared to the bus sector. This highlights different levels of resilience within different modes of

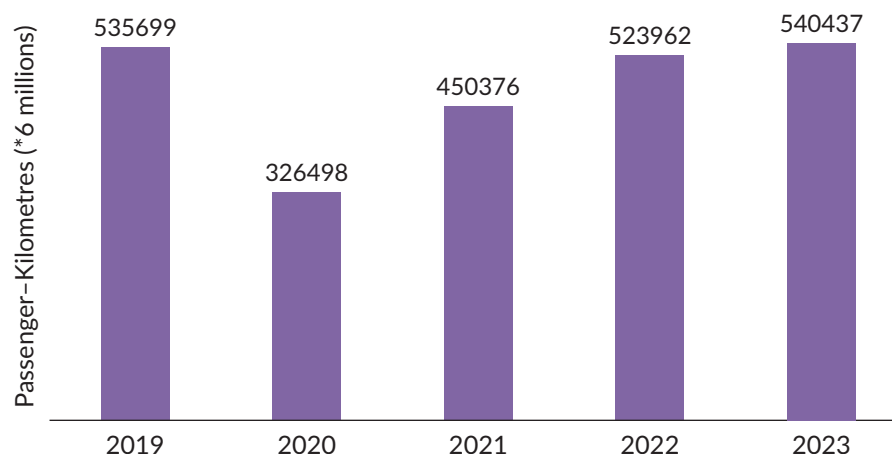


Figure 4. Bus passenger-kilometres in Mexico.

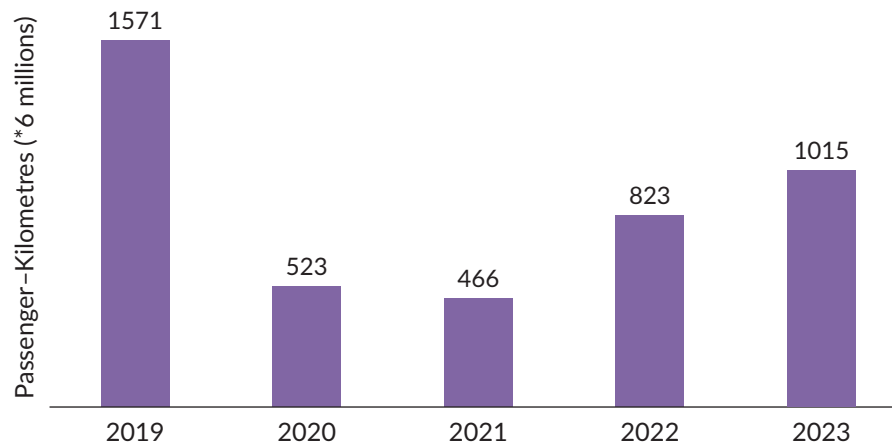


Figure 5. Rail passenger-kilometres in Mexico.

transport. To foster recovery, fuel subsidies and local tax exemptions were granted for some time to support the public transport services (World Bank, 2024). Additionally, new BRT infrastructure was constructed, transforming a car-oriented corridor in Guadalajara into a dedicated BRT route (Welle et al., 2023), thus improving redundancy. The Mexican government has also approved funding of US\$7.6 billion to enhance passenger and freight rail services (Briginshaw, 2024). These investments represent resourcefulness and aim to improve the system's redundancy and robustness. While the response was generally prompt, the variation in modal recovery highlights the need for improvement in institutional alignment to enhance overall resilience, hence the moderate resilience score.

Table 4. Comparative summary of findings.

Patterns	Storm Babet (UK)	KZN Floods (South Africa)	Covid-19 (United States)	Covid-19 (Mexico)
Nature of Disruption	Severe storms and flooding	Intense flooding	Public health crisis	Public health crisis
Extent of the Disruption	Transport delays, rail service closures, and infrastructure damage	Infrastructure damage (major roads and bridges) and communities are inaccessible	Sharp drop in public transport usage	Ridership decline
Interventions	Early warnings, emergency repairs, and resilience funding	Shelters, humanitarian aid, and slow emergency repairs	Micro-mobility, fare reform, service redesign	BRT construction, subsidies, and tax relief
Effectiveness of Interventions	Timely warning and partial repairs were adequate, as rail service was restored	Recovery was slow, therefore revealing limited institutional capacity	Moderate ridership recovery as recovery measures were implemented quickly	Effective in the bus sector as ridership recovered, not so much in rail
Lessons Learned	Importance of flood planning, proactive action and funding	Need for infrastructure maintenance and rapid institutional action	Value of innovation and rapid institutional action	Value of innovation, investment and ode specific transport planning

4.4. Discussion

The case studies reveal differences and similarities in how public transport systems respond to climate- and pandemic-induced disruptions. Both types of disruptions led to significant reductions in transport service usage, although the nature of the disruption varied. Climate events caused physical damage to infrastructure, while the pandemic primarily affected demand. This distinction reflects the difference between soft (behavioural, institutional, and policy-based) and hard (infrastructure-based) components of the transport system (Chan & Schofer, 2016; Omer et al., 2014). The responses to climate events focused on providing disaster relief, infrastructure repair, and long-term adaptation measures, whereas the pandemic responses involved service adjustments and financial support to service operators.

Regarding cross-case analysis of climate-induced disruptions, the UK and KZN demonstrated different challenges and responses. The UK's experience with Storm Babet showed the importance of robustness through early warning systems and infrastructure investments, as well as rapidity in response, as summarised in Table 4, which is consistent with the recommendations by Rogers and Tsirkunov (2010) that early warning systems coupled with investment in infrastructure would enhance resilience. Pregolato and Dawson (2018) also recommend infrastructure investment as a key component to enhance the resilience of transport infrastructure.

In contrast, the KZN floods exposed vulnerabilities related to infrastructure maintenance and rapidity in emergency response and infrastructure repairs. These findings align with a previous study by Revi et al. (2014), which highlighted the lack of consideration of climate change in the transportation sector in the Durban region of KZN, thus making it vulnerable to climate-related impacts. Satterthwaite et al. (2020) also highlighted the impact of socio-economic vulnerability and governance shortfall in the Global South regions, which impede resilience. Both cases highlight the need for long-term adaptation. Still, the KZN case shows the importance of addressing underlying socio-economic factors to improve the overall resilience of the transport system.

Comparing the United States and Mexico cases, we see that both countries experienced a sharp decline in public transport use. However, the rapidity of recovery differed. Mexico's bus system recovered rapidly compared to the United States. This could be attributed to socio-economic differences, policy responses, and the structural attributes of the system, as there was a focus on microbus route expansion and construction of a BRT route, which supports redundancy (Jenelius & Cats, 2015). Similarly, the United States focused on service extension, route expansion, micromobility services, and technological advancements. While direct quantitative comparison is limited, the analysis reveals insights into factors influencing resilience.

The comparative analysis highlighted the impact of disruption type on resilience performance and the varying adaptation capabilities of different national contexts. A summary of the implications of each climate-induced disruption tends to expose the physical vulnerabilities of transport infrastructure and challenge institutional capacity for rapid response. In contrast, pandemic-induced disruptions emphasise operational flexibility, innovation, and policy adaptation. Ultimately, the 4R framework reveals that resilience depends not only on robust infrastructure but also on governance structures, preparedness strategies, and innovation.

4.5. Summary of Key Lessons

- *Importance of Early Warning Systems:* Early warning systems are critical in minimising the impact of disruptions. The UK's effective release of emergency warnings and timely deployment of sandbags successfully safeguarded lives and infrastructure. In contrast, South Africa's lack of such systems and delayed response highlights the need for institutional frameworks to implement early action plans.
- *Resource Capacity:* Adequate financial and human resources are necessary to ensure the timely response and recovery of transportation systems and infrastructure. South Africa faced challenges in conducting an early risk assessment due to limited capacity, resulting in recovery delays, thereby forcing community-led restorative efforts. On the other hand, the UK, United States, and Mexico could quickly respond and adapt due to well-resourced agencies.
- *Long-Term Investments in Resilient Infrastructure:* Investment in resilient infrastructure is a priority. The UK focused on improving the drainage infrastructure, alleviating flood risk, and building intelligent infrastructure. Similarly, the United States and Mexico invested in innovative approaches such as redesigning transit routes and expanding BRT infrastructure. Despite resource constraints, South Africa also aimed to address structural vulnerabilities.
- *Adaptation Through Innovation:* Innovative approaches adopted by the United States, including the free-fare strategy, redesign of bus routes, micro-mobility services and technological enhancements, and the UK's investment in remote monitoring and sensing, illustrate the potential for innovation to support recovery and resilience in public transport systems.

5. Conclusion and Recommendations

Building resilience in public transportation systems is critical to addressing the increasing threats posed by climate-induced disruptions and global health crises. This study highlights the importance of proactive planning, infrastructure investment, and adaptive strategies to mitigate the impacts of such challenges. Case studies from developed and developing nations demonstrate that resilience requires a multifaceted approach, encompassing physical infrastructure improvements, institutional preparedness, and user-focused measures.

Key findings emphasise the need for investment in integrated transport infrastructure that can withstand and adapt to shocks, including multimodal networks and service expansions. Furthermore, institutional capacity strengthening is necessary through robust early warning systems, leveraging innovative solutions such as remote sensing, digitisation, and inter-agency coordination. Additionally, there is a need to prioritise the maintenance of existing infrastructure to reduce vulnerability.

This study underscores the necessity of a comprehensive and inclusive approach to resilience, offering actionable strategies to strengthen public transportation systems. However, transport systems are influenced by social, political, and spatial structures. Therefore, the findings of this study should be interpreted with caution, as the cases presented reflect diverse contexts. Rather than offering global solutions, the findings of this study offer insights into resilience-building that can inform context-specific strategies. The limitations of this study include the dependence on secondary data, which might omit undocumented resilience measures. Furthermore, the qualitative assessment framework applied is subjective and depends on the availability and consistency of the data. Moreover, using the case study

approach limits the generalisation of the study's findings. It introduces a certain level of bias, which may fail to comprehensively cover the topic of public transport resilience across different regions.

Future research should focus on conducting more local case studies based on primary data to capture the actual experiences of the disruptions, developing a standardised resilience metric that can be applied across different contexts while ensuring local relevance and examining the resilience of informal public transport systems to these disruptions, especially in developing regions, which are rarely reported.

Ultimately, this study offers insight into the resilience of public transport systems, emphasising the need for inclusive, context-specific approaches. Adapting the lessons from this study will be essential in enabling the adaptability and recovery of public transport systems in the event of a disruption.

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Conflict of Interests

The authors declare no conflict of interests.

Data Availability

The data are available on request from the KZNDOT Chair in Sustainable Transportation at the University of KwaZulu-Natal and the authors.

LLMs Disclosure

None.

References

- Acierto, J. M. L., Quilla, S. M. H., Valencia, B. J. N., Cueto, G. L., Monjardin, C. E. F., & Mohamed, W. M. W. (2023). Comparative Study on Urban Transport and the Environment (Cute) framework as strategy for the reduction of carbon dioxide emissions of road vehicles at Zapote Street. *Planning Malaysia*, 21.
- Amdal, J. R., Ankner, W. D., Callahan, T., Carnegie, J. A., MacLachlan, J., Matherly, D., Mobley, J., Peterson, E., Renne, J. L., Schwab, J. C., Venner, M., Veraart, N., Whytlaw, R. A. G., & Wolshon, B. (2017). *Improving the resilience of transit systems threatened by natural disasters. Volume 3: Literature review and case studies*. National Academies of Sciences, Engineering, and Medicine. <https://nap.nationalacademies.org/catalog/24972/improving-the-resilience-of-transit-systems-threatened-by-natural-disasters-volume-3-literature-review-and-case-studies>
- American Public Transportation Association. (n.d.). *Transit statistics: Ridership report*. <https://www.apta.com/research-technical-resources/transit-statistics/ridership-report>
- American Public Transportation Association. (2021). *On the horizon: Planning for post-pandemic travel*. <https://www.apta.com/research-technical-resources/research-reports/on-the-horizon-planning-for-post-pandemic-travel>

- Angell, C., & Potoglou, D. (2022). An insight into the impacts of Covid-19 on work-related travel behaviours in the Cardiff Capital Region and following the UK's first national lockdown. *Cities*, 124, 103602.
- Arana, P., Cabezudo, S., & Peñalba, M. (2014). Influence of weather conditions on transit ridership: A statistical study using data from Smartcards. *Transportation Research Part A: Policy and Practice*, 59, 1–12.
- Arkell, B. P., & Darch, G. (2006). Impact of climate change on London's transport network. *Proceedings of the Institution of Civil Engineers–Municipal Engineer*, 159(4), 231–237.
- Aydin, N. Y., Duzgun, H. S., Wenzel, F., & Heinemann, H. R. (2018). Integration of stress testing with graph theory to assess the resilience of urban road networks under seismic hazards. *Natural Hazards*, 91, 37–68.
- Beldarrain, G. G., Carvajal Ortega, C. A., Baan, A., & Kim, E. (2022). Framing resilience in public transportation systems, inspired by biomimicry. In D. Lockton, S. Lenzi, P. Hekkert, A. Oak, J. Sádaba, & P. Lloyd (Eds.), *DRS2022: Bilbao*. DRS. <https://doi.org/10.21606/drs.2022.323>
- Bo, K., Teng, J., Zhang, C., & Han, D. (2021). Commuting in the storm: Adaptation of transit riders and measures for transit operator—A case in Shanghai. *Journal of Advanced Transportation*, 2021(1), 6622461.
- Böcker, L., Uteng, T. P., Liu, C., & Dijst, M. (2019). Weather and daily mobility in international perspective: A cross-comparison of Dutch, Norwegian and Swedish city regions. *Transportation Research Part D: Transport and Environment*, 77, 491–505.
- Briginshaw, S. (2024). Mexican president confirms passenger rail revival. *International Rail Journal*. <https://www.railjournal.com/passenger/main-line/mexican-president-confirms-passenger-rail-revival>
- Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & Von Winterfeldt, D. (2003). A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra*, 19(4), 733–752.
- Burchart-Korol, D., & Folega, P. (2019). Impact of road transport means on climate change and human health in Poland. *Promet – Traffic&Transportation*, 31(2), 195–204.
- Buthelezi, L. (2022, September 2). After record KZN flood claims, Santam is working with municipalities to prevent future disasters. *news24*. <https://www.news24.com/business/companies/after-record-kzn-flood-claims-santam-is-working-with-municipalities-to-prevent-future-disasters-20220902>
- Calder, S. (2023, October 19). Storm Babet travel advice: How the extreme weather is affecting trains, flights and ferry services. *The Independent*. <https://www.independent.co.uk/travel/news-and-advice/storm-babet-trains-travel-roads-latest-b2432395.html>
- Calnek-Sugin, T., & Heeckt, C. (2020). *Mobility for the masses: The essential role of informal transport in the Covid-19 recovery*. LSE. <https://www.lse.ac.uk/cities/publications/blogs/mobility-for-the-masses>
- Chan, R., & Schofer, J. L. (2016). Measuring transportation system resilience: Response of rail transit to weather disruptions. *Natural Hazards Review*, 17(1), 05015004.
- Chen, R., Shalaby, A., & Silva, D. D. (2024). Trends in Toronto's subway ridership recovery: An exploratory analysis of wi-fi records. *Transportation Research Record*, 2678(11), 1156–1176.
- Colorado Department of Transportation. (n.d.). *4R framework for identifying and evaluating resiliency in transportation system assets and organizations*. <https://www.codot.gov/programs/planning/assets/risk-and-resiliency/4r-framework-remediated.pdf>
- Department of Economic Development, Tourism and Environmental Affairs. (2023). *Reflecting on the April/May 2022 KZN floods: One year later*. <https://www.kznedtea.gov.za/documents/Floods%20Article-Modified.pdf>
- Department of Planning, Monitoring and Evaluation. (2023). *Rapid assessment of the government's intervention on the April 2022 flood disaster in Kwazulu-Natal, Eastern Cape and North West*. <https://www.dpme.gov.za/keyfocusareas/evaluationsSite/Evaluation%20Reports/2.4%20Final%20Report%20on%20Rapid%20Assessment%20of%20Flood%20Disaster%20Interventions.pdf>

- Engage Environment Agency. (n.d.). *An update following Storm Babet*. <https://engageenvironmentagency.uk.engagementhq.com/36781/widgets/108260/documents/71285>
- English, E. (2023, December 20). Seven roads in East Cork damaged by Storm Babet blocked by padlocked gates. *Irish Examiner*. <https://www.irishexaminer.com/news/munster/arid-41294434.html>
- Enoch, B. (2022). *Durban residents repair flood damage, give up on government*. GroundUp. <https://groundup.org.za/article/durban-residents-repair-flood-damage-give-up-on-government>
- Environment Agency. (2023). *Nearly 100,000 properties protected from flooding during Storm Babet, but threat remains*. <https://www.gov.uk/government/news/rolling-news-story-flooding-from-storm-babet>
- Federal Transit Administration. (2024). *Effects of the Covid-19 pandemic on transit ridership and accessibility*. <https://www.transit.dot.gov/sites/fta.dot.gov/files/2024-08/FTA-Report-0268-Effects-of-the-Covid-19-Pandemic-on-Transit-Ridership-and-Accessibility.pdf>
- Flood-hit residents 'won't be home for Christmas.' (2023, October 22). BBC. <https://www.bbc.com/news/uk-scotland-67186878>
- Fraser, A. M., & Chester, M. V. (2017). Transit planning and climate change: Reducing rider's vulnerability to heat. In *International Conference on Sustainable Infrastructure* (pp. 456–464). ACSE.
- Freckleton, D., Heaslip, K., Louisell, W., & Collura, J. (2012). Evaluation of resiliency of transportation networks after disasters. *Transportation Research Record*, 2284(1), 109–116.
- Gonçalves, L., & Ribeiro, P. (2020). Resilience of urban transportation systems. Concept, characteristics, and methods. *Journal of Transport Geography*, 85, 102727.
- Haggag, M., Siam, A. S., El-Dakhakhni, W., Coulibaly, P., & Hassini, E. (2021). A deep learning model for predicting climate-induced disasters. *Natural Hazards*, 107, 1009–1034.
- Haines, A. (2021). *Resilience of rail infrastructure: Update report to the Secretary of State for Transport following the derailment at Carmont, near Stonehaven*. Network Rail.
- Hattingh, M. (2022). What did cause the April KZN floods? *Water Wheel*, 21(4), 24–27.
- Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4(1), 1–23.
- Hughes, J. F., & Healy, K. (2014). *Measuring the resilience of transport infrastructure*. NZ Transport Agency.
- Imran, M., Cheyne, C., & Harold, H. (2014). *Measuring transport resilience: A Manawatu-Wanganui region case study*. Massey University. <https://mro.massey.ac.nz/items/7f0e3154-cd67-41c1-b879-bdd3790dc561>
- Internet Geography. (n.d.). *Storm Babet case study*. <https://www.internetgeography.net/storm-babet-case-study>
- Jenelius, E., & Cats, O. (2015). The value of new public transport links for network robustness and redundancy. *Transportmetrica A: Transport Science*, 11(9), 819–835. <https://doi.org/10.1080/23249935.2015.1087232>
- Jenelius, E., & Mattsson, L.-G. (2020). Resilience of transport systems. In *International encyclopedia of transportation* (pp. 258–267). Elsevier.
- Ji, T., Yao, Y., Dou, Y., Deng, S., Yu, S., Zhu, Y., & Liao, H. (2022). The impact of climate change on urban transportation resilience to compound extreme events. *Sustainability*, 14(7), 3880. <https://www.mdpi.com/2071-1050/14/7/3880>
- Jing, J. (2021). *Post-Sandy flood resiliency in NYC: How to prevent subway systems from increasing storm surges*. Brown University.
- Kafalenos, R. S., Leonard, K. J., Beagan, D., Burkett, V., Keim, B., Meyers, A., Hunt, D., Hyman, R., Maynard, M., & Fritsche, B. (2008). What are the implications of climate change and variability for Gulf Coast transportation? In M. J. Savonis, V. R. Burkett, & J. R. Potter (Eds.), *Impacts of climate change and variability on transportation systems and infrastructure: Gulf Coast study. Phase I* (pp. 1–63). U.S. Climate Change Science Program.

- Kermanshachi, S., Li, J., & Jahan Nipa, T. (2021). *Development of a multi-level dynamic model to measure the resilience level of transportation infrastructure networks*. Transportation Consortium of South-Central States. https://repository.lsu.edu/transet_pubs/133
- Kim, K., Francis, O., & Yamashita, E. (2018). Learning to build resilience into transportation systems. *Transportation Research Record*, 2672(1), 30–42.
- KITE Projects. (2023). *Back on track: How network rail restored the railway after storms Babet & Ciarán tore through the UK*. <https://www.kite-projects.co.uk/post/back-on-track-how-network-rail-restored-the-railway-after-storms-babet-ciar%C3%A1n-tore-through-the-uk>
- Lee, S., Kim, J., & Cho, K. (2024). Temporal dynamics of public transportation ridership in Seoul before, during, and after Covid-19 from urban resilience perspective. *Scientific Reports*, 14(1), 8981.
- Leobons, C. M., Campos, V. B. G., & de Mello Bandeira, R. A. (2019). Assessing urban transportation systems resilience: A proposal of indicators. *Transportation Research Procedia*, 37, 322–329.
- Lima, G. C. L. d. S., Carvalho, G. S. D. d., & Figueiredo, M. Z. (2020). Incomplete contracts for bus service during the Covid-19 pandemic. *Revista de Administração Pública*, 54, 994–1009.
- Los Angeles County Metropolitan Transit Authority. (2015). *Resiliency indicator framework*. http://media.metro.net/projects_studies/sustainability/images/resiliency_indicator_framework.pdf
- Magubane, T. (2023). *eThekweni highlights repair, rebuilding work done one year after April floods*. IOL. <https://www.iol.co.za/mercury/news/ethekweni-highlights-repair-rebuilding-work-done-one-year-after-april-floods-14a6915f-78eb-443e-89ef-37d033e00e9f>
- Maluleke, T. (2022). *First special report on flood relief funds*. Auditor-General South Africa. <https://www.agsareports.co.za/wp-content/uploads/2022/09/First-special-report-on-flood-relief-funds-2022-1.pdf>
- Mepparambath, R. M., Huynh, H. N., Oon, J., Song, J., Zhu, R., & Feng, L. (2023). The impact of Covid-19 pandemic on the fundamental urban mobility theories using transit data from Singapore. *Transportation Research Interdisciplinary Perspectives*, 21, 100883.
- Monama, T. (2022, April 25). Flood costs revised from R950 billion to R17 billion—but KZN government says was ‘honest error.’ *news24*. <https://www.news24.com/news24/southafrica/news/flood-costs-revised-from-r950-billion-to-r17-billion-but-kzn-government-says-was-honest-error-20220425>
- Mudefi, E. (2023). Disaster management ‘deeds’ in the context of April 2022 KwaZulu-Natal floods: A scoping review. *International Journal of Disaster Risk Reduction*, 98, 104122.
- Murray-Tuite, P. M. (2006). A comparison of transportation network resilience under simulated system optimum and user equilibrium conditions. In *Proceedings of the 2006 Winter Simulation Conference* (pp. 1398–1405). IEEE.
- National Academies of Sciences, Engineering, and Medicine. (2024a). *Incorporating resilience into transportation networks*. <https://doi.org/10.17226/27919>
- National Academies of Sciences, Engineering, and Medicine. (2024b). *Sustaining zero-fare public transit in a post Covid-19 world: A guide for state DOTs*.
- Nottinghamshire: Highways update shows record £66m investment and 25,000 pothole repairs in first half year. (2025, January 14). *West Bridgford Wire*. <https://westbridgfordwire.com/nottinghamshire-highways-update-shows-25000-potholes-repairs-in-first-half-year>
- Omer, M., Mostashari, A., & Lindemann, U. (2014). Resilience analysis of soft infrastructure systems. *Procedia Computer Science*, 28, 565–574.
- Pan, S., Yan, H., He, J., & He, Z. (2021). Vulnerability and resilience of transportation systems: A recent literature review. *Physica A: Statistical Mechanics and its Applications*, 581, 126235.
- Pregnotato, M., & Dawson, D. A. (2018). Adaptation investments for transport resilience: Trends and recommendations. *International Journal of Safety and Security Engineering*, 8(4), 515–527.

- Reggiani, A. (2013). Network resilience for transport security: Some methodological considerations. *Transport Policy*, 28, 63–68.
- Revi, A., Satterthwaite, D., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., Roberts, D., Solecki, W., Gajjar, S. P., & Sverdlík, A. (2014). Towards transformative adaptation in cities: The IPCC's Fifth Assessment. *Environment & Urbanization*, 26(1), 11–28. <https://doi.org/10.1177/0956247814523539>
- Rogers, D. P., & Tsirkunov, V. V. (2010). *Global assessment report on disaster risk reduction: Costs and benefits of early warning systems*. The World Bank.
- Ruane, A. C. (2024). *Synthesis report of the IPCC Sixth Assessment Report (AR6)*. IPCC.
- Sabir, M. (2011). *Weather and travel behaviour* [Unpublished doctoral dissertation]. VU University.
- Satterthwaite, D., Archer, D., Colenbrander, S., Dodman, D., Hardoy, J., Mitlin, D., & Patel, S. (2020). Building resilience to climate change in informal settlements. *One Earth*, 2(2), 143–156. <https://doi.org/10.1016/j.oneear.2020.02.002>
- Serulle, N. U. (2011). *Transportation network resiliency: A fuzzy systems approach*. Utah State University.
- Shang, W.-L., & Lv, Z. (2023). Low carbon technology for carbon neutrality in sustainable cities: A survey. *Sustainable Cities and Society*, 92, 104489.
- Srikanth, S., Kanimozhee, S., & Ramireddy, S. (2023). Modelling of pre and post Covid-19's impact on employee's mode choice behavior. *Innovative Infrastructure Solutions*, 8(1), 11.
- Stefani, F. (2023, October 18). Storm Babet prompts closure of train lines across the Highlands tomorrow and Friday. *John O'Groat Journal and Caithness Courier*. <https://www.johnogroat-journal.co.uk/news/storm-babet-prompts-closure-of-train-lines-across-the-highla-330013>
- Stokenberga, A., Ivarsson Molina, L. E. M., & Fulponi, J. I. (2023). *The Covid-19 mark on urban mobility: A tale of two cities' journey to recovery* (Policy Research Working Paper Series 10484). The World Bank.
- Suffolk County Council. (2023). 4.7 million litres of water and 8,412 drains cleared since Storm Babet battered Suffolk one month ago. <https://www.suffolk.gov.uk/council-and-democracy/council-news/4.7-million-litres-of-water-and-8412-drains-cleared-since-storm-babet-battered-suffolk-one-month-ago>
- Sun, W., Bocchini, P., & Davison, B. D. (2020). Resilience metrics and measurement methods for transportation infrastructure: The state of the art. *Sustainable and Resilient Infrastructure*, 5(3), 168–199.
- Tabassum, N., Kalantari, H. A., Kaniewska, J., Ameli, S. H., Ewing, R., Yang, W., & Promy, N. S. (2024). Ways of increasing transit ridership-lessons learned from successful transit agencies. *Case Studies on Transport Policy*, 19, 101362.
- Tao, S., Corcoran, J., Rowe, F., & Hickman, M. (2018). To travel or not to travel: 'Weather' is the question. Modelling the effect of local weather conditions on bus ridership. *Transportation Research Part C: Emerging Technologies*, 86, 147–167.
- Testa, A. C., Furtado, M. N., & Alipour, A. (2015). Resilience of coastal transportation networks faced with extreme climatic events. *Transportation Research Record*, 2532(1), 29–36.
- The United States Environmental Protection Agency. (2025). *Climate change impacts on transportation*. <https://www.epa.gov/climateimpacts/climate-change-impacts-transportation>
- Thoithi, W., Blamey, R. C., & Reason, C. J. (2022). April 2022 floods over East Coast South Africa: Interactions between a mesoscale convective system and a coastal meso-low. *Atmosphere*, 14(1), 78.
- Tierney, K., & Bruneau, M. (2007). Conceptualizing and measuring resilience: A key to disaster loss reduction. *TR News*, 2007(250).
- Tonn, G., Czajkowski, J., Kunreuther, H., Angotti, K., & Gelman, K. (2020). Measuring transportation infrastructure resilience: Case study with Amtrak. *Journal of Infrastructure Systems*, 26(1), 05020001.
- Tori, S., de Séjournet, A., & Macharis, C. (2023). Reactions of the public transport sector to the Covid-19 pandemic. Insights from Belgium. *Travel Behaviour and Society*, 31, 244–253.

- UK Research and Innovation. (2023). *Boosting UK infrastructure resilience against climate change*. <https://www.ukri.org/news/boosting-uk-infrastructure-resilience-against-climate-change>
- Ward, S. (2023, October 24). Roads reopen after Storm Babet as £32,000 raised to help Brechin. *The Standard*. <https://www.standard.co.uk/news/environment/roads-dundee-aberdeenshire-scotland-gofundme-b1115611.html>
- Watt, E. (2024). Are seismometers valuable instrumentation for monitoring weather events? A Northeast and Central Scotland case study. *The Elphinstone Review*, 10(1), 88–117.
- Welle, B., Kustar, A., Tun, T. H., & Albuquerque, C. (2023). *Post-pandemic, public transport needs to get back on track to meet global climate goals*. TheCityFix. <https://thecityfix.com/blog/post-pandemic-public-transport-needs-to-get-back-on-track-to-meet-global-climate-goals>
- World Bank. (2024). *Mexico green & resilient transport: Urban public transport*. <https://documents1.worldbank.org/curated/en/099062424183033037/pdf/P1772791af9eca0aa19fbd1948f0ead32a5.pdf>
- Wu, J., & Liao, H. (2020). Weather, travel mode choice, and impacts on subway ridership in Beijing. *Transportation Research Part A: Policy and Practice*, 135, 264–279.
- Xia, Y., Van Ommeren, J. N., Rietveld, P., & Verhagen, W. (2013). Railway infrastructure disturbances and train operator performance: The role of weather. *Transportation Research Part D: Transport and Environment*, 18, 97–102.
- Zhou, Y., Wang, J., & Yang, H. (2019). Resilience of transportation systems: Concepts and comprehensive review. *IEEE Transactions on Intelligent Transportation Systems*, 20(12), 4262–4276.
- Zorgati, I., Zorgati, H., & Zaabi, E. (2021). Public transportation and service quality management during the Covid-19 outbreak: A case study of Tunisia. *Problems and Perspectives in Management*, 19(3), 298.

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Resilient and Sustainable Urban Infrastructure in the Global South: Strategies to Address Climate Change-Linked Vulnerabilities

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Abstract

The impacts of climate change pose serious threats to the sustainability and resilience of urban infrastructure in the Global South, where socioeconomic, technical, and governance challenges intensify vulnerabilities in water, energy, and transport systems. This article explores these vulnerabilities through a literature review and case study analyses and identifies strategies for creating resilient and sustainable urban infrastructure in developing regions. The study highlights critical challenges such as ageing infrastructure, inadequate maintenance, insufficient funding, and rapid urbanisation, which increase the susceptibility of urban systems to climate-related events like floods, droughts, and rising sea levels. Case studies from two countries reveal that the intersection of climate vulnerability with factors such as poor governance, socio-political issues, and limited technological capacity further weakens infrastructure resilience. However, emerging strategies focus on climate-resilient design, improved governance, strengthened public-private partnerships, and community-based solutions. Integrating nature-based solutions, smart technologies, and capacity-building initiatives is vital in enhancing local governments' adaptive capacity to enable the building of sustainable and resilient infrastructure. This article argues that while infrastructure vulnerabilities in the Global South are complex and rooted in historical inequalities, lack of technological competence and financial constraints, targeted strategies—centred on governance reform, climate-resilient design and retrofitting, technological innovations and nature-based solutions, strengthening public-private partnerships, community-based solutions and capacity building—are essential for building resilient and sustainable urban infrastructure. These insights offer guidance for policymakers, planners, and development agencies working to strengthen critical infrastructure in vulnerable regions of the Global South.

Keywords

climate change; Global South; resilience; sustainability; sustainable urban infrastructure; urban infrastructure; vulnerability

1. Introduction

Climate change presents significant challenges to urban infrastructure, affecting its resilience, functionality, and sustainability. Cities in the Global South, including India, South Africa, and Indonesia, face heightened risks from extreme weather events, urban heat islands, flooding, and droughts. These vulnerabilities are exacerbated by rapid urbanisation, informality, and socioeconomic disparities, leading to property loss, service disruptions, and deepening inequalities (Intergovernmental Panel on Climate Change, 2021). Extreme weather events such as hurricanes, heat waves, and heavy rainfall disrupt transportation networks, energy grids, and water systems. Urban heat islands, caused by urban expansion and reduced vegetation, increase local temperatures, compromising infrastructure efficiency and raising energy demands. Urban flooding disproportionately affects vulnerable populations, intensified by rising sea levels (Dharmarathne et al., 2024). Addressing these challenges requires holistic, innovative, and inclusive strategies, such as effective water management and equitable resource allocation, to enhance urban resilience (Ikonomova & MacAskill, 2023). However, cities in the Global South face additional obstacles, including inadequate policies, resource constraints, and a lack of context-specific adaptation strategies.

Governance and financial constraints significantly hinder sustainable urban development. Weak governance structures, short political cycles, and limited access to climate finance exacerbate infrastructure deficits (Dossa & Miassi, 2024). Outdated water and energy systems struggle to meet increasing demands, while technological gaps prevent the adoption of advanced solutions (Rahman et al., 2023). Additionally, the replication of Northern adaptation models proves ineffective, as these approaches often fail to address Southern cities' complex socio-economic and environmental conditions (Chirambo, 2022). Locally tailored solutions that consider regional contexts and constraints are therefore essential. Technological limitations further complicate climate adaptation. Many cities in the Global South lack the expertise and financial resources to implement advanced technologies such as predictive modelling and smart infrastructure. As a result, ageing water and energy systems remain highly vulnerable to climate-induced stresses, further straining urban resilience (Rahman et al., 2023).

Furthermore, climate change exacerbates socio-economic inequalities, disproportionately affecting marginalised populations, particularly those in informal settlements. Flooding, heatwaves, and other climate hazards deepen existing disparities, emphasising the need for inclusive, innovative, and context-specific strategies to enhance resilience and ensure equitable adaptation (Chen, 2024; Dias, 2024; James, 2023; Mondal, 2024). Despite advancements in climate resilience research, significant gaps persist, particularly regarding the Global South. Much of the existing research focuses on cities in the Global North, overlooking the distinct challenges faced by rapidly urbanising Southern cities with infrastructure deficits and socio-economic vulnerabilities (Parnell & Oldfield, 2014). Additionally, many studies prioritise short-term resilience measures, neglecting long-term impact assessments essential for scalable and sustainable solutions (Tyler & Moench, 2012). Climate justice integration in urban planning remains insufficient, particularly in ensuring equitable access to resilient infrastructure for marginalised communities (Schlosberg, 2012; Schlosberg et al., 2017).

To effectively adapt urban infrastructure in the Global South, systematic identification and classification of climate-linked vulnerabilities and strategic adaptation measures are necessary. For instance, critical areas such as retrofitting and infrastructure management remain underexplored (Dixit, 2024). This remains a

critical research gap in the Global South context. Additionally, implementing climate-resilient development pathways is challenging due to the absence of comprehensive frameworks that integrate adaptation, mitigation, and sustainability objectives (Langendijk et al., 2024). Another key research gap is the underutilisation of South–South climate finance, which has the potential to support community-driven innovations and enhance resource governance (Chirambo, 2022). Addressing these gaps is crucial for developing context-specific, long-term strategies that strengthen urban resilience in the Global South. To address the first significant research gap mentioned above, the study explored the following research questions:

RQ1: What are the critical infrastructure vulnerabilities and their relative severity within the context of urban systems in the Global South?

RQ2: What strategies can effectively address these vulnerabilities while enhancing the resilience and sustainability of urban infrastructure in the Global South?

The objectives of the study are to examine the key vulnerabilities in urban infrastructure within the Global South, focusing on their severity and nature. It aims to identify context-specific, sustainable strategies to mitigate these vulnerabilities and foster resilient infrastructure systems capable of addressing climate change challenges. However, the scope of the study encompasses only three sectors of urban infrastructure, including water, energy, and road transportation systems.

This study contributes by identifying critical vulnerabilities in urban infrastructure in the Global South, focusing on the three systems mentioned above. It offers context-specific, sustainable strategies to mitigate these vulnerabilities, emphasising locally tailored solutions to address socio-economic disparities, governance challenges, and technological limitations. The study also highlights the need for integrating climate justice into urban planning, providing a framework for building resilient and equitable infrastructure in the Global South.

2. Conceptualising Climate Change Vulnerabilities, Sustainable and Resilient Urban Infrastructure in the Global South

2.1. Climate Change Vulnerability in the Context of the Global South

The Global South, encompassing developing nations in Africa, Asia, Latin America, and the Pacific, faces disproportionate impacts from climate change due to high exposure to climate hazards, socioeconomic inequalities, and limited adaptive capacities. Geographic factors such as tropical and subtropical locations prone to hurricanes, droughts, and rising sea levels exacerbate these vulnerabilities. Socioeconomic challenges, including poverty, inequality, and dependence on climate-sensitive sectors like agriculture, further enhance risks. For example, smallholder farmers in sub-Saharan Africa and South Asia face declining crop yields and food insecurity due to erratic rainfall and rising temperatures (Lobell et al., 2008).

Urban areas, particularly urban infrastructure and informal settlements, are highly vulnerable to extreme events such as flooding, storms, cyclones, etc. (Hussainzad & Gou, 2024). Specifically, in the context of urban infrastructure, as illustrated in Figure 1, extreme weather events such as droughts, extreme

temperatures, heat waves, flooding, cloudbursts, storms, cyclones, hurricanes, etc., make the urban infrastructures, such as water systems, transportation systems, energy systems, etc., vulnerable. The vulnerability arises from the ageing infrastructure, rapid urbanisation and informal settlements, and poor governance and financial constraints (Figure 1). In other words, economic and political constraints in the Global South hinder robust climate adaptation and mitigation efforts, with insufficient financial resources and technological capabilities limiting effective responses to climate challenges (Garcia, 2024). Governance issues and policy gaps further exacerbate vulnerabilities, as political inequalities and inadequate government interventions undermine adaptation strategies (Boas et al., 2023; Ngcamu, 2023).

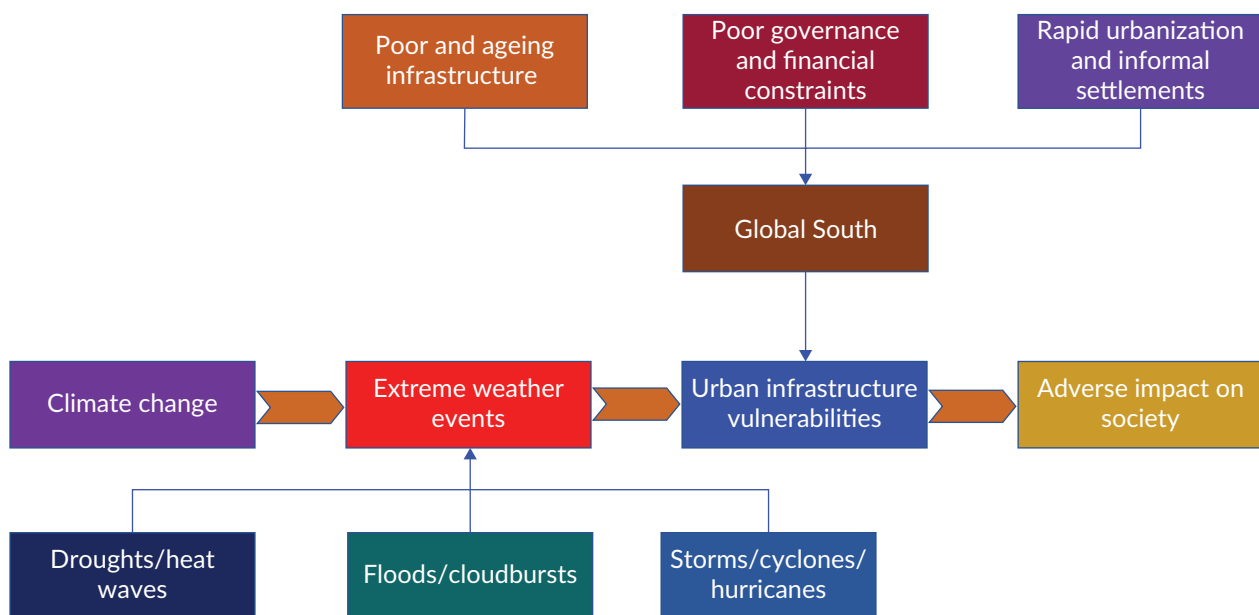


Figure 1. Climate change and urban infrastructure vulnerabilities in the Global South.

2.2. Resilience and Sustainability in Urban Infrastructure

Urban infrastructure plays a critical role in supporting the economic, social, and environmental functions of cities. As urbanisation accelerates, particularly in the Global South, ensuring resilient and sustainable infrastructure has become a priority for policymakers, urban planners, and researchers. Figure 2 presents the concept of resilient and sustainable urban infrastructure, emphasising resilience as the capacity of urban systems to withstand, adapt to, and recover from various shocks and stresses while maintaining essential functions and overall well-being (Walker & Salt, 2006). This concept has gained prominence as cities face increasing challenges from climate change, natural disasters, and rapid urbanisation. Resilient infrastructure reduces vulnerabilities to disasters, economic disruptions, and technological failures, ensuring operational stability, safety, and service continuity, particularly in smart cities that rely on seamless connectivity. The key elements of resilient urban infrastructure, as illustrated in Figure 2, include robustness (the ability to withstand extreme conditions without significant degradation), redundancy (alternative pathways or systems that ensure continued functionality during failures), and adaptability (the capacity to evolve and improve in response to emerging threats; Cao, 2023; Kapse & Jangale, 2024; Li et al., 2023).

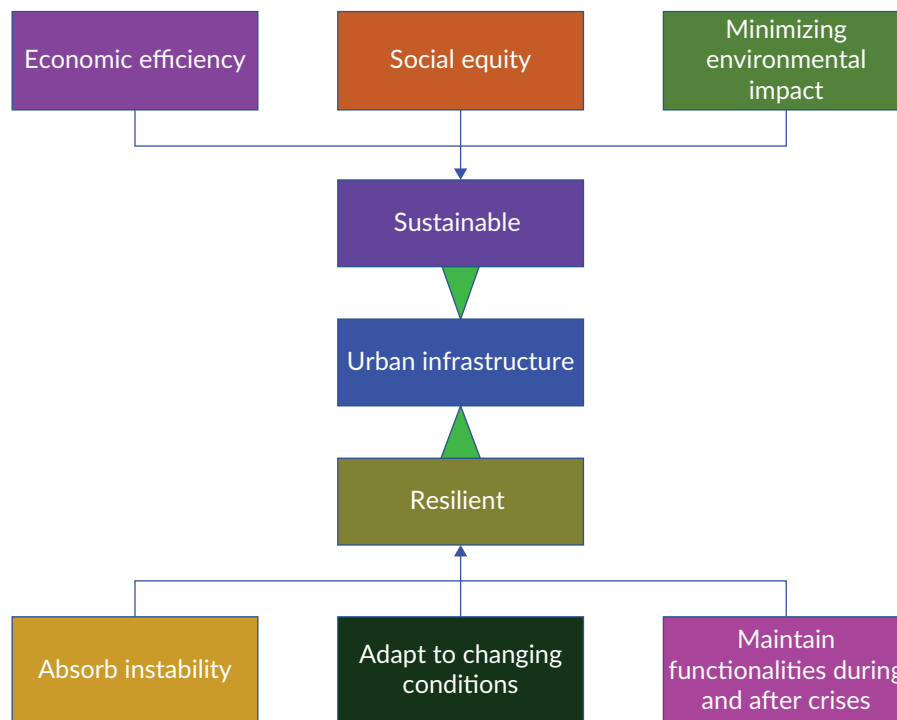


Figure 2. Conceptualising sustainable and resilient urban infrastructure.

Sustainability emphasises the long-term viability of infrastructure systems, focusing on minimising environmental impact, promoting social equity, and ensuring economic efficiency (Adams et al., 2012; El-Diraby & Osman, 2011; Ferrer et al., 2018). It includes environmental stewardship (reducing greenhouse gas emissions and conserving biodiversity), social inclusivity (ensuring equitable access to infrastructure services for marginalised communities), and economic viability (balancing costs with long-term benefits through innovative financing models). Sustainability and resilience are interdependent, as resilient infrastructure ensures recovery and functionality during and after disruptions, while sustainability promotes resource efficiency and minimizes environmental impacts (Trejo & Gardoni, 2022). Performance-based assessments and life cycle analyses help evaluate the environmental impacts of resilient structures, balancing trade-offs between these priorities (Tanguay & Amor, 2024). Additionally, sustainable infrastructure must integrate environmental and societal considerations, ensuring equity and justice while maintaining functionality during adverse events (Sánchez-Silva et al., 2025). The integration of resilience and sustainability into infrastructure planning is essential to addressing vulnerabilities and supporting long-term economic, social, and environmental goals.

2.3. Conceptual Framework for Resilient and Sustainable Infrastructure in Response to Climate Change Vulnerabilities

Premised on the concept of sustainable and resilient urban infrastructure, Figure 3 presents a conceptual framework that explicitly addresses climate change challenges in the Global South. Urban infrastructure in these regions is particularly vulnerable due to intertwined socio-economic and environmental factors, which necessitate a systematic identification of vulnerabilities across various climate scenarios to inform effective mitigation strategies. As depicted in Figure 3, governance, socio-technical systems, and adaptive capacity are central to shaping urban resilience. Governance plays a pivotal role; however, progress is often hindered

by weak institutions, corruption, and policy gaps (Bulkeley & Betsill, 2013). Inclusive governance—engaging governments, the private sector, and civil society—can foster collaboration and promote equitable outcomes (Anguelovski et al., 2014). Adaptive governance, in particular, offers a flexible, collaborative, and learning-oriented approach to managing environmental and resource challenges. It emphasises stakeholder participation, cross-scale coordination, and the ability to revise policies and practices in response to evolving conditions. Characterised by flexibility, inclusivity, and social learning, adaptive governance strengthens resilience by dynamically addressing socio-ecological complexities (Akther & Evans, 2024). Building urban climate resilience further requires capacity development through transformative planning, multi-actor engagement, and robust knowledge-sharing mechanisms (Wieszczeczynska et al., 2024).

Socio-technical systems—encompassing the interactions between technology, society, and infrastructure—are critical to advancing sustainability. As illustrated in Figure 3, rapid urbanisation and resource constraints in the Global South necessitate innovative, context-sensitive solutions such as Internet of Things-enabled infrastructure and the integration of renewable energy. The complexity and interdependence of urban infrastructure systems in these regions demand adaptive designs and inclusive service delivery models that account for diverse needs and vulnerabilities (Gürsan et al., 2023; Oates & Sudmant, 2024). Adaptive capacity, shaped by institutional readiness, financial resources, and community engagement, is essential for enhancing resilience. Investments in climate-resilient infrastructure, such as flood-resistant housing and urban green spaces, not only mitigate the impacts of climate change but also generate social and environmental co-benefits (Pelling, 2011). The emerging paradigm of climate urbanism integrates climate adaptation and mitigation into urban planning and governance as it emphasises resilience, sustainability, and equity, promoting climate-smart infrastructure and sustainable urban systems (Rahman et al., 2023). However, it also carries the risk of entrenching social inequalities and displacing marginalised communities if not carefully implemented. Therefore, it is argued that strategic measures and frameworks should be grounded in this conceptual framework for sustainable and resilient urban infrastructure in response to climate change.

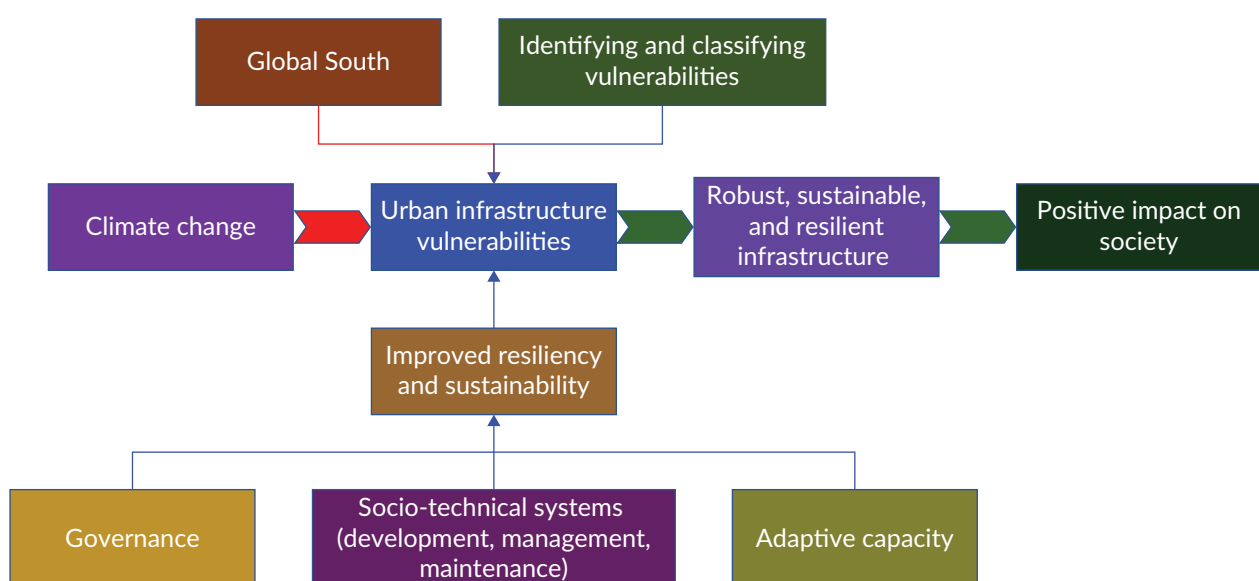


Figure 3. Conceptual Framework for Resilient and Sustainable Infrastructure in response to climate change vulnerabilities.

3. Methodology

This study adopted a qualitative methodology, centring on an in-depth review of literature and case studies to explore the complexities of climate change and the vulnerability, sustainability, and resilience of urban infrastructure. A qualitative approach was selected for its strength in uncovering context-specific dynamics that quantitative methods may overlook, particularly in understanding the lived experiences of marginalised communities and identifying nuanced vulnerabilities within urban systems (Creswell & Poth, 2017). Unlike quantitative techniques, qualitative methods capture the social, cultural, and political dimensions that shape infrastructure resilience (Stake, 1995), making them especially suitable for addressing the socio-economic and governance challenges prevalent in the Global South (Patton, 2002). Moreover, qualitative research emphasises rich, contextual insights into how communities adapt to climate-related impacts, offering a deeper understanding of the factors that contribute to resilience (Denzin & Lincoln, 2011). To support this interdisciplinary analysis, a broad range of sources—including peer-reviewed journal articles, books, policy reports, and reputable online publications—were incorporated.

3.1. Literature Survey and Compilation

A structured methodology guided the literature search process, encompassing the development of a robust search strategy, systematic curation of scholarly materials, application of inclusion and exclusion criteria, and thematic organisation and analysis of selected literature. The review focused on published works addressing climate change, urban infrastructure, vulnerabilities, and strategies.

Peer-reviewed journal articles were the primary sources, supplemented by conference proceedings, books, book chapters, reports, and online articles. Multiple databases, including Web of Science, Scopus, and Google Scholar, were explored. Articles were systematically gathered, categorised, and critically assessed, and search strings tailored to each database used relevant keywords such as climate change, urban infrastructure, vulnerability, disaster, resilience, strategy, Global South, climate change adaptation, and governance.

3.1.1. Inclusion/Exclusion Criteria and Data Extraction

The inclusion criteria were aligned with the RQs and focused on the impacts of climate change on urban systems, infrastructure vulnerabilities, sustainability, and resilience. It also encompassed various sectors of urban infrastructure, such as water, energy, and transportation systems, and strategies addressing these challenges. Conversely, topics unrelated to the impact of climate change on urban infrastructure were excluded, including economic, environmental, social, and cultural aspects outside the study's scope.

Data were systematically extracted using a standardised form, capturing details such as authorship, publication date, research aims, methodology, findings, contributions, recommendations for future research, and limitations. Extracted data were organised in an Excel spreadsheet and evaluated based on four criteria: authenticity, credibility, representation, and meaning. Only articles meeting these criteria were included for further analysis.

3.2. Organisation of Literature

The initial search yielded 4,172 articles and, following a screening process, 504 articles were retrieved. After applying inclusion and exclusion criteria and organising the materials into themes and subthemes, 127 articles were selected for the final review and analysis (Figure 4). Of these, 70.08% were peer-reviewed journal articles, 1.57% conference proceedings, 8.66% books, 3.15% book chapters, 15.75% reports, and 0.79% working papers (Table 1).

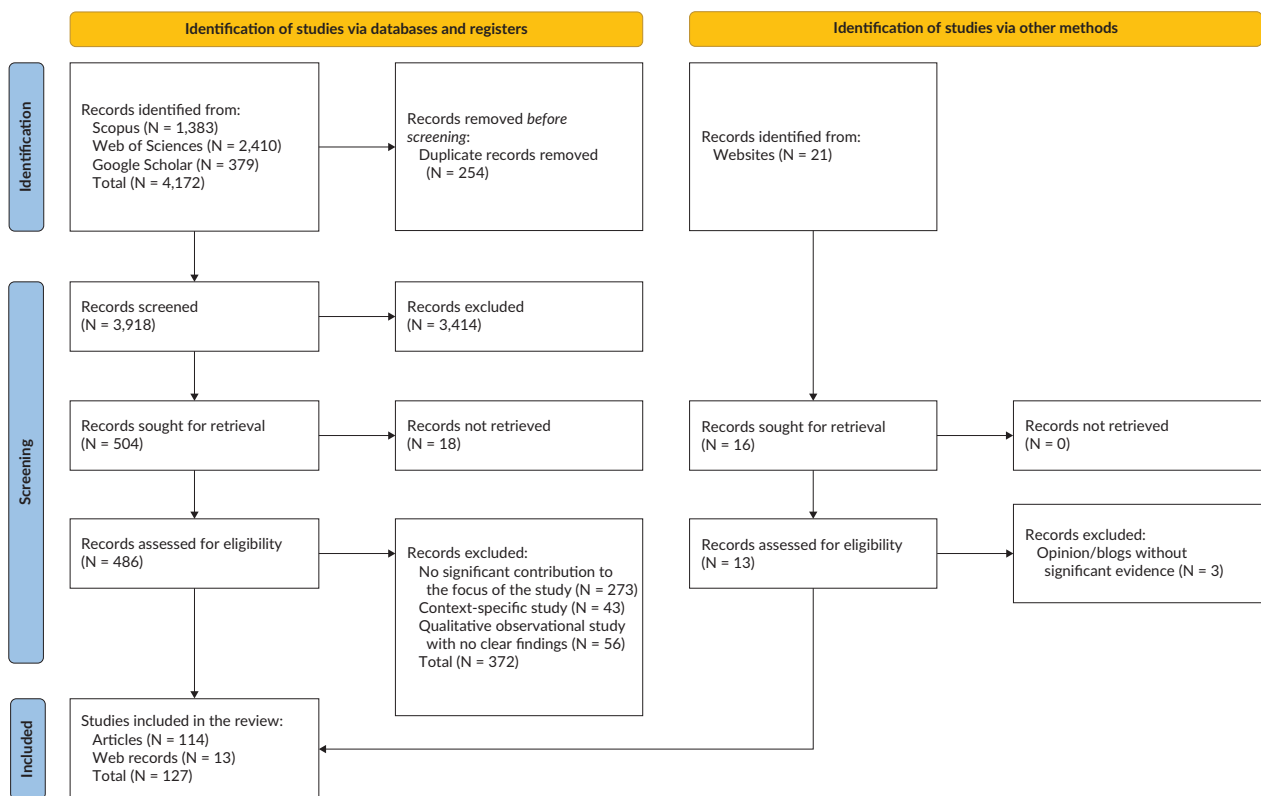


Figure 4. Flow diagram for search and selection of literature.

Table 1. Summary of literature reviewed.

Type of Articles	Numbers	Percentage
Peer-reviewed journals	89	70.08
Books	11	8.66
Book chapters	4	3.15
Conference proceedings	2	1.57
Reports	20	15.75
Others (working papers)	1	0.79
Total	127	100

3.3. Analysis of Literature and Case Study Selection and Analysis

The collected literature was systematically reviewed and analysed, organised into specific themes and subthemes. This thematic analysis provided a structured framework for understanding the study's focus areas, including the interconnections between urban infrastructure, vulnerabilities, and strategies for resilience and sustainability.

The thematic analyses were supplemented with case studies from India and South Africa. The case studies were selected for their significant history of climate-linked extreme events, natural disasters, urban infrastructure vulnerabilities, and the strategic measures undertaken to address these challenges. In India, cities from Odisha, Maharashtra, Delhi, West Bengal, Uttarakhand, Tamil Nadu, and Karnataka were chosen due to their exposure to recurring floods and cyclones. Similarly, Cape Town, Durban, and Johannesburg from South Africa were included for their frequent experiences with extreme weather events, particularly floods and droughts. These case studies offered valuable insights into practical applications and highlighted the potential for transformative strategies to improve urban infrastructure systems in the wake of climate change.

By integrating diverse scholarly sources and case studies, this study offered a comprehensive understanding of the interplay between climate change, urban infrastructure, and sustainable and resilient strategies, contributing to the broader discourse on sustainable and resilient urban infrastructure development.

3.4. Addressing Potential Bias and Limitations of the Methodology

The literature survey may have introduced several biases, including publication bias (overrepresentation of high-impact journals) and geographical bias (overreliance on Global North research). Additionally, methodological bias could arise from focusing on either quantitative or qualitative studies, potentially overlooking valuable insights from the other. Confirmation bias may have influenced the selection of studies that align with existing views on climate change and infrastructure resilience. To mitigate these biases, the study incorporated a broad range of sources—peer-reviewed articles, books, conference proceedings, and reports—while prioritising research from the Global South. Case studies were specifically chosen from India and South Africa, two countries heavily impacted by climate change. Furthermore, the qualitative methodology adopted addressed context-specific challenges and provided a more balanced understanding of urban infrastructure resilience.

It is also acknowledged that the qualitative methodology employed has limitations, including limited generalizability, potential selection bias, reliance on secondary data, and context-specific findings. However, these limitations have been addressed through careful case selection, source triangulation, and critical analysis. While the methodology does not establish causality or incorporate primary data, it effectively captures patterns, challenges, and strategic responses that are relevant to the study's objectives. Despite these constraints, the combination of literature review and case study analysis offers a valuable and acceptable approach for gaining meaningful insights.

4. Climate-Linked Vulnerabilities in Urban Infrastructure

The climate-linked vulnerabilities were examined in terms of their severity and impact on various infrastructures, including water systems, transportation networks, and energy systems, as well as cross-cutting issues. They are discussed in the following sections.

4.1. Level of Vulnerabilities

Table 2 presents the climate-linked vulnerabilities that are generally associated with urban infrastructure. Climate-linked vulnerabilities can be categorised by severity level based on their impact. Generally, there are four levels of vulnerabilities: critical, high, medium, and low severity. Critical vulnerabilities involve catastrophic system failures, often triggered by low-probability but high-consequence events or cascading climate tipping points. Examples include flooded transport systems and energy grid collapses, which can result in widespread disruption and societal impacts (Hallegatte et al., 2013). High-severity vulnerabilities lead to significant disruptions caused by extreme weather events, sea-level rise, and coastal erosion. These events can result in water shortages and thermal damage to infrastructure, posing substantial challenges to urban resilience (Aboulnaga et al., 2019; Proag, 2021). Medium and low vulnerabilities can be grouped and have more localised and incremental impacts, such as urban heat islands and overwhelmed stormwater systems. While these impacts are less severe, they still strain infrastructure and require adaptive measures to mitigate their effects (Dong et al., 2020; Proag, 2021). The classification underscores the need for targeted strategies to address vulnerabilities at different levels of severity.

Table 2. Severity levels of vulnerabilities.

Severity Level	Impact	Examples	Source
Critical	Catastrophic system failure	Low-risk, high-consequence events, with cascading climate tipping points: flooded transport systems, energy grid collapse	Hallegatte et al. (2013)
High	Significant disruption	Extreme weather events, sea level rise, and coastal erosion: water shortages, thermal damage to infrastructure	Aboulnaga et al. (2019); Proag (2021)
Medium/moderate and low	Moderate or minor localised impact and manageable disruptions	Incremental climate variations: urban heat islands, localised flooding and drought, and overwhelmed stormwater systems	Dong et al. (2020); Proag (2021)

4.2. Sectoral Analysis of Vulnerabilities

4.2.1. Water Systems

Water infrastructure systems—including dams, reservoirs, pipelines, treatment plants, and distribution networks—are fundamental to ensuring water security, safeguarding public health, and supporting economic stability. However, climate change is intensifying vulnerabilities within these systems, threatening their reliability and performance. Rising incidences of floods and droughts have profound impacts: Flooding can

damage critical infrastructure such as dams and levees, while droughts diminish surface and groundwater availability, placing significant stress on water supply systems, especially in urban areas with limited adaptive capacity (Dong et al., 2020; Wei, 2024). Coastal infrastructure is particularly vulnerable to sea level rise, storm surges, and saltwater intrusion, all of which compromise water quality and underscore the need for climate-resilient infrastructure designs (Nicholls & Cazenave, 2010; Pal et al., 2023). Rising temperatures further exacerbate water system stress by increasing demand and degrading water quality through algal blooms and microbial contamination, complicating treatment processes (Whitehead et al., 2009). Many existing systems, often designed for historical climate patterns, are ageing and ill-equipped to withstand contemporary climate extremes, necessitating urgent modernisation and resilience-focused upgrades (Gleick, 2010). Hydropower systems, which depend on steady water flows, are also at risk. Reduced precipitation can limit energy generation capacity, while extreme weather events pose physical threats to infrastructure integrity (Kumar et al., 2011).

In the Global South, the severity of such vulnerabilities ranges from high to critical. For instance, Mumbai experienced catastrophic flooding in 2005, Chennai in 2022 (“Mumbai under water,” 2005; “Severe flooding in Chennai,” 2022), Cape Town faced severe drought and water scarcity in 2017 (Cassim, 2018), and KwaZulu-Natal suffered major flood-related damage in 2022 (PreventionWeb, 2023). To address these challenges, key interventions include the deployment of advanced water recycling systems that repurpose treated wastewater for potable and non-potable uses, employing membrane filtration and UV disinfection to enhance water self-sufficiency. During severe droughts, strategies such as water conservation, demand-side management, and rainwater harvesting have proven effective in mitigating scarcity (Devaisy et al., 2023; Movva, 2024; Stankiewicz et al., 2023).

4.2.2. Energy Systems

Climate change has profound implications for energy infrastructure systems, undermining their reliability, efficiency, and security through both direct and indirect impacts associated with extreme weather events and long-term climatic changes. Extreme events—such as heatwaves, storms, and floods—can severely damage power plants, transmission lines, and substations. Flooding, for instance, may submerge critical components, causing widespread outages and costly repairs (Panteli & Mancarella, 2015), while heatwaves reduce the transmission capacity of power lines and heighten the risk of blackouts (Schaeffer et al., 2012). Rising global temperatures increase cooling demands, placing additional stress on energy systems and decreasing the performance of renewable technologies such as solar panels and wind turbines (van Vliet et al., 2016). Water-related risks also jeopardise the operation of thermal and nuclear power plants, as droughts and reduced river flows impair cooling processes. Notably, nearly 40% of thermal power plants are located in water-stressed regions (Byers et al., 2014). Coastal energy infrastructure is particularly exposed to sea-level rise and storm surges, while shifts in wind patterns, solar radiation, and precipitation reduce the reliability of wind, solar, and hydropower generation.

Much of the existing infrastructure, built for past climate norms, is ageing and poorly equipped to handle these new extremes, resulting in escalating maintenance costs and diminished resilience (Sovacool, 2011). Moreover, climate change indirectly increases overall energy demand, exacerbates security risks, and heightens cybersecurity vulnerabilities, emphasizing the need for integrated and adaptive resilience strategies in future energy systems (Cherdantseva et al., 2016; Mohsin et al., 2024).

Energy access remains a critical issue, particularly in peri-urban areas where infrastructure is less developed than in urban centres (Singh et al., 2015; Smith et al., 2022). While urban populations often benefit from robust electricity grids and renewable energy integration, rural and peri-urban communities continue to rely on costly and polluting energy sources such as kerosene and biomass. This disparity highlights the urgency of targeted interventions, including the deployment of off-grid solar systems and microgrids, to enhance energy access, promote equity, and reduce emissions.

4.2.3. Transport Systems

Transport infrastructure—including roads, railways, airports, and ports—is critical to economic development and societal well-being, but is increasingly vulnerable to climate change. Flooding remains one of the most severe threats, causing structural damage, erosion, and service disruptions. The 2011 floods in Thailand, for instance, significantly damaged highways and railways, disrupting supply chains and economic activities (Haraguchi & Lall, 2015). Coastal infrastructure faces additional risks from rising sea levels and storm surges (Lane-Visser & Vanderschuren, 2024).

Extreme temperatures pose further challenges by softening asphalt, buckling rail tracks, and increasing maintenance costs (Chapman, 2007). Heatwaves also affect air travel by reducing aircraft lift and payload capacity (Coffel et al., 2017). Heavy rainfall can trigger landslides and road washouts, while droughts compromise soil stability, undermining infrastructure integrity (Wang et al., 2024). Sea-level rise threatens ports and coastal airports (Yesudian & Dawson, 2021). Cyclone Idai in 2019, for example, devastated transport infrastructure in Mozambique, particularly in Beira, highlighting the vulnerability of the Global South to extreme storms.

Ageing infrastructure, often designed for historical climate conditions, lacks the resilience to cope with current and projected climate stresses (Rising et al., 2022). Addressing these vulnerabilities requires innovative, climate-resilient interventions. Elevated railways offer improved flood resilience and reduce congestion, while climate-proof urban metros incorporate flood barriers and durable materials. Expanding bicycle infrastructure promotes sustainable, low-emission mobility, and the adoption of electric buses, especially when integrated with renewable energy, reduces air pollution and greenhouse gas emissions (Amdal et al., 2017; Singla, 2024). Thus, strengthening the climate resilience of transport systems is essential for sustainable development, especially in the Global South, where infrastructure gaps and exposure to extreme weather events are more pronounced.

4.3. Cross-Cutting Challenges

4.3.1. Socio-Economic Inequalities and Rapid Urbanisation

Climate change disproportionately affects marginalised and low-income communities across infrastructure systems, deepening existing social and economic inequalities. In energy infrastructure, these populations are more likely to experience prolonged outages and have limited access to adaptive technologies and reliable energy sources (Simcock et al., 2017). Similarly, climate-induced disruptions to water infrastructure increase vulnerability among these groups, who often face greater exposure to service interruptions and water scarcity due to inadequate adaptive capacity (Srinivasan et al., 2017). Transport infrastructure also presents

significant challenges. Marginalised communities typically rely on public transportation, which is more vulnerable to extreme weather events. The absence of alternative transport options further exacerbates social inequities, highlighting the urgency of inclusive and resilient transport planning (Cinderby et al., 2024).

To address these disparities, inclusive infrastructure planning is essential. This involves actively engaging marginalised groups in decision-making, prioritising equity-focused investments, ensuring affordability and accessibility, and using disaggregated data to guide and evaluate interventions. Such an approach ensures that resilience measures are tailored to the specific needs of vulnerable populations, promoting more just and sustainable outcomes (Cinderby et al., 2024).

4.3.2. Governance and Policy Gaps

Addressing urban infrastructure vulnerabilities requires integrated governance, firm policies, and community engagement, yet significant gaps hinder effective resilience implementation. Governance challenges stem from fragmented approaches to interconnected systems like energy, transport, and water, with delayed initiatives due to poor communication and coordination between local and national governments. Centralised decision-making in the Global South limits local strategies, making decentralisation, capacity building, and resource allocation essential (Aylett, 2015; Leck & Simon, 2013; Tanner et al., 2009). Transparent governance and robust monitoring mechanisms are crucial for accountability, but institutional barriers impede cross-sector collaboration.

Policy gaps further confound resilience efforts, with short-term development priorities often sidelining long-term adaptation. Inclusive policies addressing socioeconomic vulnerabilities are critical (Carmin et al., 2012; Greenwalt et al., 2018). Limited data and financial resources hinder effective planning, emphasising the need for investment in urban big data and computational tools (Rosenzweig et al., 2018). However, arguments have been made to meet the challenges that smart infrastructure standards should be adapted to local contexts and supported by technology transfer (Nguyen et al., 2024). Similarly, social considerations, including intersectionality and participatory approaches, would likely ensure marginalised communities are included and enhance resilience strategies (Greenwalt et al., 2018; Sitas et al., 2021).

5. Case Study Analyses

5.1. Case Study 1: India

Table 3 presents the climate-linked natural disasters and their impact on urban infrastructure. It exposes vulnerabilities exacerbated by rising temperatures, frequent floods, and cyclones in cities like Chennai, Mumbai, Delhi, and Cuttack (Revi & Satterthwaite, 2014). Ageing infrastructure, such as outdated drainage systems and overburdened transportation networks, undermines urban resilience, while social inequities disproportionately affect marginalised communities during disasters (Sharma & Tomar, 2010).

To address these challenges, India has adopted multiple strategies (Gupta, 2020). Climate-resilient infrastructure initiatives include Ahmedabad's Heat Action Plan and Odisha's cyclone shelters. Green and blue infrastructure, such as Kolkata's East Kolkata Wetlands and urban forests, enhances ecological resilience (Pasi, 2014). Integrated water management practices, like Chennai's rainwater harvesting

mandates, improve sustainability (Sharma & Tomar, 2010) and smart city programs leverage digital technologies, as seen in Delhi's smart grids and e-governance systems. Infrastructure upgrades are driven by public-private partnerships (PPPs) and policy reforms under programs like the Atal Mission for Rejuvenation and Urban Transformation and the Smart Cities Mission (National Institute of Urban Affairs, 2021). Renewable energy projects, including Gujarat's solar rooftops and Rajasthan's wind farms, further advance sustainability goals (Revi & Satterthwaite, 2014).

Table 3. Severity impact of climate-linked natural events on urban infrastructure in India.

Year	Place	Type of Event	Severity	Major Infrastructure Impacted	Impact on Infrastructure
1999	Odisha	Super cyclone	Critical	Transportation and energy	Destroyed nearly 1.6 million homes, caused power outages, and disrupted communication networks
2005	Mumbai, Maharashtra	Flood	Critical	Transportation	Overwhelmed drainage systems, submerged roads, disrupted rail and air traffic, and caused significant damage to homes and businesses
2008	Cuttack, Odisha	Flood	High	Transportation and water	Submerged low-lying areas, damaged houses, and disrupted local transportation and water supply systems
2013	Kedarnath, Uttarakhand	Flood and landslides	Critical	Transportation and buildings	Destroyed roads, bridges, and homes, disrupted pilgrimage routes, and caused severe transportation challenges
2022	Chennai, Tamil Nadu	Flood	Critical	Transportation, water and energy	Submerged large parts of the city, disrupted transportation, and caused extensive damage to homes, roads, and public utilities, with losses estimated at \$3 billion
2020	West Bengal, Odisha	Cyclone Amphan	High	Transportation, water, and energy	Damaged power lines, uprooted trees, and caused significant destruction to homes and public infrastructure, with losses estimated at \$13.4 billion
2024	Bengaluru, Karnataka	Flood	High	Transportation	Flooded urban areas, submerged roads, disrupted public transport, and renewed concerns about unplanned urban expansion
2024	Delhi	Heatwave and flood	High	Transportation	Caused airport roof collapse, metro station closures, flight cancellations, and significant damage to public and private infrastructure.

Sources: Indo-Asian News Service (2008), Sayeed (2022), "At 52.9°C, Delhi's Mungeshpur records" (2024), "Here is what happened" (2018), "Severe flooding in Chennai" (2022), "Mumbai under water" (2005), "Cyclone Amphan at 165 kmph" (2020), UN Disaster Management Team (1999).

5.2. Case Study 2: South Africa

Table 4 highlights the climate-linked natural disasters and their impact on urban infrastructure in South Africa. Extreme weather events such as droughts, floods, and rising temperatures have significantly affected cities like Cape Town, Durban, and Johannesburg (Ziervogel et al., 2014).

To address these challenges, South Africa has implemented various climate adaptation strategies. Cape Town's water strategy, developed after the 2018 Day Zero crisis, includes desalination, groundwater extraction, and water reuse to ensure water security (Enqvist & Ziervogel, 2019). Durban's eThekweni Municipality employs ecosystem-based adaptation, such as the Buffelsdraai Landfill Site Community Reforestation Project, which enhances flood resilience, restores ecosystems, and creates jobs (Roberts et al., 2012). Green infrastructure, including urban wetlands, permeable pavements, and green roofs, helps manage stormwater and reduce urban heat islands.

Energy resilience is promoted through the Renewable Energy Independent Power Producer Procurement Programme, which integrates renewable energy into urban grids, reducing coal dependency and improving energy security (Montmasson-Clair, 2020). Urban governance reforms, such as the integrated urban development framework, support climate-resilient planning and equitable service delivery. PPPs, like the Gautrain rapid rail system, enhance sustainable transportation, reducing carbon emissions and congestion.

Table 4. Severity impact of climate-linked natural events on urban infrastructure in South Africa.

Year	Place	Type of Event	Severity	Major Infrastructure Impacted	Impact on Infrastructure
2015–2023	Northern Cape (Karoo region)	Drought	High	Water	The drought reshaped community identity and priorities, fostering a deeper connection to the environment and community
2018	Cape Town	Water crisis	Critical	Water	Cape Town faced the prospect of becoming the first major city to run out of water
2022	KwaZulu-Natal	Floods and landslides	Critical	Transportation, energy, and water	The disaster resulted in the deaths of at least 459 people and destroyed more than 12,000 houses. It severely damaged infrastructure, including roads, health centres, and schools.
2024	New Castle and Utrecht, Eastern Cape, KwaZulu-Natal	Storm complex	High	Transportation and buildings	It damaged over 7,000 houses, caused power outages, and caused significant damage to roads and bridges. The total damage was estimated at US \$344 million
2024–2025	Johannesburg	Water crisis	High	Water	Johannesburg experienced severe water crises, with supply cuts lasting up to 86 hours

Sources: Cassim (2018), Coleman (2017), International Federation of Red Cross and Red Crescent Societies (2024), PreventionWeb (2023), Ntisa (2024).

5.3. Insights From the Case Studies

India and South Africa face significant climate-linked natural disasters, such as floods, droughts, rising temperatures, and cyclones, which expose vulnerabilities in urban infrastructure as seen from cities like Chennai, Mumbai, Delhi, Cuttack, Cape Town, Durban, and Johannesburg. Social inequities also

disproportionately affect marginalised communities during such disasters, underscoring the need for more inclusive and adaptive solutions.

In response, both countries have adopted strategies to build climate-resilient infrastructure. India's initiatives include climate-resilient infrastructure projects, a Heat Action Plan, cyclone shelters, and green and blue infrastructure. Similarly, South Africa has implemented ecosystem-based adaptation and integrated water management practices, such as desalination and groundwater extraction. Both countries focus on smart city initiatives, green infrastructure, renewable energy projects, and PPPs to enhance sustainability and resilience.

6. Strategies for Building Resilient and Sustainable Infrastructure

Addressing the challenges of urban infrastructure vulnerabilities because of climate change in the Global South requires well-designed and balanced strategic interventions.

Resilient and sustainable urban infrastructure in the Global South is essential due to climate change-related vulnerabilities. Rapid urbanisation, socio-economic disparities, and environmental risks present unique challenges. While there is agreement on the need for resilience, differing viewpoints exist on how to achieve it, particularly regarding the balance between resilience and sustainability, community engagement, and the role of innovative technologies (Oloke et al., 2021). Effective strategies must consider the socio-economic and political contexts (Chu et al., 2017; Greenwalt et al., 2018; Oates & Sudmant, 2024). Smart technologies, such as early warning systems and data analytics, offer potential for enhancing resilience but face challenges in the Global South, including limited resources and technical capacity. Moreover, technology-driven solutions may overlook underlying socio-economic and environmental issues (Osheyor et al., 2024). Tailored solutions that integrate community perspectives and innovative technologies are necessary for equitable and sustainable outcomes. Based on the balanced viewpoints, findings from literature, and case study analyses, the following strategies foster resilient and sustainable urban infrastructure.

6.1. Governance Reforms

Strengthening institutions and decision-making processes is crucial for building resilient and sustainable infrastructure in the Global South to address climate change impacts. In this context, governance reforms, including decentralisation, resource allocation, and technical training, empower local governments to implement context-specific strategies (Aylett, 2015; Tanner et al., 2009). Integrating resilience into urban planning and aligning policies across levels ensures coherent action (Carmin et al., 2012; Leck & Simon, 2013). Data-driven decision-making would enable targeted interventions, and participatory governance would engage marginalised communities, enhancing inclusivity (Georgios & Abdolrasoul, 2024; Rosenzweig et al., 2018). Innovative financing mechanisms and robust regulatory frameworks further strengthen resilience and sustainability (Fankhauser & McDermott, 2014; Lawrence et al., 2018). Governance reforms also play a critical role in ensuring the long-term servicing and financing of infrastructure by clarifying institutional responsibilities, enhancing intergovernmental coordination, and promoting transparency. Tools such as fiscal decentralisation, performance-based budgeting, and PPPs help make infrastructure investments more financially sustainable and adaptive to evolving urban challenges.

6.2. Climate-Resilient Design and Retrofitting

Climate-resilient design and retrofitting are essential for addressing climate change challenges in the Global South, where rapid urbanisation and vulnerability require tailored solutions. Innovative architectural and engineering approaches enhance infrastructure durability and adaptability, with smart technologies improving energy efficiency despite cybersecurity risks (Rasheed et al., 2024). For example, renewable energy systems, like solar panels, reduce carbon footprints despite varying effectiveness across climatic zones (Rasheed et al., 2024). Resilient design for affordable housing enhances flood resistance and disaster preparedness (Adeyemi et al., 2024) and sustainable practices and low-emission materials ensure environmental balance (Hifza & Tariq, 2023). Integrating climate data into planning, geographic information systems-based frameworks, and adaptive measures tailored to local conditions supports resilience and sustainability (Buhl & Markolf, 2022; D'Ambrosio et al., 2023).

6.3. Technological Innovations and Nature-Based Solutions

The integration of smart technologies and nature-based solutions is crucial for resilient and sustainable infrastructure to address climate change. Smart technologies like machine learning and the Internet of Things enable real-time monitoring, predictive analytics, and energy optimisation, enhancing resilience (Rajendran et al., 2025). Nature-based solutions, such as green infrastructure and sustainable urban drainage systems, provide ecosystem services for stormwater management and climate adaptation (Aghaloo et al., 2024). Blue/green infrastructures, including wetlands and parks, mitigate urban heat islands, reduce floods, and boost biodiversity (Hassan et al., 2023). Combining nature-based solutions with traditional infrastructure fosters sustainability, though challenges like financial constraints and social equity must be addressed (Prado et al., 2024; Yilmaz, 2023).

6.4. Strengthening PPPs

PPPs are essential for building sustainable and resilient infrastructure by leveraging the strengths of both the public and private sectors to address climate change. Strategies such as wastewater treatment plants and nature-based solutions have significantly reduced flood risks in Singapore (30%) and Thailand (25%), while Malaysia's networks have prevented 85% of contamination during extreme weather events (Goh et al., 2024). Public-private-people partnerships further enhance inclusivity by involving local communities, with legal frameworks and monitoring mechanisms ensuring accountability (Leshinka et al., 2023).

Financial incentives, such as tax credits, attract investment in renewable energy, aligning PPPs with sustainable development goals (Ugwu et al., 2024). In low-income settings, micro-finance institutions and community-based businesses can act as private partners, funding small-scale projects and delivering essential local services (Putri et al., 2025; Ritchie, 2010). Their participation fosters community ownership, expands stakeholder engagement, and ensures that infrastructure solutions are tailored to local needs.

6.5. Community-Based Solutions

Engaging local stakeholders and fostering inclusivity is essential for developing sustainable, resilient infrastructure in the face of climate change. Participatory processes integrate local knowledge through

storytelling and mapping, particularly in smaller cities and rural areas (Eisenhauer et al., 2024). Green infrastructure projects benefit from socioeconomic studies and effective communication channels to involve communities (Mason et al., 2024). Asset-based community development empowers informal settlements by leveraging local resources (Appau et al., 2024). Social capital, including community networks, strengthens resilience (Wambura, 2024). Respecting cultural practices and addressing barriers like resource constraints and language challenges unlocks community-based climate resilience solutions (Haque et al., 2022).

6.6. Capacity-Building Initiatives: Enhancing Local Governments' Technical and Financial Capacities

Enhancing local governments' technical and financial capacities is crucial for sustainable, resilient infrastructure to address climate change. Policies integrating scientific research and local conditions can guide adaptation strategies, leveraging technology to build disaster-resistant infrastructure (Situmorang et al., 2024; Warouw et al., 2023). Active community participation ensures locally relevant measures, while education fosters awareness and sustainability (Situmorang et al., 2024). Cross-regional collaboration enhances knowledge sharing, addressing bureaucratic and resource constraints (Shah, 2024). Training programs address skill gaps, improving governance and adaptation strategies (Perney & D'Angelo, 2023).

7. Discussions and Implications

Urban infrastructure in the Global South faces significant vulnerabilities exacerbated by climate change, necessitating urgent adaptation strategies for resilience and sustainability. Extreme weather events such as flooding, droughts, and rising temperatures disrupt essential services like water, energy, and transportation, which are already strained by socio-economic inequalities and infrastructure deficits (Parnell & Oldfield, 2014). While research on urban resilience is growing, studies addressing the specific challenges of the Global South remain limited, particularly regarding infrastructure ill-equipped to handle new climate stressors (Tyler & Moench, 2012). Many proposed solutions focus on short-term fixes, overlooking the need for scalable, sustainable strategies (Schlosberg et al., 2017). Integrating climate justice into urban planning is also inadequate, leaving marginalized communities vulnerable to climate impacts (Srinivasan et al., 2017). The literature emphasises the need for a nuanced approach to urban infrastructure vulnerabilities, especially in water, energy, and transportation sectors (Dixit, 2024; Langendijk et al., 2024).

To address these challenges, the study of urban resilience must focus on identifying critical infrastructure vulnerabilities and developing context-specific, sustainable strategies. Water systems in cities like Mumbai and Cape Town are increasingly vulnerable to climate-induced disruptions, such as flooding and droughts, requiring climate-resilient designs and retrofitting (Dong et al., 2020; Wei, 2024). Energy infrastructure is similarly at risk, exacerbating energy insecurity, especially in low-income communities (Panteli & Mancarella, 2015; Schaeffer et al., 2012). Transportation infrastructure, particularly in coastal areas, faces threats from rising sea levels and extreme storms (Lane-Visser & Vanderschuren, 2024). These vulnerabilities disproportionately affect marginalized populations, exacerbating social inequities (Simcock et al., 2017).

Infrastructure development involves multiple actors: national governments, local authorities, the private sector, civil society organisations, and international agencies. Governments set policies and regulations, while local authorities oversee implementation but often face capacity gaps (Tanner et al., 2009). The private sector brings innovation but may prioritise profit over equitable access (Leshinka et al., 2023). Civil society

organisations ensure marginalised voices are included (Rosenzweig et al., 2018), and international agencies provide financial support, although often limited by local dynamics (Fankhauser & McDermott, 2014).

Capacity gaps in project management and financial oversight hinder effective local governance (Cinderby et al., 2024). A multi-actor approach is essential for inclusive and sustainable infrastructure development (Carmin et al., 2012). This approach must address power imbalances and ensure marginalised groups benefit from infrastructure improvements (Leck & Simon, 2013). Successful collaboration requires capacity building, improved governance, and enhanced accountability (Lv & Sarker, 2024).

Figure 5 presents a strategic framework for overcoming these challenges, including robust governance frameworks for effective coordination (Aylett, 2015; Tanner et al., 2009). Decentralised decision-making and participatory governance are essential (Aylett, 2015; Tanner et al., 2009), but local governments in the Global South face constraints. Smart technologies like the Internet of Things and machine learning can enhance resilience through real-time monitoring and predictive analytics (Rajendran et al., 2025). Nature-based solutions, such as green infrastructure, provide sustainable solutions for managing climate risks (Aghaloo et al., 2024). These solutions must be paired with inclusive governance to ensure marginalized communities participate, fostering local resilience (Eisenhauer et al., 2024; Wambura, 2024).



Figure 5. Strategic framework for sustainable and resilient infrastructure.

Critical implications include enhancing the technical and financial capacities of local governments, promoting cross-regional collaboration, and prioritizing community engagement to develop resilient and sustainable infrastructure in the Global South. As climate change intensifies vulnerabilities, adopting long-term, context-specific resilience strategies is crucial to safeguard urban systems (Situmorang et al., 2024; Warouw et al., 2023).

Policymakers and urban planners must focus on strengthening governance by building local governments' technical and financial capacities (Aylett, 2015; Fankhauser & McDermott, 2014; Lawrence et al., 2018), integrating smart technologies for enhanced resilience (Rajendran et al., 2025), prioritising nature-based solutions for climate risk management (Aghaloo et al., 2024), and promoting multi-actor collaboration (Carmin et al., 2012). Community engagement is crucial to building social capital and enhancing collective resilience (Eisenhauer et al., 2024). Urban planning should incorporate long-term, context-specific strategies, retrofitting existing infrastructure to withstand climate risks (Dong et al., 2020; Wei, 2024). Integrating climate justice into urban planning is essential for ensuring equitable access to resilient infrastructure for vulnerable groups (Srinivasan et al., 2017). By prioritizing these strategies, urban planners can create infrastructure better equipped to handle climate change impacts in the Global South.

8. Conclusion

In response to the impact of climate change on urban infrastructure, this study examined the key vulnerabilities within the Global South, focusing on water, energy, and road transportation systems. It also identified sustainable strategies for mitigating these vulnerabilities and fostering resilient infrastructure systems capable of addressing climate change challenges. Urban infrastructure in the Global South is found to be highly vulnerable to climate change impacts, including extreme weather events such as flooding, droughts, and rising temperatures. These disruptions are further exacerbated by socioeconomic inequalities and infrastructure deficits, highlighting the urgent need for effective adaptation strategies. Key strategies for addressing these challenges include robust governance systems to address policy gaps, climate-resilient design and retrofitting, technological innovations, nature-based solutions, and enhancing the technical and financial capacities of local governments. Community-based solutions and strengthening PPPs are also critical to enabling resilient and sustainable infrastructure in the face of climate change impacts in the Global South.

However, the study has limitations. It is based on a qualitative approach, consisting of a literature review and case study analyses, which lack empirical validation. Despite these limitations, the study contributes significantly by identifying critical urban infrastructure vulnerabilities and proposing relevant strategies to alleviate these vulnerabilities, specifically within the context of the Global South.

Future research on urban infrastructure resilience in the Global South should focus on integrating AI and machine learning for predictive modelling and real-time monitoring, improving the efficiency and adaptability of urban systems. Furthermore, studies into nature-based solutions, their scalability, and cost-effectiveness in diverse urban settings may be explored. Climate-resilient infrastructure designs should be developed, particularly for retrofitting existing systems to handle extreme weather events. Moreover, exploring decentralised, participatory governance models will be key for ensuring inclusive, context-specific adaptation strategies. These areas of the studies are likely to help build long-term, sustainable urban resilience in the face of climate change.

Conflict of Interests

The author declares no conflict of interests.

LLMs Disclosure

Tools such as Spispace for literature search and ChatGPT were used for improving the clarity of the text.

References

- Aboulnaga, M. M., Elwan, A. F., & Elsharouny, M. R. (2019). *Urban climate change adaptation in developing countries: Policies, projects, and scenarios*. Springer.
- Adams, R., Jeanrenaud, S., Bessant, J., Overly, P., & Denyer, D. (2012). *Innovating for sustainability: A systematic review of the body of knowledge*. Network for Business Sustainability.
- Adeyemi, A. B., Ohakawa, T. C., Okwandu, A. C., Iwuanyanwu, O., & Ifechukwu, G. (2024). Affordable housing and resilient design: Preparing low-income housing for climate change impacts. *International Journal of Applied Research in Social Sciences*, 6(9), 2179–2190. <https://doi.org/10.51594/ijarss.v6i9.1585>
- Aghaloo, K., Sharifi, A., Habibzadeh, N., Ali, T., & Chiu, Y. (2024). How nature-based solutions can enhance urban resilience to flooding and climate change and provide other co-benefits: A systematic review and taxonomy. *Urban Forestry and Urban Greening*, 95, Article 128320. <https://doi.org/10.1016/j.ufug.2024.128320>
- Akther, S., & Evans, J. (2024). Emerging attributes of adaptive governance in the global south. *Frontiers in Environmental Science*, 12, Article 1372157. <https://doi.org/10.3389/fenvs.2024.1372157>
- Amdal, J., Ankner, W., Callahan, T., Carnegie, J. A., Voorhies, A. M., MacLachlan, J., Berger, L., Matherly, D., Mobley, J., Peterson, E., Renne, J., Schwab, J., Venner, M., Veraart, N., Whytlaw, R., & Wolshon, B. (2017). Improving the Resilience of Transit Systems Threatened by Natural Disasters, Volume 3: Literature Review and Case Studies. *Transportation Research Board*. <https://doi.org/10.17226/24972>
- Angelovski, I., Chu, E., & Carmin, J. (2014). Variations in approaches to urban climate adaptation: Experiences and governance challenges in the Global South. *Global Environmental Change*, 27, 156–167. <https://doi.org/10.1016/j.gloenvcha.2014.05.010>
- Appau, P. K., Asibey, M. O., & Grant, R. (2024). Enabling asset-based community development solutions: Pro-poor urban climate resilience in Kumasi, Ghana. *Cities*, 145, Article 104723. <https://doi.org/10.1016/j.cities.2023.104723>
- At 52.9°C, Delhi's Mungeshpur records the highest-ever temperature amid severe heatwave. (2024, May 31). *The Hindu*. https://www.thehindu.com/news/cities/Delhi/delhi-records-highest-ever-temperature-amid-severe-heatwave/article68228346.ece?utm_source=chatgpt.com
- Aylett, A. (2015). Institutionalising the urban governance of climate change adaptation: Results of an international survey. *Urban Climate*, 14, 4–16.
- Boas, I., Gautam, A., & Olayiwola, A. (2023). Climate change and human mobility in the Global South. In H. Crawley & J. K. Teye (Eds.), *The Palgrave handbook of South-South migration and inequality* (pp. 435–453). Palgrave Macmillan. https://doi.org/10.1007/978-3-031-39814-8_20
- Buhl, M., & Markolf, S. (2022). A review of emerging strategies for incorporating climate change considerations into infrastructure planning, design, and decision-making. *Sustainable and Resilient Infrastructure*, 8(Sup1), 157–169. <https://doi.org/10.1080/23789689.2022.2134646>
- Bulkeley, H., & Betsill, M. M. (2013). Revisiting the urban politics of climate change. *Environmental Politics*, 22(1), 136–154. <https://doi.org/10.1080/09644016.2013.755797>
- Byers, E., Hall, J. W., & Amezaga, J. M. (2014). Electricity generation and cooling water use: UK pathways to 2050. *Global Environmental Change*, 25, 16–30.
- Cao, H. (2023). Urban resilience: Concept, influencing factors and improvement. *Frontiers in Business, Economics and Management*, 9(1), 343–346. <https://doi.org/10.54097/fbem.v9i1.8777>

- Carmin, J., Nadkarni, N., & Rhie, C. (2012). *Progress and challenges in urban climate adaptation planning: Results of a global survey*. MIT.
- Cassim, Z. (2018, January 19). Cape Town could be the first major city in the world to run out of water. *USA Today*. <https://www.usatoday.com/story/news/world/2018/01/19/cape-town-could-first-major-city-run-out-water/1047237001>
- Chapman, L. (2007). Transport and climate change: a review. *Journal of Transport Geography*, 15(5), 354–367. <https://doi.org/10.1016/j.jtrangeo.2006.11.008>
- Chen, Q. L. (2024). The intersection of global inequality and climate change. *International Journal of Education and Humanities*, 15(2), 378–381. <https://doi.org/10.54097/3s08zx60>
- Cherdantseva, Y., Burnap, P., Blyth, A., Eden, P., Jones, K., Soulsby, H., & Stoddart, K. (2016). A review of cybersecurity risk assessment methods for SCADA systems. *Computers & Security*, 56, 1–27. <https://doi.org/10.1016/j.cose.2015.09.009>
- Chirambo, D. (2022). Improving climate change resilience in Global South cities through South-South climate finance. In Information Resources Management Association (Ed.), *Research anthology on environmental and societal impacts of climate change* (pp. 440–448). IGI Global. <https://doi.org/10.4018/978-1-6684-3686-8.ch022>
- Chu, E., Anguelovski, I., & Roberts, D. (2017). Climate adaptation as strategic urbanism: Assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities*, 60(Part A), 378–387. <https://doi.org/10.1016/j.cities.2016.10.016>
- Cinderby, S., Haq, G., Opiyo, R., Muhoza, C., Ngabirano, A., Wasike, Y., Mwamba, D., & Cambridge, H. (2024). Inclusive climate-resilient transport challenges in Africa. *Cities*, 146, Article 104740. <https://doi.org/10.1016/j.cities.2023.104740>
- Coffel, E. D., Thompson, T. R., & Horton, R. M. (2017). The impacts of rising temperatures on aircraft takeoff performance. *Climatic Change*, 144(2), 381–388. <https://doi.org/10.1007/s10584-017-2018-9>
- Coleman, A. (2017, November 28). Drought-stricken Northern Cape farmers reducing herds. *farmer's weekly*. https://www.farmersweekly.co.za/agri-news/south-africa/drought-stricken-northern-cape-farmers-reducing-herds/?utm_source=chatgpt.com4:27pm
- Creswell, J. W., & Poth, C. N. (2017). *Qualitative inquiry and research design: Choosing among five approaches* (4th ed.). Sage.
- Cyclone Amphan at 165 kmph slays a dozen in West Bengal. (2020, May 21). *Times of India*. <https://timesofindia.indiatimes.com/city/kolkata/monster165kmph-slays-a-dozen/articleshow/75857041.cms>
- D'Ambrosio, V., Di Martino, F., & Tersigni, E. (2023). Towards climate resilience of the built environment: A GIS-based framework for the assessment of climate-proof design solutions for buildings. *Buildings*, 13(7), Article 1658. <https://doi.org/10.3390/buildings13071658>
- Denzin, N. K., & Lincoln, Y. S. (2011). *The Sage handbook of qualitative research* (4th ed.). Sage.
- Devaisy, S., Kandaswamy, J., Nguyen, T. V., Ratnaweera, H., & Vigneswaran, S. (2023). Membranes in water reclamation: Treatment, reuse and concentrate management. *Membranes*, 13(6), Article 605. <https://doi.org/10.3390/membranes13060605>
- Dharmarathne, G., Waduge, A. O., Bogahawaththa, M., Rathnayake, U., Meddage, D. (2024). Adapting cities to the surge: A comprehensive review of climate-induced urban flooding. *Results in Engineering*, 22, Article 102123. <https://doi.org/10.1016/j.rineng.2024.102123>
- Dias, R. (2024). *The complex interconnectedness of climate change and social inequality*. Seven Editora. <https://doi.org/10.56238/sevened2023.006>
- Dixit, D. (2024). Impact of climate change on infrastructure resilience and adaption strategies. *Indian Scientific Journal of Research in Engineering and Management*, 8(3). <https://doi.org/10.55041/ijrsrem29175>

- Dong, X., Jiang, L., Zeng, S., Guo, R., & Zeng, Y. (2020). Vulnerability of urban water infrastructures to climate change at city level. *Resources Conservation and Recycling*, 161, Article 104918. <https://doi.org/10.1016/J.RESCONREC.2020.104918>
- Dossa, K. F., & Miassi, Y. (2024). Urban planning and green infrastructure under a changing climate in Africa. *International Journal of Regional Development*, 11(1). <https://doi.org/10.5296/ijrd.v11i1.21694>
- Eisenhauer, E., Maxwell, K., Kiessling, B., Henson, S., Matsler, M., Nee, R., Shacklette, M., Fry, M., & Julius, S. (2024). Inclusive engagement for equitable resilience: Community case study insights. *Environmental research communications*, 6(12), Article 125012. <https://doi.org/10.1088/2515-7620/ad9242>
- El-Diraby, T. E., & Osman, H. (2011). A domain ontology for construction concepts in urban infrastructure products. *Automation Construction*, 20(8), 1120–1132. <https://doi.org/10.1016/j.autcon.2011.04.014>
- Enqvist, J. P., & Ziervogel, G. (2019). Water governance and justice in Cape Town: An overview of the drought crisis. *Wiley Interdisciplinary Reviews: Water*, 6(4), Article e1354.
- Fankhauser, S., & McDermott, T. (2014). Understanding the adaptation deficit: Why are poor countries more vulnerable to climate events than rich countries? *Global Environmental Change*, 27, 9–18. <https://doi.org/10.1016/j.gloenvcha.2014.04.014>
- Ferrer, A. L. C., Thomé, A. M. T., & Scavarda, A. J. (2018). Sustainable urban infrastructure: A review. *Resources, Conservation and Recycling*, 128, 360–372. <https://doi.org/10.1016/j.resconrec.2016.07.017>
- Garcia, L. (2024). Finance, the green transition and climate justice in the Global South. In J. Jäger & E. Dziwok (Eds.), *Understanding green finance* (pp. 147–158). Edward Elgar. <https://doi.org/10.4337/9781803927558.00020>
- Georgios, R., & Abdolrasoul, H. (2024). When participatory design meets data-driven decision making: A literature review and the way forward. *Management Science Letters*, 14, 107–126. <https://doi.org/10.5267/j.msl.2023.9.002>
- Gleick, P. H. (2010). Roadmap for sustainable water resources in southwestern North America. *Proceedings of the National Academy of Sciences*, 107(50), 21300–21305. <https://doi.org/10.1073/pnas.1005473107>
- Goh, K. C., Kurniawan, T. A., Goh, H. H., Zhang, D., Jiang, M., Dai, W., Khan, M. I., Othman, M. H. D., Aziz, F., Anouzla, A., & Meidiana, C. (2024). Strengthening infrastructure resilience for climate change mitigation: Case studies from the Southeast Asia region with a focus on wastewater treatment plants in addressing flooding challenges. *ACS ES&T water*, 4(9), 3725–3740. <https://doi.org/10.1021/acsestwater.4c00591>
- Greenwalt, J., Raasakka, N., & Alverson, K. (2018). Building urban resilience to address urbanization and climate change. In Z. Zommers & K. Alverson (Eds.), *Resilience: The science of adaptation to climate change* (pp. 151–164). Elsevier. <https://doi.org/10.1016/B978-0-12-811891-7.00012-8>
- Gupta, K. (2020). Challenges in developing urban flood resilience in India. *Philos Trans A Math Phil. Trans. R. Soc. A*, 378, Article 20190211. <https://doi.org/10.1098/rsta.2019.0211>
- Gürsan, C., de Gooyert, V., de Bruijne, M., & Rouwette, E. (2023). Socio-technical infrastructure interdependencies and their implications for urban sustainability; recent insights from the Netherlands. *Cities*, 140, Article 104397. <https://doi.org/10.1016/j.cities.2023.104397>
- Hallegatte, S., Green, C., Nicholls, R., & Corfee-Morlot, R. (2013). Future flood losses in major coastal cities. *Nature Clim Change*, 3, 802–806. <https://doi.org/10.1038/nclimate1979>
- Haque, A. K. E., Mukhopadhyay, P., Nepal, M., & Shammin, M. R. (2022). Communities, climate change adaptation and win-win solutions. In A. K. E. Haque, P. Mukhopadhyay, M. Nepal, M. R. Shammin (Eds.), *Climate change and community resilience* (pp. 445–454). Springer. https://doi.org/10.1007/978-981-16-0680-9_29
- Haraguchi, M., & Lall, U. (2015). Flood risks and impacts: A case study of Thailand's floods in 2011 and research

- questions for supply chain decision making. *International Journal of Disaster Risk Reduction*, 14(Part 3), 256–272. <https://doi.org/10.1016/j.ijdrr.2014.09.005>
- Hassan, Z., Shahbaz, B., & Lopez, F. G. (2023, Spetember 20–22). Enhancing blue/green infrastructure for resilient urban environments: Smart solutions and nature-based strategies. [Proceedings book] 3rd International Congress on Engineering and Life Science Proceedings Book, Tabzon, Turkey. <https://doi.org/10.61326/icelis.2023.18>
- Here is what happened in Kedarnath, and rest of Uttarakhand, in 2013. (2018, December 7). *The Indian Express*. https://indianexpress.com/article/research/here-is-what-happened-in-kedarnath-and-rest-of-uttarakhand-in-2013-5482050/?utm_source=chatgpt.com
- Hifza, E., & Tariq, H. (2023). Adaptive and sustainable design for building construction considering climate change. *Jurnal Kejuruteraan*, 35(6), 1513–1521.
- Hussainzad, E. A., & Gou, Z. (2024). Climate risk and vulnerability assessment in informal settlements of the Global South: A critical review. *Land*, 13(9), Article 1357. <https://doi.org/10.3390/land13091357>
- Ikonomova, M., & MacAskill, K. (2023). Climate change hazards, physical infrastructure systems and health pathways. *Environmental Research: Infrastructure and Sustainability*, 3(4), Article 045001. <https://doi.org/10.1088/2634-4505/acfabd>
- Indo-Asian News Service. (2008, September 19). Orissa floods: 7 dead, 1 million affected, worse to come. *India Today*. https://www.indiatoday.in/latest-headlines/story/orissa-floods-7-dead-1-million-affected-worse-to-come-30173-2008-09-19?utm_source=chatgpt.com
- Intergovernmental Panel on Climate Change. (2021). *Sixth assessment report: Impacts, adaptation, and vulnerability*.
- International Federation of Red Cross and Red Crescent Societies. (2024). ZAF: Complex emergency—Eastern Cape floods and KwaZulu-Natal Tornado. <https://go.ifrc.org/field-reports/17071>
- James, N. (2023). The effects of climate change on informal settlements. *Town and Regional Planning*, 82, 1–3. <https://doi.org/10.38140/trp.v82i.6616>
- Kapse, N., & Jangale, T. (2024). Resilience and sustainability through green infrastructure. *Journal of Recent Activities in Architectural Sciences*, 9(1), 6–17. <https://doi.org/10.46610/JoRAAS.2024.v09i01.002>
- Kumar, A., Schei, T., Ahenkorah, A., Rodriguez, R. C., Devernay, J., Freitas, M., Hall, D., Killingtveit, A., Liu, Z., Branche, E., Burkhardt, J., Descloux, S., Heath, G., Seelos, K., Morejon, C. D., & Krug, T. (2011). Hydropower. In O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. Von Stechow, & P. Matschoss, (Eds.), *Renewable energy sources and climate change mitigation: Special report of the intergovernmental panel on climate change* (pp. 437–496). Cambridge University Press.
- Lane-Visser, T. E., & Vanderschuren, M. (2024). A climate-impact-related transport infrastructure risk assessment for the City of Cape Town. *Journal of South African Institute of Civil Engineering*, 65(4). <https://doi.org/10.17159/2309-8775/2023/v65n4a5>
- Langendijk, G., McEvoy, S., Jeuken, A., & Haasnoot, M. (2024, April 14–19). Urban resilience through integrating adaptation, mitigation and sustainable development—A novel approach to operationalise climate-resilient development pathways [Paper presentation]. EGU General Assembly 2024, Vienna, Austria. <https://doi.org/10.5194/egusphere-egu24-18661>
- Lawrence, A., Joseph, N., Jae, L., & John, B. (2018). *Enhancing climate finance readiness: A review of selected investment frameworks as tools of multilevel governance*. Center for Energy and Environmental Policy. <https://doi.org/10.13140/RG.2.2.23219.73766>
- Leck, H., & Simon, D. (2013). Fostering multiscalar collaboration and co-operation for effective governance of climate change adaptation. *Urban Studies*, 50(6), 1221–1238.

- Leshinka, P. S., Tembo, M., & Mwanaumo, E. (2023). Role of public-private partnerships in developing sustainable cities: Framework, opportunities, mechanisms. *International Journal of Innovations and Interdisciplinary Research*, 1(1), 1–15. <https://doi.org/10.61108/ijir.v1i1.1>
- Li, Z., Zhonglei, Y., Chang, S., & Xiaojing, H. (2023). The evaluation and obstacle identification of urban infrastructure resilience in China. *Chinese Journal of Urban and Environmental Studies (CJUES)*, 11(3), 1–28. <https://doi.org/10.1142/S234574812350015x>
- Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritising climate change adaptation needs for food security in 2030. *Science*, 319(5863), 607–610.
- Lv, Y., & Sarker, M. N. I. (2024). Integrative approaches to urban resilience: Evaluating the efficacy of resilience strategies in mitigating climate change vulnerabilities. *Heliyon*, 10(6), Article e28191. <https://doi.org/10.1016/j.heliyon.2024.e28191>
- Mason, M. A. N., Ohueri, C. C., Azman, A., & Chan, M. (2024). Guidelines for facilitating stakeholders roles in community engagement in green social infrastructure development. *International Journal of Sustainable Construction Engineering and Technology*, 15(1), 1–14. <https://doi.org/10.30880/ijscet.2024.15.01.001>
- Mohsin, M., Kazmi, S. S., Imran, M., Rashid, J., & Abubakar, M. (2024). Fragile lines: Climate-security nexus on power transmission infrastructure. *Journal of Asian Development Studies*, 13(3), 1363–1379. <https://doi.org/10.62345/jads.2024.13.3.111>
- Mondal, D. (2024). Socio-economic impacts of climate change. *International Journal on Agricultural Sciences*, 15(2), 95–96. <https://doi.org/10.53390/ijas.2024.15203>
- Montmasson-Clair, G. (2020). *A case for renewable energy in South Africa's post-lockdown economic recovery stimulus package* (Policy Brief). Trade & Industrial Policy Strategies.
- Movva, S. S. (2024). Rainwater treatment and reuse using membrane technology. *Journal of Technology and Systems*, 6(2), 38–55. <https://doi.org/10.47941/jts.1816>
- Mumbai under water, city at a standstill. (2005, July 27). *Times of India*. <https://timesofindia.indiatimes.com/india/mumbai-under-water-city-at-a-standstill/articleshow/1183555.cms>
- National Institute of Urban Affairs. (2021). *Urban resilience framework for Indian cities*.
- Ngcamu, B. S. (2023). Climate change effects on vulnerable populations in the Global South: A systematic review. *Natural Hazards*, 118, 977–991. <https://doi.org/10.1007/s11069-023-06070-2>
- Nguyen, D. N., Usuda, Y., & Imamura, F. (2024). Gaps in and opportunities for disaster risk reduction in urban areas through international standardisation of smart community infrastructure. *Sustainability*, 16(21), Article 9586. <https://doi.org/10.3390/su16219586>
- Nicholls, R. J., & Cazenave, A. (2010). Sea-level rise and its impact on coastal zones. *Science*, 328(5985), 1517–1520. <https://doi.org/10.1126/science.1185782>
- Ntisa, N. (2024, December 31). Johannesburg water crisis 2025: What residents need to know. *Gauteng News*. <https://gauteng.news/2024/12/31/johannesburg-water-crisis-2025>
- Oates, L., & Sudmant, A. (2024). Infrastructure transitions in Southern cities: Organising urban service delivery for climate and development. *Urban Planning*, 12, Article 8302. <https://doi.org/10.17645/up.8302>
- Oloke, O., Oluwunmi, A., Oyeyemi, K. D., Ayedun, C. A., & Peter, N. (2021). Fire risk exposure and preparedness of peri-urban neighbourhoods in Ibadan, Oyo State, Nigeria. *IOP Conference Series: Earth and Environmental Science*, 655, Article 012079. <https://doi.org/10.1088/1755-1315/655/1/012079>
- Osheyor, J., Ezeigweneme, C., Daraojimba, C., Tula, O., Adegbite, A., & Gidiagba, J. (2024). A review of technological innovations and environmental impact mitigation. *World Journal of Advanced Research and Reviews*, 21, 75–082. <https://doi.org/10.30574/wjarr.2024.21.1.2687>
- Pal, I., Kumar, A., & Mukhopadhyay, A. (2023). Risks to coastal critical infrastructure from climate change.

- Annual Review of Environment and Resources*, 48, 681–712. <https://doi.org/10.1146/annurev-environ-112320-101903>
- Panteli, M., & Mancarella, P. (2015). The grid: Stronger, bigger, smarter? Presenting a conceptual framework of power system resilience. *IEEE Power and Energy Magazine*, 13(3), 58–66.
- Parnell, S., & Oldfield, S. (2014). (Eds.). *The Routledge handbook on cities of the Global South*. Routledge.
- Pasi, N. (2014). *Urban rainwater harvesting—Case studies from different agroclimatic regions*. Centre for Science and Environment.
- Patton, M. Q. (2002). *Qualitative research and evaluation methods* (3rd ed.). Sage.
- Pelling, M. (2011). *Adaptation to climate change: From resilience to transformation*. Routledge.
- Perney, M. E. P., & D'Angelo, G. (2023). Local governance support tools for disaster risk reduction and climate adaptation strategies: The EU contribution in the case study of the municipality of Naples. *Sustainability*, 15(15), Article 11716. <https://doi.org/10.3390/su151511716>
- Prado, H. A., Rodrigues, T., Stella, M., Kasecker, T., Vale, M. M., Scarano, F. B., & Pires, A. P. F. (2024). Designing nature to be a solution for climate change in cities: A meta-analytical review. *Science of The Total Environment*, 954, Article 176735. <https://doi.org/10.1016/j.scitotenv.2024.176735>
- PreventionWeb. (2023). *The 2022 Durban floods were the most catastrophic yet recorded in KwaZulu-Natal*. https://www.preventionweb.net/news/2022-durban-floods-were-most-catastrophic-yet-recorded-kwazulu-natal?utm_source=chatgpt.com
- Proag, V. (2021). *Infrastructure planning and management: An integrated approach*. Springer.
- Putri, S. R., Aldine, T. T., Darus, M. A. R., Aulia, D. R., & Hayati, F. (2025). The role of microfinance institutions in community economic empowerment: Perspectives of actors and customers. *International Journal of Education, Social Studies, and Management*, 4(3), 1310–1317. <https://doi.org/10.52121/ijessm.v4i3.561>
- Rahman, A. M., Hossain, Md. Z., Rahaman, K., R. (2023). Climate urbanism as a new urban development paradigm: Evaluating a city's progression towards climate urbanism in the Global South. *Climate*, 11(8), Article 159. <https://doi.org/10.3390/cli11080159>
- Rajendran, R. K., Priya, T. M., Musa, A. I., Mahalakshmi, S. B., & Anand, T. R. (2025). Smart solutions for climate resilience harnessing machine learning and sustainable WSNs. In P. Mahalle, D. Takale, S. Sakhare, & G. Regulwar (Eds.), *Machine learning for environmental monitoring in wireless sensor networks* (pp. 213–232). IGI Global. <https://doi.org/10.4018/979-8-3693-3940-4.ch010>
- Rasheed, A., Abiodun, A., Ifechukwu, G., Obinna, I., Tochi, O., & Baalah, G. (2024). Future cities and sustainable development: Integrating renewable energy, advanced materials, and civil engineering for urban resilience. *Magna Scientia Advanced Research and Reviews*, 12(2), 235–250. <https://doi.org/10.30574/msarr.2024.12.2.0204>
- Revi, A., & Satterthwaite, D. (2014). Urban areas and climate change: Review of current issues and trends. *Annual Review of Environment and Resources*, 39, 1–29.
- Rising, J. A., Taylor, C., Ives, M. C., & Ward, R. E. T. (2022). Challenges and innovations in the economic evaluation of the risks of climate change. *Ecological Economics*, 197, Article 107437, <https://doi.org/10.1016/j.ecolecon.2022.107437>
- Ritchie, A. (2010). *Community-based financial organisations* (2020 Vision briefs no. 18(3)). International Food Policy Research Institute. [https://econpapers.repec.org/RePEc:fpr:2020br:18\(3\)](https://econpapers.repec.org/RePEc:fpr:2020br:18(3))
- Roberts, D., Boon, R., Diederichs, M. N., Douwes, E., Govender, N., McInnes, A., McLean, C., O'Donoghue, S.H., & Spires, M. (2012). Exploring ecosystem-based adaptation in Durban, South Africa: “Learning-by-doing” at the local government coal face. *Environment and Urbanization*, 24(1), 167–195.
- Rosenzweig, C., Solecki, W., Romero-Lankao, P., Mehrotra, S., Dhakal, S., Bowman, T., & Ibrahim, S. A. (2018).

- Climate change and cities: Second assessment report of the urban climate change research network*. Cambridge University Press.
- Sánchez-Silva, M., Gardoni, P., Val, D. V., Yang, D. Y., Frangopol, D.M., Limongelli, M. P., Honfi, D., Acuña, N., & Straub, D. (2025). Moving toward resilience and sustainability in the built environment. *Structural Safety*, 113, Article 102449. <https://doi.org/10.1016/j.strusafe.2024.102449>
- Sayed, V. A. (2022, September 22). Bengaluru floods: When lakes overflowed, unplanned urban development was behind the recent floods in Bengaluru. *Frontline*. https://frontline.thehindu.com/environment/bengaluru-floods-when-lakes-overflowed/article65894031.ece?utm_source=chatgpt.com
- Schaeffer, R., Szklo, A. S., de Lucena, A. F. P., Borba, B. S. M. C., Nogueira, L. P. P., Fleming, F. P., Troccoli, A., Harrison, M., & Boulahya, M. S. (2012). Energy sector vulnerability to climate change: A review. *Energy*, 38(1), 1–12.
- Schlosberg, D. (2012). Climate justice and capabilities: A framework for adaptation policy. *Ethics & International Affairs*, 26(4), 445–461. <https://doi.org/10.1017/S0892679412000615>
- Schlosberg, D., Collins, L., & Niemeyer, S. (2017). Adaptation policy and community discourse: Risk, vulnerability, and just transformation. *Environmental Politics*, 26, 1–25. <https://doi.org/10.1080/09644016.2017.1287628>
- Severe flooding in Chennai as heavy showers continue. (2022, November 2). *The Indian Express*. <https://indianexpress.com/photos/india-news/chennai-floods-again-as-heavy-showers-continue-in-the-city-8244611>
- Shah, J. (2024). The adaptation wedge: Capacity-building scenarios for India's cities. *Midwest Social Sciences Journal*, 26(2). <https://doi.org/10.22543/2766-0796.1146>
- Sharma, D., & Tomar, S. (2010). Mainstreaming climate adaptation in Indian cities. *Environment and Urbanization*, 22(2), 451–465.
- Simcock, N., Thomson, H., Petrova, S., & Bouzarovski, S. (2017). *Energy poverty and vulnerability: A global perspective*. Routledge.
- Singh, R., Wang, X., Mendoza, J. C., & Ackom, E. (2015). Electricity (in)accessibility to the urban poor in developing countries. *Wiley Interdisciplinary Reviews: Energy and Environment*, 4(4), 339–353. <https://doi.org/10.1002/WENE.148>
- Singla, A. (2024). Resilient transportation systems: Strategies for mitigating climate change impacts and enhancing infrastructure stability. *International Journal for Research Publication and Seminar*, 15(3), 129–135. <https://doi.org/10.36676/jrps.v15.i3.1453>
- Sitas, N., Selomane, O., Hamann, M., & Gajjar, S. P. (2021). Towards equitable urban resilience in the Global South within a context of planning and management. In C. M. Shackleton, S. S. Cilliers, E. Davoren, & M. J. du Toit (Eds.), *Urban ecology in the Global South: Cities and nature*. Springer. https://doi.org/10.1007/978-3-030-67650-6_13
- Situmorang, M. T. N., Djaya, S., Astuti, T. A. K., Hermansyah, M., & Sulisty, A. (2024). Building climate resilience: Innovative strategies by Indonesian local governments. *Visioner*, 16(1), 34–45. <https://doi.org/10.54783/jv.v16i1.1041>
- Smith, S., Monstadt, J., & Otsuki, K. (2022). Enabling equitable energy access for Mozambique? Heterogeneous energy infrastructures in Maputo's growing urban periphery. *Energy Research and Social Science*, 90, Article 102684. <https://doi.org/10.1016/j.erss.2022.102684>
- Sovacool, B. K. (2011). Hard and soft paths for climate change adaptation. *Climate Policy*, 11(4), 1177–1193.
- Srinivasan, V., Konar, M., & Sivapalan, M. (2017). A dynamic framework for water security. *Water Security*, 1, 12–20. <https://doi.org/10.1016/j.wasec.2017.03.001>

- Stake, R. E. (1995). *The art of case study research*. Sage.
- Stankiewicz, K., Boroń, P., Prajsnar, J., Źelazny, M., Heliasz, M., Hunter, W., & Lenart-Boroń, A. (2023). *Second life of water and wastewater in the context of circular economy—Do the membrane bioreactor technology and storage reservoirs make the recycled water safe for further use?* SSRN. <https://doi.org/10.2139/ssrn.4639378>
- Tanguay, X., & Amor, B. (2024). Assessing the sustainability of a resilient built environment: Research challenges and opportunities. *Journal of Cleaner Production*, 458, Article 142437. <https://doi.org/10.1016/j.jclepro.2024.142437>
- Tanner, T., Mitchell, T. W., Polack, E., & Guenther, B. (2009). Urban governance for adaptation: Assessing climate change resilience in ten Asian cities. *IDS Working Papers*, 315, 1–47. https://doi.org/10.1111/J.2040-0209.2009.00315_2.X
- Trejo, D., & Gardoni, P. (2022). Special issue on adaptive pathways for resilient infrastructure: An introduction. *Sustainable and Resilient Infrastructure*, 8(Sup1), 1–2. <https://doi.org/10.1080/23789689.2022.2139564>
- Tyler, S., & Moench, M. (2012). A framework for urban climate resilience. *Climate and Development*, 4(4), 311–326. <https://doi.org/10.1080/17565529.2012.745389>
- Ugwu, M. C., Adewusi, A. O., & Nwokolo, N. E. (2024). The role of public-private partnerships in building clean energy infrastructure in the United States and Nigeria. *International Journal of Management & Entrepreneurship Research*, 6(4). <https://doi.org/10.51594/ijmer.v6i4.984>
- UN Disaster Management Team. (1999). *Orissa super cyclone situation report 9*. <https://reliefweb.int/report/india/orissa-super-cyclone-situation-report-9>
- van Vliet, M. T. H., Wiberg, D., Leduc, S., & Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, 6(4), 375–380.
- Walker, B., & Salt, D. (2006). *Resilience thinking: Sustaining ecosystems and people in a changing world*. Island Press.
- Wambura, S. P. (2024). Building resilient communities: The interplay between climate change and social capital. *World Journal of Advanced Research and Reviews*, 24(2), 1801–1812. <https://doi.org/10.30574/wjarr.2024.24.2.3491>
- Wang, Q., Li, K., Wang, M., Koks, E., & Wang, H. (2024). Exposure of global rail and road infrastructures in future record-breaking climate extremes. *Earth's Future*, 12(1), Article e2023EF003632. <https://doi.org/10.1029/2023ef003632>
- Warouw, F. F., Waty, R. R., Mayasari, Y., Syam, A. R., & Muksin, I. (2023). Local government adaptation strategies in facing climate change: An innovative framework. *Visioner*, 15(2), 29–41. <https://doi.org/10.54783/jv.v15i2.863>
- Wei, X. (2024). Analysis of the impact of climate change on the safety of water conservancy facilities. *Forum on Research and Innovation Management*, 2(5), 83–85. <https://doi.org/10.18686/frim.v2i5.4519>
- Whitehead, P. G., Wilby, R. L., Battarbee, R. W., Kernan, M., & Wade, A. J. (2009). A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal*, 54(1), 101–123. <https://doi.org/10.1623/hysj.54.1.101>
- Wieszczczynska, K. A., Tollin, N., & Spaliviero, M. (2024). Capacity building within urban climate resilience in the Global South—A literature review. *Frontiers in Sustainable Cities*, 6, Article 1380936. <https://doi.org/10.3389/frsc.2024.1380936>
- Yesudian, A. N., & Dawson, R. J. (2021). Global analysis of sea level rise risk to airports. *Climate Risk Management*, 31, Article 100266. <https://doi.org/10.1016/j.crm.2020.100266>
- Yilmaz, D. G. (2023). Nature-based solutions for climate-resilient cities: A proposal of a model for successful implementation. *Journal of Design for Resilience in Architecture and Planning*, 4(2), 189–203. <https://doi.org/10.47818/drarch.2023.v4i2092>

Ziervogel, G., New, M., Archer van Garderen, E., Midgley, G., Taylor, A., Hamann, R., & Warburton, M. (2014). Climate change impacts and adaptation in South Africa. *Wiley Interdisciplinary Reviews: Climate Change*, 5(5), 605–620.

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Data-Driven Equitable Planning for Urban Resilience: Innovation, Risk, and Outcomes in Boston, New Orleans, and Norfolk

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Abstract

Coastal cities around the world seek to mitigate the intensifying impacts of sea-level rise and stormwater on urban infrastructure and human safety and well-being. Our comparative case study of Boston, New Orleans, and Norfolk examines how cities use data and smart technologies to inform resilient infrastructure planning, with a focus on equity and social justice outcomes. Drawing on Kitchin’s (2021) critical framework of data as socially constructed, we analyze how data is defined, collected, and deployed in coastal resilience planning in each of these cities. Findings demonstrate how data practices can reinforce existing power dynamics. The comparison points to three critical factors affecting equitable data-driven resilience planning: (a) centering community participation in determining what data is collected and how it is used; (b) making technical data accessible and meaningful to diverse audiences; and (c) implementing transparent monitoring mechanisms that enable communities to track progress and address unintended consequences. This study contributes to a nuanced understanding of the opportunities and challenges in using data for equitable urban resilience planning, offering insights for policymakers and urban planners grappling with similar challenges globally.

Keywords

climate adaptation; coastal cities; community engagement; flood mitigation; infrastructure improvement; public policy; risk management; urban development; urban governance; urban resilience

1. Introduction

As coastal cities worldwide face the impacts of climate change, data-driven approaches to resilience planning have become central to urban adaptation strategies. The stakes for getting data-driven coastal resilience planning right are considerable. By 2050, sea levels along US coastlines are projected to rise

10–12 inches on average, threatening infrastructure valued at over \$1 trillion (National Oceanic and Atmospheric Administration, 2022). Traditional risk assessment approaches, which often rely on property values and cost-benefit analyses to determine where protective measures should be implemented, frequently overlook social vulnerabilities. With global cities investing billions in climate adaptation infrastructure every year (UN Environment Programme, 2021), it becomes urgent to understand how data practices shape outcomes. Decisions made today about what data to collect, how to analyze it, and how to translate it into policy will determine not only physical infrastructure but also patterns of advantage and disadvantage for generations to come.

Our study examines how three coastal cities in the US—Boston, New Orleans, and Norfolk—approach data-driven climate resilience planning while also grappling with legacies of segregation that have concentrated vulnerable populations in flood-prone areas. Although they face similar climate vulnerabilities, there are distinct institutional approaches to data governance in each city, providing unique insights into how different data practices might shape equity outcomes. By analyzing how these cities define, collect, and communicate resilience data, we highlight the opportunities and challenges of integrating social justice considerations into urban climate adaptation.

While the academic literature discussed below has begun to emphasize the central role that equity and social resilience play in climate resilience, there is less consideration of the central role that data practices can play in this. There remains a significant gap in understanding how data practices themselves—the ways in which information is collected, analyzed, and deployed in decision-making—either challenge or reinforce existing inequities. Data-driven approaches are often taken for granted without acknowledging the limitations and both implicit and explicit bias in the data and data management processes. As Kitchin (2021) argues, data is not neutral but rather socially constructed, reflecting the values, priorities, and power structures of those who collect and deploy it. This critical perspective on data has not been adequately integrated into analyses of climate resilience planning, especially given that data-driven decision-making increasingly determines which communities and assets receive protection. While these approaches utilizing data analytics offer more precise measurement to guide interventions, they may inadvertently reproduce or amplify existing social disparities if not implemented with careful attention to equity considerations.

This study addresses this gap by exploring the data practices underpinning coastal resilience planning in three American cities, each with distinct approaches to climate adaptation. We focus in particular on the ways in which data practices either challenge or reinforce existing inequities and examine how different approaches to data collection and community engagement can shape outcomes for historically marginalized communities. In doing so, this study extends resilience scholarship by emphasizing the critical role of participatory data governance in addressing systemic inequalities.

The article is organized as follows: The following section introduces the literature on climate resilience and the ways in which this has evolved to address social equity concerns. We then elaborate on our analytical framework, drawing from Kitchin's (2021) critical perspectives on data, which examine how data is socially constructed, governed, ethically managed, and made accessible. We then introduce our three case studies and discuss why a comparison of these three cities in particular provides a useful juxtaposition from which to draw these conclusions. Each city is then explored in detail. We conclude with a synthesis of the lessons learned across all three cases and what recommendations can be drawn from these.

2. Climate Resilience

To understand how data practices shape equity outcomes in climate adaptation, it is essential to first examine the evolution of climate resilience as both a theoretical concept and a practical framework for urban planning. The development of resilience theory has increasingly incorporated social equity concerns, yet the role of data practices in either advancing or hindering these equity goals remains underexplored. This section traces the theoretical development of climate resilience principles and their real-world application.

The concept of resilience is often traced back to Holling (1973, p. 14), who wrote of it as “a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between the state variables.” The concept of climate resilience builds on this ecological concept, referring to a system’s capacity to endure disruption associated with climate change. One of the most highly cited definitions is the one offered by the Intergovernmental Panel on Climate Change: “The capacity of interconnected social, economic, and ecological systems to cope with a hazardous event, trend, or disturbance, responding or reorganizing in ways that maintain their essential function, identity, and structure” (Lonsdale et al., 2024). Widely adopted by practitioners, such as those part of the Resilient Cities Network, the concept provides a holistic framework that recognizes the ability to address physical challenges (e.g., storms and floods) and social stresses that exist in a community (e.g., economic hardships and social inequality; Resilient Cities Network, n.d.).

The concept of resilience has evolved across a variety of fields in the past 50 years since Holling’s pioneering work. However, climate resilience has emerged as a distinct focus that extends beyond traditional engineering or ecological resilience paradigms, which primarily concerned the ability of a system to adapt to disturbances and recover normal functioning. For example, early frameworks of resilience tended to focus on the functionality and recovery of systems and prioritized technical efficiency and stability over social considerations (Harris et al., 2023; Martin-Breen & Anderies, 2011). By concentrating on outcomes over processes, these frameworks gave inadequate consideration to how they were reached or who they benefited (Raciti et al., 2023). Thus, these models largely overlooked how systemic inequalities shape communities’ abilities to adapt to and recover from climate challenges (Doost et al., 2023; Lioubimtseva et al., 2024). In contrast, the contributions of social resilience theory have aimed to ameliorate these shortcomings (Keck & Sakdapolrak, 2013). These emphasize power relations and community capacities, whereas ecological resilience stresses adaptation and engineering resilience concentrates on system recovery (Norris et al., 2008). For example, several recent reports on flood infrastructure planning emphasize community resilience and collaboration (Hughes et al., 2022; National Association for the Advancement of Colored People, 2021). Scholars now advocate for more process-oriented approaches that build capacities, foster community connections, and ensure effective and equitable governance (for example, see Doost et al., 2023; Meerow et al., 2019).

All of this suggests that there is a rising understanding that social, economic, and political inequality significantly influences vulnerability to climate threats, in theory at least. As climate impacts intensify, it has become increasingly evident that resilience frameworks must address not just the physical infrastructure challenges but also the social disparities that shape vulnerability and adaptive capacity. This recognition has led to the integration of social resilience frameworks that consider power dynamics, community capacity, and social equity (Ungar, 2011) and has led to calls for more comprehensive strategies across domains

and growing awareness of the interdependencies of ecological, engineering, and social systems (Davidson et al., 2016).

3. Analytical Framework

Given the central place of equity in the conceptualization of climate resilience, our study seeks to explore how this is reflected (or not) in the often data-driven approaches to climate resilience planning. Our analytical framework draws directly from Rob Kitchin's (2021) critical examination of data practices, identifying four key dimensions and applying these to coastal resilience data practices in our three case studies. Kitchin challenges the notion of data as neutral, instead framing all data as a product of and therefore a reflection of the social and political context in which it was gathered and analyzed. He emphasizes the importance of diverse knowledge systems, particularly those traditionally marginalized by technocratic approaches. This includes local, experiential, and indigenous knowledge that may be overlooked in favor of "expert" technical data. The integration of these diverse knowledge systems is critical for developing more equitable and effective resilience strategies. This perspective provides a critical lens for examining how data practices in resilience planning may reinforce or challenge existing power dynamics and inequities.

This also aligns with emerging trends in climate resilience scholarship, calling for more situational and contextual approaches to data. For example, Brodie et al. (2024, p. 140) argue, "environmental data power is also a tool that can be wielded by communities, activists, and political groups towards environmental justice." Taking a similarly critical perspective, Nost (2018) argues that the influence of environmental modeling on policy development is due more to political, financial, and technical factors than to the model's accuracy. C. Johnson and Osuteye (2019) observe that data-gathering procedures themselves can either challenge or reinforce existing disparities. Traditional loss databases and city-scale resilience frameworks often overlook the everyday risks faced by marginalized communities, while community-generated information techniques may offer more equitable approaches to knowledge production. Thus, they argue that communities that have traditionally been the subjects of data collection rather than active contributors to the creation of knowledge must be given the authority to influence the gathering, interpretation, and application of resilience data about them. In coastal resilience planning specifically, Craig (2022) and Goytia (2024) show how more transparent flood risk information could create fairer conditions for both residents and potential property buyers. Yet the accessibility and interpretability of such data often varies across communities, potentially reinforcing existing inequities. These insights suggest that data can be both a tool of marginalization and of empowerment, depending on how it is governed and deployed.

We therefore draw from Kitchin's (2021) specific critiques, framing these as four broad dimensions that we utilize to examine how data practices in resilience planning may reinforce or challenge existing power dynamics and inequities:

1. Data as socially constructed: Data is not neutral but reflects the values, priorities, and power structures of those who collect, analyze, and deploy it. In resilience planning, this means questioning what is measured, by whom, and for what purpose.
2. Data sovereignty and governance: Communities should have rights regarding data about them, including input into how it is collected, interpreted, and used. This is especially important for communities that have historically been subjects of data collection rather than active participants in knowledge creation.

3. Ethics of data collection: Data practices should be guided by principles of care, accountability, and transparency, with attention to potential harms and benefits.
4. Infrastructure and access: The technical systems through which data is collected, stored, and analyzed can either enable or restrict equity, depending on who can access and use these systems.

These four dimensions are operationalized, and the analytical framework is defined in Figure 1.

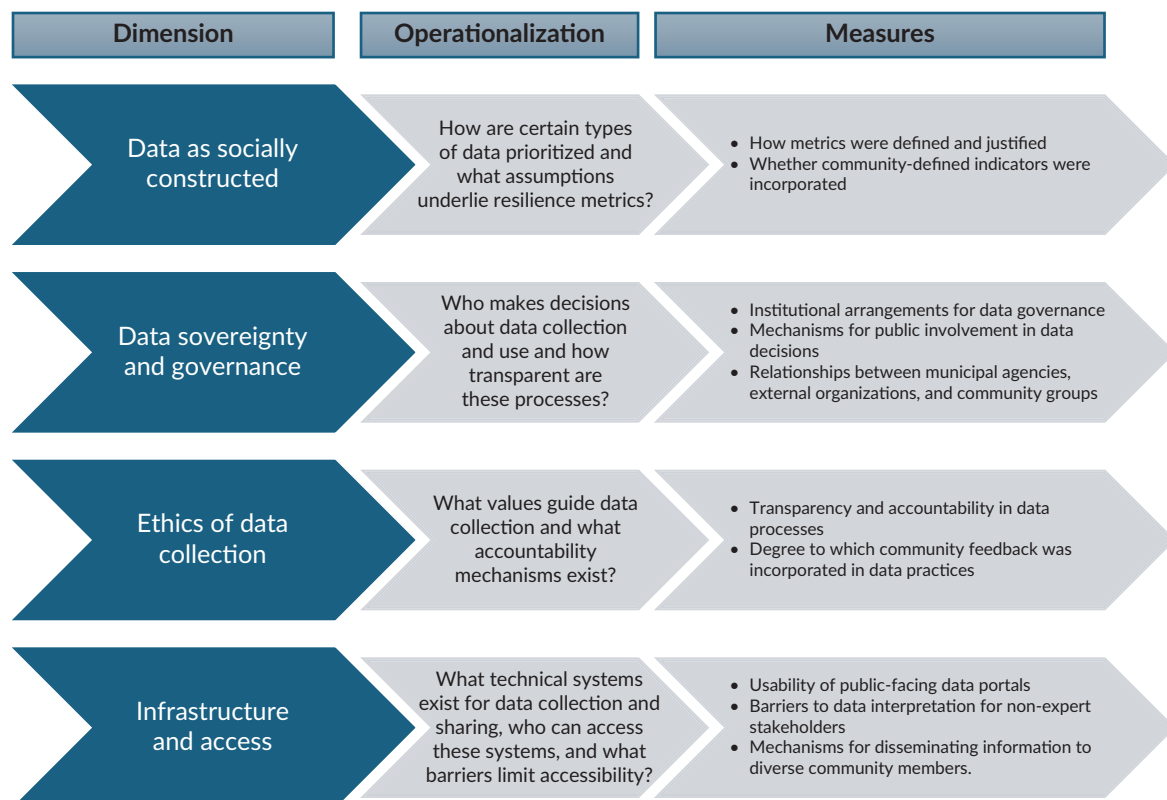


Figure 1. Analytical framework. Source: Adapted from Kitchin (2021).

4. Methodology

To more closely explore the ways in which these data-driven approaches have implications for equity in climate resilience efforts, this study examines three US coastal cities: Boston, New Orleans, and Norfolk, and their coastal resilience efforts in particular. The specific coastal contexts vary: New Orleans contends with subsidence and deltaic processes, Norfolk seeks to balance military infrastructure with residential needs, and Boston is developing its waterfront even as it must manage vulnerabilities that stem from historic land reclamation. Still, they all share the common challenges of sea-level rise and increased flooding.

All three cities were among the first American cities selected for the 100 Resilient Cities Network in 2013 (The Rockefeller Foundation, n.d.). Participation in the program provided each city with resources to hire chief resilience officers and develop comprehensive resilience strategies. It also meant they were all early adopters of this approach to urban resilience planning, which recognizes that the ability to address physical challenges—like storms and floods—is impacted by the social stresses that exist in a community—like economic hardships

and social inequality (Resilient Cities Network, n.d.). Their participation in this network thereby provides a common starting point for examining how data-driven approaches to resilience planning have evolved over the past decade, particularly in addressing issues of equity and social justice.

The demographic makeup of these three cities also makes them an interesting comparison. Most notably, all three are rated as having “high segregation” (Othering & Belonging Institute, n.d.). New Orleans in particular ranked in the top ten of most segregated statistical areas for 2019, while Boston ranks in the top ten metropolitan areas with the greatest increase in segregation between 1990 and 2019 (Menedian et al., 2021). These demographic realities intersect with the geographical risks each city faces. In Boston, historically redlined and segregated neighborhoods like East Boston and Dorchester have higher populations of racial minorities and lower-income residents and face elevated flood risks from sea level rise due to their coastal location. In Norfolk, many predominantly Black neighborhoods, such as Tidewater Gardens and other areas in the St. Paul’s district, are in low-lying areas with poor drainage infrastructure, issues that only worsen with sea level rise. New Orleans presents the starkest example. Historical patterns of segregation pushed many African American residents into lower-lying areas of the city, particularly those below sea level. The Lower Ninth Ward, which was devastated during Hurricane Katrina, exemplifies how racial segregation led to Black residents being concentrated in areas most vulnerable to flooding. This neighborhood was originally considered less desirable real estate precisely because of its flood risk, and discriminatory housing practices concentrated minority populations there.

This study analyzes how these three cities define, construct, and deploy data in their resilience planning, with the aim of better understanding the opportunities and challenges in developing equitable approaches to urban climate adaptation. Our methodology focuses on conducting a critical comparative review of resilience planning processes across the three cities, utilizing official planning documents and other publications to build profiles of data practices in each city. The case study profiles were built using four primary categories of documents:

1. Official resilience planning documents: City-produced resilience strategies and planning documents published between 2013 (when all three cities joined the 100 Resilient Cities Network) and 2025. These included: for New Orleans—The Gentilly Resilience District project plan (City of New Orleans, 2018), the city’s hazard mitigation plan (Office of Homeland Security and Emergency Preparedness, 2021), and *A Priority List for Climate Action in New Orleans: Net Zero by 2050* (City of New Orleans, 2022); for Norfolk—*Norfolk Resilient City* (City of Norfolk, 2015), *Norfolk Vision 2100* (City of Norfolk, 2016), and the Virginia Community Flood Preparedness Fund Grant Application (City of Norfolk, 2021); and for Boston—The series of neighborhood-specific Coastal Resilience Plans developed between 2017 and 2022 for Charlestown, Downtown/North End, South Boston, Dorchester, and East Boston/Charlestown (City of Boston, 2025)
2. Scholarly evaluations: Academic analyses of each city’s resilience planning efforts, including peer-reviewed articles published in the last decade that specifically address data practices and equity considerations.
3. Media coverage: Local news reporting on resilience planning efforts in each city, focusing on coverage that documented community responses to planning processes and implementation. Sources included the Boston Globe, New Orleans Times-Picayune, and Virginian-Pilot.

4. Evaluation and assessment reports: Reports from non-governmental organizations, research institutes, and government oversight bodies that evaluated the implementation and outcomes of resilience planning. These included *The Inaugural Boston Climate Progress Report* (Fitzgerald & Walsh, 2022), reports from the Boston Green Ribbon Commission (Foster & Johnson, 2020; Plastrik, 2023), and the Louisiana Equity Metrics Framework (Habans et al., 2023).

Our selection criteria prioritized documents that: explicitly discussed data collection, analysis, and deployment in resilience planning; addressed equity considerations or community engagement in data practices; provided insights into institutional decision-making processes regarding data; and documented community perspectives on data access and usage.

It is important to note that the use of secondary sources for community responses represents a limitation of this study. While the documents analyzed included substantial reporting of community perspectives, these are necessarily filtered through the interpretive lens of researchers, journalists, and planners. Direct engagement with community members through interviews or participatory research was beyond the scope of this particular study.

Once the profiles were established, we then applied the framework outlined above (see Figure 1) to gauge how data practices reflect and shape power dynamics in each context. This approach allowed us to evaluate the social and political dimensions that determine whose knowledge counts, whose needs are prioritized, and whose voices are heard in adaptation decision-making. The following sections present each case study, followed by an analysis comparing the three cities on the measures in the analytical framework. The concluding section contrasts the data practices of the three cities and presents recommendations for local planners and policymakers.

5. Case Study Results

5.1. New Orleans

Data-driven planning is useful for all cities, but none more so than New Orleans. Situated within a natural basin, the city faces an array of flood risks from river surges, storms, and heavy rains. Occupied by indigenous peoples in the prehistoric era, the region was home to European settlements by 1700. The history of New Orleans is that of technological innovation, as the city's residential area expanded after the early 20th-century improvements in water pumping systems allowed for drainage of several area swamps, wetlands, and marshes and the expansion of the city's levee system in the 1930s (Campanella, 2006). Currently, land subsidence is exacerbating this situation, as the city slips lower each year with regard to sea level (D. R. Johnson et al., 2015). In the past, the area's coastal wetlands provided natural barriers to help protect the city, but they are predicted to continue to shrink in the years to come (Hobor et al., 2014).

New Orleans has a checkered history regarding governmental transparency and effective delivery of municipal services. At the dawn of the 21st century, the city continued to struggle in the face of increasingly sophisticated expectations around municipal data. Many of the city's IT staff were employed on a temporary basis, and the geographic information systems functions typically performed by a city division were outsourced. Factual and timely city data was in short supply (Gardere et al., 2020). The Greater New Orleans

Community Data Center (later known simply as The Data Center) was established in 1997 with a mission of “democratizing” regional data by making it relevant and accessible to the public (Martin, 2023). The Center’s role evolved from providing demographic data to becoming the region’s source for climate resilience information, reflecting both the organization’s growth and persistent gaps in public data infrastructure.

Hurricane Katrina fundamentally transformed New Orleans’ approach to data. In August 2005, the storm devastated the city, leaving nearly 2,000 people dead and entire neighborhoods abandoned and in disrepair. Historically, many of the least desirable and most dangerous areas of the city were home to low-income Black residents, tying climate resilience dramatically to patterns of discrimination and social inequity (Jayawardhan, 2017). In the years following the storm, demand spiked for accurate and granular data of all types as The Data Center drew up to 120,000 users per month (Gardere et al., 2020).

During the following decade, the city joined the wave of municipalities sponsoring open data initiatives, establishing an open data policy in 2016 (Gardere et al., 2020). The data available on the city’s open data portal (see Figure 2) remains limited even today, however. The site features relatively few datasets and none focusing on climate resilience and flooding, topics that are addressed instead by The Data Center’s website (City of New Orleans, n.d.). This limited array of data reflects broader and long-lasting challenges in data coordination across agencies. The relegation of critical climate resilience data to a non-governmental entity begs the question regarding data governance: Who ultimately controls and is accountable for this essential public information?

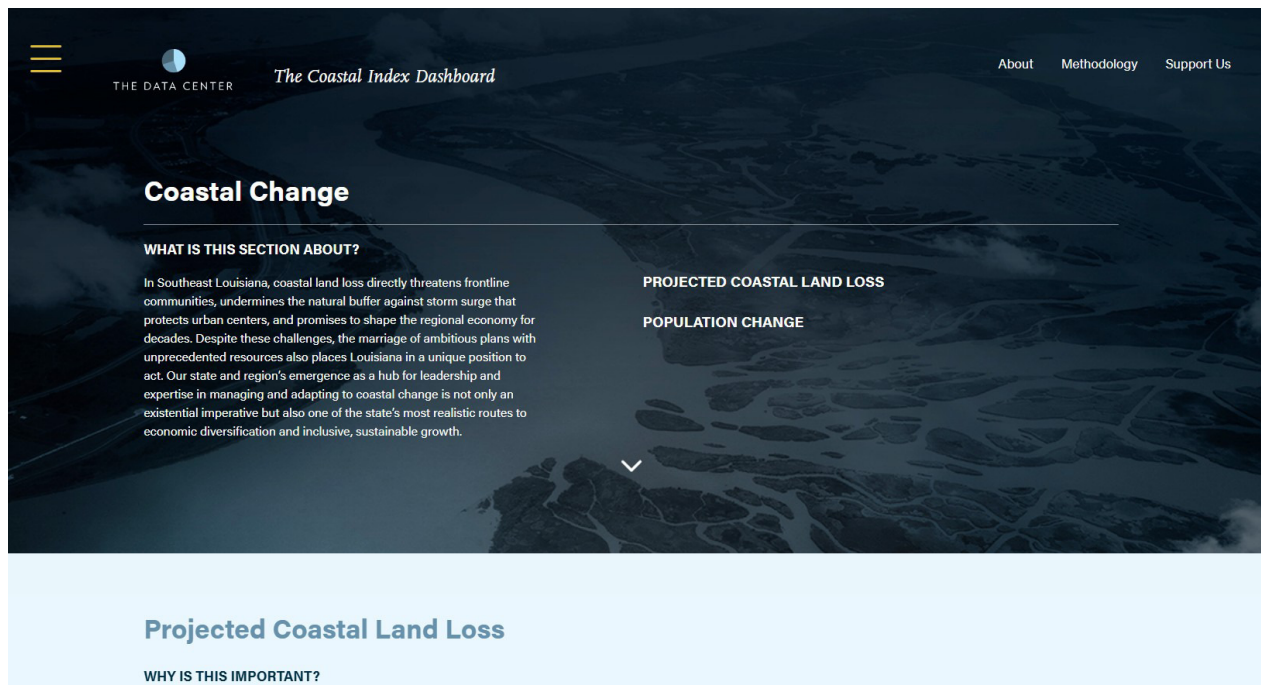


Figure 2. New Orleans: The Data Center coastal index dashboard. Source: The Data Center (n.d.).

The BlightStat program exemplifies both progress and ongoing challenges in data management. Modeled on the Baltimore CitiStat program, the BlightStat system began in 2010 under the Mitch Landrieu administration (Gardere et al., 2020) with the goal of facilitating the elimination of 10,000 blighted properties within four years. The initiative included public meetings where city staff came together to review

data and assess progress, marking a departure in a city accustomed to little transparency around data. BlightStat data included information gathered about each parcel from municipal city divisions, including code enforcement and the city attorney's office. An online tool, "BlightStatus," was produced by Code for America fellows in 2012, making the data more accessible and easier to use. Two years later, the city boasted of having eliminated nearly 13,000 blighted properties. BlightStat is sometimes cited as a turning point in the city's relationship to data, as the potential usefulness of data sharing and transparency was more widely understood. While BlightStat demonstrated data's potential for addressing specific urban challenges, it also demonstrated the extent to which data collection is shaped by broader cultural values and priorities. Definitions of "blight" are not monolithic, and centering its elimination prioritized specific perspectives that would not have been universally held. This exemplifies Kitchin's critical framework around the social construction of data.

New Orleans has made progress in terms of data gathering and sharing in recent years, but the city's data practices still reflect and enforce social inequities. Recent state-level efforts include The Data Center and the Louisiana Governor's Office framework for climate equity metrics, which recommends creating tailored data resources for various audiences through an interactive hub exploring indicators like hazard exposure, income, and inclusive economic growth (Habans et al., 2023). While this framework has great potential, it has not yet been implemented. In the wake of Hurricane Katrina, some neighborhoods, such as Broadmoor, used existing social and institutional connections to gain access to data regarding permitting; other less well-connected communities struggled without such access (Gardere et al., 2020). Although over 300 government datasets are now publicly available, the city's crucial climate resilience data remains housed by The Data Center. This arrangement raises some ethical questions about accountability and transparency that align with Kitchin's framework. That is, who ensures this data is collected and utilized in ways that serve vulnerable communities, and what recourse do residents have if they believe their needs are not being represented?

New Orleans uses tools like the Social Vulnerability Index, which draws upon over a dozen census variables to identify the relative vulnerability of various neighborhoods to environmental hazards such as hurricanes and flooding and facilitate complex multivariable analysis (Office of Homeland Security and Emergency Preparedness, 2021). Regional organizations work to ensure equitable access to resources and information. The Water Collaborative focuses on public education and water policy to ensure equitable access to water (City of New Orleans, 2022), and the Neighborhoods Partnership Network fosters connections and information sharing between neighborhoods to leverage public and private investments (City of New Orleans, 2020). Despite these efforts, data integration and privacy concerns persist, and stakeholders often disagree about priorities and risk assessment (Rumson et al., 2017).

In recent years, New Orleans has attempted to implement data-driven planning around climate resilience. Funded by a \$141 million grant from the National Disaster Resilience Competition, the Gentilly Resilience District project showcases the potential and challenges in this area (City of New Orleans, 2018). The project is designed to minimize flood risk and limit land subsidence. More broadly, it seeks to center water and land management in urban development by addressing stormwater and other potential risks through the implementation of green stormwater infrastructure (Trust for Public Land, 2023). Although the project has ambitious data collection and visualization goals, the project reflects the gap Kitchin identified between technically sophisticated efforts and community-centered data governance.

The project makes extensive use of data. The Trust for Public Land's Climate and Smart Cities New Orleans Decision Support Tool allows users to visualize climate equity concerns such as demographic data in an interactive geographic information systems format (Trust for Public Land, 2023). A comprehensive digital database of infrastructure plans, spatial data, and surveys will be used in planning and design (Office of Homeland Security and Emergency Preparedness, 2021).

Despite these plans, the Gentilly Resilience District has faced extensive logistical challenges and delays. A US Department of Housing and Urban Development (2024) audit cited several factors for the delay, including Covid-19, hurricanes, a cyberattack, and insufficient coordination, staffing plans, and progress monitoring, as well as misallocation of costs.

Our analysis finds that New Orleans' data practices reflect both progress and challenges in climate resilience planning. Institutional arrangements and culture shape data governance and resilience planning. Initiatives like BlightStat demonstrate the potential power of data-driven resilience solutions, while the city's continued reliance on The Data Center reflects an ongoing gap in municipal agency capacity. Key stakeholders in the city have undeniably moved toward greater data transparency. Under-resourced offices, miscommunication, and project delays amplify the persistent social inequity that continues to plague the city and pose continued risks associated with rising climate threats.

5.2. Norfolk

Positioned at the mouth of the Chesapeake Bay in the Tidewater region of Virginia, Norfolk developed as an important colonial port in early America, much like Boston and New Orleans. The growth and development of military and transportation in the city, along with the continued growth of the central business district, reflect significant sunk costs and concomitant difficult decisions about urban and regional planning in the face of climate change.

Norfolk's climate challenges are related to preserving vital national security infrastructure, including important commercial shipping and the world's largest naval base, while shielding established residential and commercial districts from rising flood dangers. With one of the greatest rates of sea level rise on the East Coast, coastal storms pose a serious risk to a city that is relatively flat and mostly below 15 feet and sinking (City of Norfolk, 2021). The city's climate resilience plan, The Norfolk Vision 2100, aims to use a data-driven approach to balance competing commercial, military, and residential flood risk management (City of Norfolk, 2015).

Norfolk's approach to resilience planning is unique in that it integrates military and civilian demands. One example of this integration is the city's collaboration with Palantir Technologies, Inc (a publicly traded company specializing in software platforms for data analytics), to create an innovative Resilience Data Dashboard (see Figure 3). This system allows for better operational reactions and decision-making in both the military and civilian sectors by integrating important city data, such as building rules, permits, flooding statistics, and service calls (City of Norfolk, 2015). Similar to The Data Center arrangement in New Orleans, this raises questions about who controls and who has access to critical resilience data and whose interests are prioritized.



Figure 3. Norfolk open data. Source: City of Norfolk (n.d.).

All cities must coordinate inherent challenges with multiple jurisdictions of municipal, state, and federal jurisdiction. Norfolk's multijurisdictional challenges are extreme, with the strong military presence and the position at the mouth of the Chesapeake Bay. This requires creative solutions for data coordination. Some of the coordination with diverse stakeholders is managed by the office of the chief resilience officer, but there remain difficulties associated with the disparate institutional agendas and data platforms (City of Norfolk, 2015). The data landscape is further complicated by commercial port operations. Public and commercial sector organizations must carefully coordinate to integrate shipping and commerce data with flood planning (City of Norfolk, 2016). While sophisticated data-sharing methods have resulted from this collaboration, it remains unclear how well these systems work for everyone in the community (Ruckert et al., 2019). Technical sophistication does not necessarily mean ease of access or equitable access for diverse community stakeholders.

As part of its resilience plan, Norfolk has proposed a coastal flood mitigation project that includes a major seawall in the Elizabeth River. As the largest (proposed) public infrastructure project in the history of Norfolk, the \$2.7 billion floodwall project needs to be understood in the context of complex relationships, community involvement, equity considerations, and data-driven decision-making in climate resilience planning. The project is controversial for several reasons. One key criticism of the project is that several majority-Black neighborhoods, including Berkley and Campostella, are excluded from the benefits of the project (Ruckert et al., 2019). In this way, the project reflects embedded assumptions about what kinds of assets are worth protecting. The US Army Corps of Engineers and other agencies led technical studies that included economic impact analyses, storm surge data, and sea level projections. This data-driven strategy reflected conventional cost-benefit calculations that frequently prioritized property values over social equality considerations (Ruckert et al., 2019). Many residents are concerned about the disproportionate number of resources allocated to the seawall project, while under-resourced areas would not see any difference in their flood risk (Hafner, 2023). Data are not value neutral, and that is demonstrated in public

debate about the Coastal Resilience Plan in Norfolk. The Coastal Resilience Plan inspired significant community outrage for a variety of reasons, particularly because of the way data was used to identify protected areas. Residents in historically underserved neighborhoods that experienced environmental injustice and redlining in the past challenged the fairness of decision-making procedures and the allocation of resources to some projects at the expense of others. Community organizer Kim Sudderth's observation that "it struck me, like, 'Oh my God, it's happening again'" illustrates how data-driven infrastructure choices reflect and perpetuate past discriminatory trends (Hafner, 2023). Some residents expressed strong disapproval of both the data collection procedure and the lack of transparency in the planning process. Lawrence Brown, president of the Campostella Heights Civic League, emphasized how the project was proceeding "really without our knowledge," highlighting significant problems with data sharing and community involvement (Morrison, 2023).

Traditional cost-benefit calculations prioritize economic assets and property values. This strategy disadvantages communities with lower property values, even if they have considerable social and cultural significance. The Federal Emergency Management Agency (FEMA) and the Army Corps of Engineers' models find it difficult to provide much protection and support for people with low property values (Hafner, 2023). The Environmental Defense Fund criticized this narrow focus on storm surge at the expense of chronic flood risk, which disproportionately affects lower-income areas (Hafner, 2023). There are some efforts noted by city planners to change the way that cost-benefit is to be calculated by the Federal Emergency Management Agency during times of disaster.

Even with regard to the sophisticated Resilience Dashboard, there is growing tension between the use of institutional data collection (such as flood sensors and sea level monitors) and community knowledge. Historic African American neighborhoods like Tidewater Gardens are experiencing what Kitchin would describe as a lack of "dominion" over data used to make decisions about flood prevention. This uncertainty highlights the fact that technically sophisticated data collection does not necessarily lead to equitable access for all community members, consistent with Kitchin's critical framework. This challenge is most apparent when residents see the allocation of public resources in the business districts along the Elizabeth River to protect high-value property, while at the same time, the cost-benefit analysis does not yield significant investments in neighborhoods with lower property values.

Public input in community charettes in different neighborhoods (Resilient Norfolk, 2025), along with news reports (Hafner, 2023), suggests that different stakeholders across the city engage with data and public decision-making differently. Part of that difference has to do with the legacy of bias and discrimination, and that bias is embedded in the data. Community input is an indication of the differing degrees of participation with and trust in official data systems, even though those data systems are robust and relatively accessible. Project planners have begun reevaluating their methods for gathering and valuing different forms of data to include social equity criteria to complement conventional cost-benefit evaluations and integrate other forms of community knowledge. These concerns about public engagement and equity in decision-making have included critical reflection on the use of data in resilience planning and inspired public officials to devise more inclusive methods for gathering and analyzing data and valuing local knowledge and diverse perspectives. In the end, the scale of the floodwall project and the controversy around it have forced the city to think differently about equitable data practices in resilience planning and public decision-making in general.

5.3. Boston

Originally, Boston was a small peninsula with hilly and uneven terrain, surrounded by marshes and tidal flats. Land reclamation over the centuries allowed the city to evolve and grow to accommodate its growing population and economy while reflecting the city's changing priorities and ambitions over time (Seasholes, 2018). Even in the 21st century, Boston has been held up as an example of how post-industrial cities can revitalize waterfronts to foster urban renewal, drawing from its rich maritime and industrial history to inform contemporary waterfront redevelopment projects (Marshall, 2001). The city's historical practice of filling tidal flats and marshlands, particularly in areas like Back Bay and South Boston, has created significant environmental risks, disrupting natural water flow systems and diminishing the protective capacity of wetlands and natural barriers (Penna & Wright, 2009; Seasholes, 2018). As climate change intensifies, these areas of the city are especially vulnerable, with sea levels rising nearly a foot over two centuries (Talke et al., 2018) and aging flood infrastructure struggling to address contemporary challenges (Mertz, 2016).

Boston developed a series of neighborhood-specific Coastal Resilience Plans between 2017 and 2022. These plans, grounded in research, modeling, and community engagement, identified vulnerabilities and potential interventions (City of Boston, 2025). The planning process emphasized a collaborative approach that brought together public agencies, private property owners, nonprofits, and community organizations through workshops, public meetings, and stakeholder consultations (Foster & Johnson, 2020). Climate Ready Boston (now the Office of Climate Resilience) focused on five coastal neighborhoods: Charlestown, Downtown/North End, South Boston, Dorchester, and East Boston/Charlestown. The combined plans cover all 47 miles of Boston's coastline. Each one involved significant community input and engagement while making a point to encourage ongoing public-private collaboration. The specific combinations of hard infrastructure and nature-based solutions (like living shorelines and restored wetlands) have been the source of conflict (Hadjis, 2022; Omoeva, 2022) but ultimately aim to address the unique needs of each neighborhood (City of Boston, 2025). While not entirely unique in this decentralized approach, Boston's Coastal Resilience Plans are distinctive for the level of integration between them, their comprehensive coverage, and the explicit connection between local plans and citywide policy.

While ambitious, the plans have faced criticism. The neighborhood-level focus itself has been critiqued as being too narrow (Hadjis, 2022) while raising broader concerns about inter-municipal coordination (Flint, 2021; Foster & Johnson, 2020; Omoeva, 2022). Although the establishment of the Office of Climate Resilience and cabinet-level leadership changes aimed to address these challenges (Boston Environment Department, 2024; Wasser, 2024), barriers remain. In particular, funding is a critical challenge, complicated by the fact that much of Boston's coastline is under private ownership. Dependence on private development creates uncertainty in the timeline and delivery of flood protection projects, and this reliance on the private sector has drawn particular criticism (Douglas & Carlock, 2024; Flint, 2021; Omoeva, 2022). Moreover, with estimates suggesting at least \$3 billion is needed for 70 separate resilience projects, this dynamic raises questions about who benefits from and who pays for resilience measures (Fitzgerald & Walsh, 2022). Finally, while the slow pace of climate planning is understandable given the obstacles, critics are concerned that the pace is not enough given how immediate some of the climate effects are (Omoeva, 2022; Rickley, 2024). As oceanographer John Englander warns, "As good as Boston's current plan is—and it is among the best in the world at the moment—they're not thinking big enough. Nobody's thinking big enough" (Flint, 2021).

Another important area of concern relates to climate vulnerabilities disproportionately borne by low-income communities and communities of color. In the case of Boston's coastal flooding, these vulnerabilities manifest in a number of ways: disrupted transit access affecting work and healthcare access, revenue losses for small businesses, property damage costs, and housing displacement. These, in turn, increase the financial stress these populations already experience (Plastrik, 2023). The Office of Climate Resilience has formally recognized these challenges by emphasizing equitable outcomes and prioritizing frontline communities that face the highest climate disaster risks. Several key climate resilience planning documents incorporate climate justice principles, acknowledging historical injustices and emphasizing transparency and accountability for climate justice outcomes (Plastrik, 2023). However, the implementation of these principles has at times fallen short of community expectations. Although planners have tried, Boston's Climate Progress Report (Fitzgerald & Walsh, 2022) documents residents' frustration with the lack of meaningful engagement and transparency. This was particularly acute in communities like East Boston, Roxbury, and Mattapan, where residents reported feeling that their input was ignored or deliberately overlooked. Further concerns of green gentrification in neighborhoods like East Boston and Dorchester, though, remain an unresolved controversy (Rios, 2019).

These equity concerns motivate a closer look at just how equitable the data-driven aspects of Boston's coastal resilience planning actually are. With its concentration of universities and experts, it makes sense that Boston might be considered at the forefront of a data-driven approach to coastal resilience. Boston, too, maintains an open data portal with publicly accessible datasets on various climate and environmental indicators (see Figure 4). Yet, as with the other case studies explored here, Boston faces challenges with inequities that exist with the data itself, as well as in the way the community has been engaged with the data that drives the city's coastal resilience planning and decision-making.

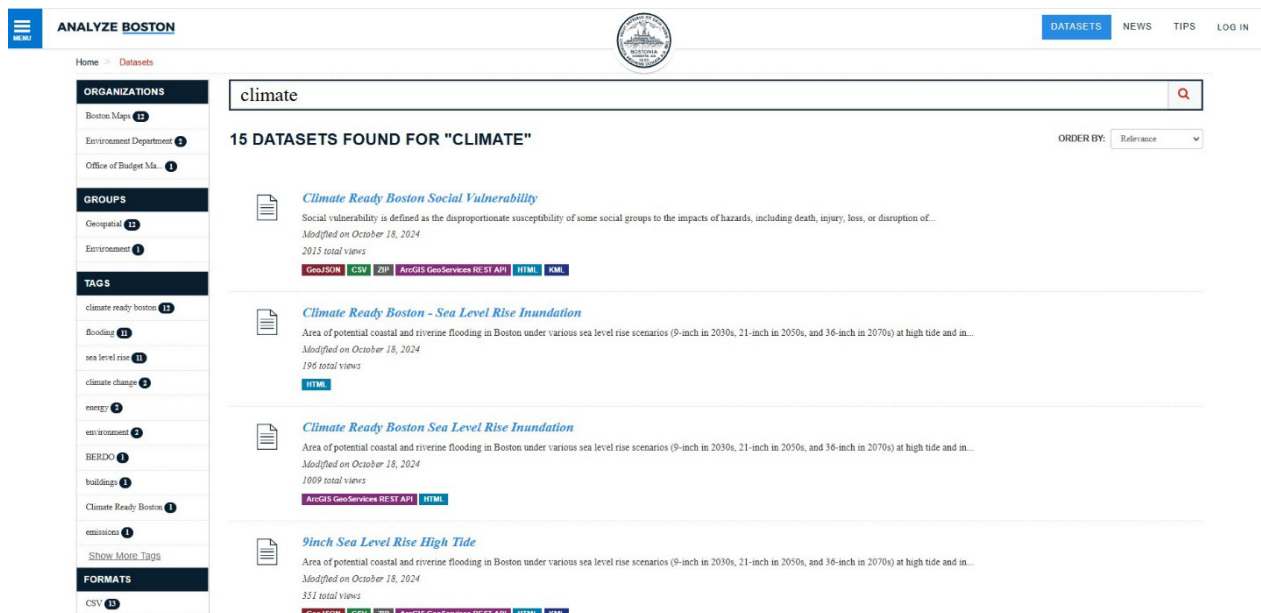


Figure 4. Analyze Boston open data portal. Source: City of Boston (n.d.).

One problem is the technical nature that is inherent to a data-driven process. Here, Boston can learn much from McIntyre et al.'s (2024) findings on community engagement with extreme heat and air quality in East

Boston and Chelsea (a neighboring city), which found considerable barriers stemming from data accessibility and interpretation. Community members reported difficulty understanding technical metrics due to reliance on technical language and a lack of user-friendly visualization tools. The study's authors also found that insufficient climate forecasting data and longitudinal data on environmental exposures and their health impacts made it more difficult for community members to grasp "why should the average person care?" (McIntyre et al., 2024). A separate study of perceptions on managed retreat found similar views (Urban Harbors Institute, 2023). The issue is compounded by the reality that the average resident may not have the technical expertise required to access and interpret scientific findings, in addition to academic paywalls that may make it cost-prohibitive. These were found to further alienate non-expert stakeholders (McIntyre et al., 2024).

Despite comprehensive planning efforts, there are additional weaknesses in how Boston specifically has engaged the community with data throughout this process. Even data on the implementation process itself could be useful here. Malloy et al. (2022) found that there was insufficient transparency on things like team formation and selection processes, which makes policy evaluation difficult. Community members have reported getting the impression that agencies conducting public outreach often fail to share community input data with each other, even when addressing similar environmental issues (Belloy et al., 2021). Having data on the actual processes and the kinds of input that were generated is important for equitable, data-informed decisions. As McIntyre et al. (2024) point out, research conducted without local community involvement or feedback becomes "just data for data's sake."

Thus, there is room for additional input on how evaluation criteria are determined and what specific data is being collected. Community definitions of resilience are not always integrated into planning, which can then lead to unintended outcomes. Developing and monitoring metrics based on those definitions ensures that communities remain "on the path toward resilience as defined by the community" (Belloy et al., 2022, p. 10). Particularly in the early stages of climate resilience planning, evaluation criteria prioritized technical and financial feasibility, and in the process marginalized community needs. For instance, although equity was ranked a top priority by community participants in the planning for South Boston's plan, it was excluded from the final project report (Malloy et al., 2022). Notably, Boston did address these concerns in its next phase of planning.

Engaging the community at these stages helps to ensure that the indicators being tracked make sense. At present, there is insufficient tracking of key indicators like housing stock, health metrics, and certain climate impacts that would allow for the evaluation of resilience measures and any unintended consequences (Belloy et al., 2022). This is further complicated by the lack of transparency in private sector involvement discussed above further complicates evaluation of spending and outcomes (Flint, 2021; Omoeva, 2022; Rickley, 2024). Having a more collaborative, participatory monitoring process can help enable communities to address unintended consequences as they arise (Belloy et al., 2022). The Green Ribbon Commission has recommended the creation of a "climate justice scorecard" to track progress on climate justice outcomes in particular. This would include establishing a baseline along with key performance indicators, defined data sets for measurement, and user-friendly ways to share data with the community (Plastrik, 2023).

Inequitable data dissemination and access result in community members missing critical planning meetings and information. In one study, residents suggested that the city was not effectively utilizing existing resources,

such as the school system, to distribute information to families (Belloy et al., 2021). The absence of transparent and participatory monitoring mechanisms weakens trust and impedes effective evaluation of resilience efforts. Improved dissemination strategies, such as user-friendly data-sharing platforms and accessible metrics, are essential to fostering trust and community participation. Ultimately, the Boston case illustrates how even in contexts where inequalities are recognized as part of the planning process, there can be weaknesses in implementation that stem from these data management concerns.

6. Discussion

The preceding case studies reveal that data practices in coastal resilience planning are neither neutral nor inevitable. Rather, they reflect specific institutional choices, power dynamics, and historical legacies that shape whose knowledge counts and whose needs are prioritized. While New Orleans, Boston, and Norfolk each developed distinct approaches to data governance and community engagement, all three cities demonstrate how seemingly technical decisions about data collection, analysis, and deployment have profound implications for equity in climate adaptation. The following analysis synthesizes these findings through the four dimensions of our theoretical framework to identify patterns and mechanisms that go beyond individual city contexts. This synthesis is summarized in Table 1, and further insights follow.

Table 1. Case comparison analysis.

Framework	New Orleans	Norfolk	Boston
Data as Socially Constructed	Data priorities have included: • Technical data on flood risk • “Blight” data on abandoned and deteriorated properties post-Katrina • Social vulnerability indicators Assumptions about metrics have been shaped by experience with Hurricane Katrina and subsequent rebuilding priorities; definitions of “blight” in the context of historically marginalized communities; how vulnerabilities and risks are defined.	Data priorities have included: • Technical data on storm surges and flood events • Military and national security infrastructure needs • Commercial and shipping data • Property values • Economic impact • Social equity criteria Assumptions about metrics have been shaped by the way infrastructure and economic considerations have been prioritized; recent reevaluations to include social equity criteria.	Data priorities have included: • Technical data on risk projections • Property value and economic development • Social equity measures Assumptions about metrics have been shaped by formal recognition of climate justice principles; debates over who pays and who benefits from resilience measures; and whose definition of resilience is being used to develop the metrics.

Table 1. (Cont.) Case comparison analysis.

Framework	New Orleans	Norfolk	Boston
Data Sovereignty and Governance	• Critical climate resilience data housed in a non-governmental data center • Persistent coordination challenges across agencies • Formal open data policy established but with limited implementation	• Centralized approach integrating military and civilian data demands • Multi-jurisdictional challenges requiring coordination across federal, state, and municipal entities • African American neighborhoods lacking “dominion” over data used for flood prevention decisions	• Decentralized neighborhood-specific plans with citywide coordination • Multi-agency coordination challenges, including failure to share community input • Insufficient transparency on plan implementation processes and monitoring, as well as stemming private sector involvement
Ethics of Data Collection	• Vulnerabilities determined by historical patterns of discrimination and reinforced by BlightStat’s focus • Uneven access to permitting data based on social and institutional connections • Despite efforts to address climate justice indicators as part of the Gentilly Resilience District project, implementation challenges have undermined these	• Concern over how data was used to identify protected areas and ultimately perpetuate discriminatory patterns • Growing recognition of the need to value local knowledge alongside technical data • Different stakeholders’ varying engagement with data and decision-making	• The significance of private sector raises questions about who benefits from resilience measures • Despite formal recognition and efforts to address climate justice, there are weaknesses in community engagement with metric definitions, collaborative monitoring, and data dissemination
Infrastructure and Access	• The Data Center established to make regional data “relevant and accessible” • City’s open data portal offered limited datasets, none on climate resilience • BlightStat online tool improved accessibility of property data, while the Gentilly Resilience District Project provided online visualization tools	• Sophisticated resilience dashboard maintained by the city • Differing levels of community trust and engagement with official data systems • Differing degrees of participation and trust in official data systems	• Maintains the Boston Open Data portal with publicly accessible datasets • Concerns raised about academic paywalls and technical expertise requirements for some data • Inequitable and insufficient data dissemination reported

In terms of the first dimension, data as socially constructed, the summary of the case studies in Table 1 provides confirmation that data is not neutral. Across all three cities, we observe a tendency to prioritize quantifiable economic and technical data over social equity metrics or community knowledge, especially in earlier stages of planning. Part of this stems from a bias toward technical expertise over local knowledge and

a desire for more quantifiable metrics over qualitative experience. Traditional cost-benefit analyses tend to emphasize economic interests, as we see in the case of the Bligh-State program's focus on property in New Orleans, on Norfolk's military and commercial shipping interests, and in the reality of private waterfront ownership in Boston. This type of analysis also tends to reinforce existing power structures. We see this in New Orleans, with more politically connected communities like Broadmoor having their data needs better represented and historical patterns of discrimination playing out in these processes. In Norfolk, residents of historically Black neighborhoods like Berkley, Campostella, and Tidewater Gardens reported feeling left out of the planning proceedings. Even in Boston, where planning processes were purportedly centered around equity principles, low-income residents and communities of color in vulnerable areas felt their input was not always incorporated. Where social equity metrics were eventually included, these too reflect assumptions about how vulnerabilities are measured and who is defining them. Though there are variations across the case studies, overall, these patterns align with Kitchin's framework, reflecting existing power structures rather than being neutral or objective.

The second dimension considers data sovereignty and governance, how it is collected and utilized. The case studies reveal interesting variations in terms of how centralized or decentralized these processes are, with Norfolk representing the most centralized approach to climate data management, and Boston the most decentralized with its neighborhood-centric approach. In the case of New Orleans, capacity gaps have translated to reliance on external data providers. All three cities face challenges in terms of multi-agency coordination. There is also limited transparency about how data decisions are made, with a lack of clarity and consistency on how community input is translated and incorporated into data processes. While we see efforts to collect data on historically marginalized communities vulnerable to climate effects, it remains data *about* those communities, and it is less clear how those communities can be directly involved with data governance.

This relates to the ethics of data collection in terms of the accountability and transparency of data processes. In all three cases, we do see efforts to articulate and measure social equity impacts. In the case of Boston, formal commitments to environmental justice were part of planning from the start. In New Orleans, the Gentilly Resilience District initiative represents a step forward. And in Norfolk, responses to community outrage have meant growing recognition of equity considerations. In all cases, there are weaknesses in implementation, however, and recognition does not necessarily come with accountability. Whether it is insufficient progress monitoring as in New Orleans, or room for more collaborative monitoring processes as in Boston, there is room for improvement.

The final dimension under consideration looks at infrastructure and access. All three cities do strive to make data accessible to the public. Boston through its Analyze Boston open data portal and Norfolk with its Resilience Dashboard. Although New Orleans Open Data does not include climate resilience datasets, these are available through the Data Center's website. However, these open data initiatives do not necessarily address fundamental accessibility issues related to digital divides. As discussed in the Boston case study, additional consideration is needed for improved dissemination strategies and techniques. Our comparison illustrates how the gap between data *availability* and meaningful *accessibility* particularly affects historically marginalized communities across all three cities.

Together, these findings advance Kitchin's (2021) critical data framework by providing a systematic application to climate resilience planning, while contributing empirical evidence for the social resilience theories advanced by scholars like Meerow et al. (2019) and Doost et al. (2023), who argue for more process-oriented approaches that build community capacity and ensure equitable governance.

7. Conclusion

Analysis of the experiences of Boston, Norfolk, and New Orleans lends insight into how data practices can challenge or reinforce existing inequities, particularly in communities that are vulnerable to climate impacts. Our comparison reveals systemic inequities across diverse urban contexts and offers a conceptual bridge between critical data studies and climate justice scholarship.

Each case demonstrates that data is not unbiased technical information. Instead, as Kitchin argues, data is socially constructed, and emerges from specific social, political, and institutional contexts. New Orleans' BlightStat program, Norfolk's flood wall controversy, and Boston's gaps in community engagement highlight the fact that the way data is constructed can perpetuate historical patterns of marginalization. Those developing and evaluating data metrics should consider the question: cost-benefit for whom?

Data governance can shape planning outcomes and either inspire or degrade community trust. New Orleans' reliance on external organizations for crucial climate data, Norfolk's challenges with integrating military and civilian data systems, and Boston's issues with private sector data coordination demonstrate how governance structures impact data accessibility and effectiveness.

Participatory approaches are critical. Meaningful community engagement in data collection, analysis, and decision-making can ensure that resilience measures address local needs and priorities. Traditional public comment periods and community forums are not enough to achieve this goal. Instead, impacted communities must be actively involved in determining what data is collected, how it is analyzed, and how it informs decision-making. Boston's evolution toward more community-defined indicators and New Orleans' growing emphasis on participatory data governance indicate the potential for more inclusive approaches, while at the same time highlighting challenges with implementation.

This research advances both critical data and urban studies by applying Kitchin's framework to climate resilience planning. The four-dimensional analytical framework offers a replicable approach for examining data justice in urban environmental policy, while our comparative methodology reveals how institutional arrangements and data governance structures produce different outcomes even under similar challenges. Empirically, we document specific mechanisms through which data practices exclude or empower communities, offering concrete guidance for practitioners seeking to implement more equitable approaches to urban climate adaptation.

7.1. Recommendations

Our case studies suggest several recommendations for cities seeking more equitable coastal resilience planning. First, centering equity and community participation is vital. Community engagement entails not just collecting data about vulnerable communities but actively involving them in determining what data is

collected and how it is used. Second, technical data should be made more accessible and meaningful to diverse audiences. This includes (but is not limited to) the inclusion of community-defined indicators and the development of more user-friendly platforms for data sharing and interpretation. Finally, more transparent and participatory monitoring mechanisms are needed that allow communities to track progress and address unintended consequences as they arise.

Social equity is frequently insufficiently considered in current methods of assessing performance in both climate and urban resilience. Ecological frameworks and socioeconomic techniques need to be better integrated with explicit attention to justice and equality considerations, even while ecological frameworks stress system-level analysis and socioeconomic approaches concentrate on neighborhood consequences. Accomplishing this integration requires creating measures that account for the acute and ongoing pressures faced by historically underserved communities, ensuring that underserved populations are actively included in resilience planning, establishing systems of responsibility for equitable results in resilience projects, and ameliorating the fundamental political and social issues that lead to vulnerability.

In addition to strengthening the processes for converting community knowledge into policy action, future efforts must concentrate on creating frameworks that prioritize social fairness. This entails paying close attention to the creation, interpretation, and deployment of resilience data to ensure the methods of measurement do not perpetuate exclusionary and marginalizing patterns.

7.2. Limitations and Implications

Several limitations do warrant acknowledgement. Reliance on secondary sources for community responses means perspectives are filtered through researchers and journalists rather than captured directly. Furthermore, document-based analysis captures formal data practices but may miss informal approaches that emerge during implementation. Future research in this area might be served by incorporating primary data collection with community members or employing participatory methods that engage communities directly in evaluating and redesigning data practices.

Although our focus was on three US cities, many of the patterns we have identified can apply across diverse urban contexts worldwide. Particularly in rapidly urbanizing coastal megacities in the Global South, policymakers should be cautious of data practices that reinforce power dynamics, technical barriers that exclude marginalized communities, and institutional arrangements that privilege certain knowledge. Beyond climate adaptation, our framework provides a template for evaluating data justice across urban policy domains as cities increasingly adopt “smart city” technologies and big data analytics.

As coastal cities continue to wrestle with climate change impacts, these lessons become increasingly crucial. While data-driven approaches offer powerful tools for resilience planning, their effectiveness ultimately depends on how well they address existing inequities and empower vulnerable communities. Building urban resilience necessitates a commitment to social justice and equity in addition to technical solutions. This requires addressing the structural injustices that increase vulnerability to climate hazards and ensuring that data infrastructure serves all populations rather than reproducing existing inequalities.

Conflict of Interests

The authors declare no conflict of interests.

LLMs Disclosure

Claude.ai was prompted for feedback on narrative cohesion and minor edits.

References

- Belloy, P., Herst, R., & Raciti, A. (2022, March 10). Make a green future work for all Bostonians: The urgency to act on the climate crisis should not get in the way of a truly inclusive process. *Boston Globe*.
- Belloy, P., Raciti, A., Rivera-Kientz, K., & Herst, R. (2021). *Opportunity in the complexity: Recommendations for equitable climate resilience in East Boston* [Working Paper]. UMass Boston Sustainable Solutions Lab. https://www.umb.edu/media/umassboston/content-assets/documents/Opportunity_in_the_Complexity_Recommendations_English_final.pdf
- Boston Environment Department. (2024). *Boston revamps environment, energy and open space cabinet for dedicated climate resilience focus and leadership*. City of Boston. <https://www.boston.gov/news/boston-revamps-environment-energy-and-open-space-cabinet-dedicated-climate-resilience-focus>
- Brodie, P., Fratzczak, M., Gkotsopoulou, O., Halkort, M., Hoyng, R., Quinn, P., Nost, E., & Bates, J. (2024). Environmental data power. In J. Bates & J. Jarke (Eds.), *Dialogues in data power* (1st ed., pp. 138–158). Bristol University Press. <https://doi.org/10.2307/jj.15617032.12>
- Campanella, R. (2006). *Geographies of New Orleans: Urban fabrics before the storm*. Center for Louisiana Studies.
- City of Boston (2025). *Coastal resilience planning*. <https://www.boston.gov/departments/climate-resilience/coastal-resilience-planning>
- City of Boston. (n.d.). *Analyze Boston*. <https://data.boston.gov>
- City of New Orleans. (n.d.). *Data driven*. <https://datadriven.nola.gov/home>
- City of New Orleans. (2018). *Gentilly Resilience District—Fact sheet*. Office of Resilience and Sustainability. <https://nola.gov/archived/resilience-sustainability/resources/fact-sheets/gentilly-factsheet>
- City of New Orleans. (2020). *A plan for the 21st century: New Orleans 2030*. City Planning Commission. <https://masterplan.nola.gov>
- City of New Orleans. (2022). *Net zero by 2050: A priority list for climate action in New Orleans*. Office of Resilience and Sustainability. <https://nola.gov/nola/media/Climate-Action/2022/Net-Zero-by-2050-A-Priority-List-for-Climate-Action-in-New-Orleans.pdf>
- City of Norfolk. (n.d.). *Norfolk open data*. <https://data.norfolk.gov>
- City of Norfolk. (2015). *Norfolk resilient city*. <https://www.epa.gov/system/files/documents/2023-12/norfolk-va-resilient-strategy-2015.pdf>
- City of Norfolk. (2016). *Norfolk Vision 2100*. <https://www.norfolk.gov/DocumentCenter/View/27768/Vision-2100---FINAL>
- City of Norfolk. (2021). *Virginia department of conservation and recreation: 2021 Virginia community flood preparedness fund grant*. <https://www.dcr.virginia.gov/dam-safety-and-floodplains/document/CFPF-21-01-22-S-CID510104-CityofNorfolk-CFPF.pdf>
- Craig, M. (2022). An overview of flood risk to the housing finance ecosystem. *Cityscape: A Journal of Policy Development and Research*, 24(1), 345–368.
- Davidson, J. L., Jacobson, C., Lyth, A., Dedekorkut-Howes, A., Baldwin, C. L., Ellison, J. C., Holbrook, N. J., Howes, M. J., Serrao-Neumann, S., Singh-Peterson, L., & Smith, T. F. (2016). Interrogating resilience. *Ecology and Society*, 21(2), Article 27. <https://www.jstor.org/stable/26270410>

- Doost, D. M., Brunetta, G., & Caldarice, O. (2023). In search of equitable resilience: Unravelling the links between urban resilience planning and social equity. *Sustainability*, 15(18), Article 18. <https://doi.org/10.3390/su151813818>
- Douglas, E., & Carlock, C. (2024, April 7). Boston's defenses against rising seas lean on private development. What happens when the money dries up? The development slowdown highlights the downside of asking waterfront builders to bulk up the city's protections against sea level rise. *Boston Globe*. <https://www.bostonglobe.com/2024/04/05/science/boston-sea-level-rise-real-estate-development-slowdown>
- Fitzgerald, J., & Walsh, M. J. (2022). *The inaugural Boston climate progress report*. The Boston Foundation. <https://www.tbf.org/news-and-insights/reports/2022/november/2022-climate-report-card-20221103>
- Flint, A. (2021, April 27). Boston takes on climate change. *Planning Magazine*. <https://www.planning.org/planning/2021/spring/boston-takes-on-climate-change>
- Foster, C. A., & Johnson, T. (2020). *Expanding Boston's capacity to build coastal resilience infrastructure lessons from the seaport district*. Boston Green Ribbon Commission. <https://greenribboncommission.org/document/expanding-bostons-capacity-to-build-coastal-resilience-infrastructure-lessons-from-the-seaport-district>
- Gardere, L., Plyer, A., & Ross, D. (2020). How data became part of New Orleans' DNA during the Katrina recovery. *New England Journal of Public Policy*, 32(1), Article 21. <https://scholarworks.umb.edu/nejpp/vol32/iss1/21>
- Goytia, C. (2024). *Examining opportunities and challenges for implementing land-based financing instruments for funding climate action: A study of land markets and flood risk pricing in different contexts* [Working Paper]. Lincoln Institute of Land Policy. <https://www.lincolninst.edu/publications/working-papers/examining-opportunities-challenges-implementing-land-based-financing-instruments-funding-climate-action-miami>
- Habans, R., Losh, J., & Tomlin, H. (2023). *Equity metrics to support the Louisiana climate action plan*. The Data Center. <https://gov.louisiana.gov/assets/Proclamations/2023/CAPEquityMetricsfullReport.pdf>
- Hadjis, E. (2022, January 24). In the race to solve Boston Harbor's coastal flooding problem, who calls the shots? *The Scope*. <https://thescopeboston.org/7534/news-and-features/features/in-the-race-to-solve-boston-harbors-coastal-flooding-problem-who-calls-the-shots>
- Hafner, K. (2023, September 2). *At risk from rising seas, Norfolk, Virginia, plans massive, controversial floodwall*. NPR. <https://www.npr.org/2023/09/02/1193726251/at-risk-from-rising-seas-norfolk-virginia-plans-massive-controversial-floodwall>
- Harris, E., Franz, A., & O'Hara, S. (2023). Promoting social equity and building resilience through value-inclusive design. *Buildings*, 13(8), Article 8. <https://doi.org/10.3390/buildings13082081>
- Hobor, G., Plyer, A., & Horwitz, B. (2014). *The coastal index: The problem and possibility of our coast*. The Data Center. https://www.datacenterresearch.org/reports_analysis/the-coastal-index
- Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1–23.
- Hughes, S., Dobie, S., Schwarz, K., LaMarr LeMee, G., Lane, M., & Gonzalez, A. (2022). Centering racial justice in urban flood resilience policy and planning: Tools for practitioners. *Environmental Justice*, 15(2), 83–89. <https://doi.org/10.1089/env.2021.0045>
- Jayawardhan, S. (2017). Vulnerability and climate change induced human displacement. *Consilience*, 17, 103–142. <https://www.jstor.org/stable/26188784>
- Johnson, C., & Osuteye, E. (2019). Data gaps and resilience metrics. In M. A. Burayidi, A. Allen, J. Twigg, & C. Wamsler (Eds.), *The Routledge handbook of urban resilience* (pp. 59–70). Routledge.

- Johnson, D. R., Fischbach, J. R., & Kuhn, K. (2015). *Current and future flood risk in greater New Orleans*. The Data Center. https://www.datacenterresearch.org/reports_analysis/flood-risk
- Keck, M., & Sakdapolrak, P. (2013). What is social resilience? Lessons learned and ways forward. *Erdkunde*, 67, 5–18. <https://doi.org/10.3112/erdkunde.2013.01.02>
- Kitchin, R. (2021). *Data lives: How data are made and shape our world*. Bristol University Press.
- Lioubimtseva, E., Zylman, H., Carron, K., Poynter, K., & Rashrash, B. M.-E. (2024). Equity and inclusion in climate action and adaptation plans of Michigan cities. *Sustainability*, 16(17), Article 17. <https://doi.org/10.3390/su16177745>
- Lonsdale, K., Arnell, N., Coles, T., Lock, K., O'Connell, E., O'Hare, P., & Tompkins, E. (2024). Climate resilience: Interpretations of the term and implications for practice. In S. Dessai, K. Lonsdale, J. Lowe, & R. Harcourt (Eds.), *Quantifying climate risk and building resilience in the UK* (pp. 15–23). Palgrave Macmillan. https://doi.org/10.1007/978-3-031-39729-5_2
- Malloy, J. T., Ashcraft, C. M., Kirshen, P., Safford, T. G., Aytur, S. A., & Rogers, S. H. (2022). Implementing just climate adaptation policy: An analysis of recognition, framing, and advocacy coalitions in Boston, U.S.A. *Frontiers in Sustainable Cities*, 4, Article 928230. <https://doi.org/10.3389/frsc.2022.928230>
- Marshall, R. (2001). *Waterfronts in post-industrial cities*. Routledge.
- Martin, N. C. (2023, December 18). Inside New Orleans' data-driven recovery. *Next City*. <https://nextcity.org/urbanist-news/inside-new-orleans-data-driven-recovery>
- Martin-Breen, P., & Anderies, J. (2011). *Resilience: A literature review*. The Bellagio Initiative. <https://www.semanticscholar.org/paper/Resilience%3A-A-Literature-Review-Martin-Breen-Anderies/98200d79e342ef435f3311eea80e8b39fb2ee443>
- McIntyre, A., Heidari, L., Hagen, M., Bongiovanni, R., Bowman, B. N., Fabian, P., Kinney, P., & Scammell, M. K. (2024). Extreme heat and air quality: Community leader perspectives on information barriers and opportunities in two environmental justice communities. *NEW SOLUTIONS: A Journal of Environmental and Occupational Health Policy*, 34(4), 256–267. <https://doi.org/10.1177/10482911241290557>
- Meerow, S., Pajouhesh, P., & Miller, T. R. (2019). Social equity in urban resilience planning. *Local Environment*, 24(9), 793–808.
- Menedian, S., Gambhir, S., & Gales, A. (2021). *The roots of structural racism project: Twenty-first century racial residential segregation in the United States*. Othering & Belonging Institute. <https://belonging.berkeley.edu/roots-structural-racism>
- Mertz, Z. G. (2016). *Tracking the flood—Gaining a new perspective on flood management in Boston using socio-hydrology* [Unpublished master's thesis]. University of Massachusetts Boston. <https://www.proquest.com/docview/1803939528/abstract/6A72BC14A2D14AE7PQ/1>
- Morrison, J. (2023, December 17). Norfolk has a plan to save itself from rising seas. For many, it's a \$2.7 billion mystery. *Virginia Center for Investigative Journalism*. <https://vcij.org/stories/norfolkfloodwall>
- National Association for the Advancement of Colored People. (2021). *Turning the tide: Advancing racial justice in federal flood infrastructure projects*. <https://naacp.org/resources/turning-tide-advancing-racial-justice-federal-flood-infrastructure-projects>
- National Oceanic and Atmospheric Administration. (2022). *Global and regional sea level rise scenarios for the United States: Updated mean projections and extreme water level probabilities along U.S. coastlines* (NOAA Technical Report NOS 01). <https://earth.gov/sealevel/us/resources/2022-sea-level-rise-technical-report>
- Norris, F. H., Stevens, S. P., Pfefferbaum, B., Wyche, K. F., & Pfefferbaum, R. L. (2008). Community resilience as a metaphor, theory, set of capacities, and strategy for disaster readiness. *American Journal of Community Psychology*, 41(1/2), 127–150. <https://doi.org/10.1007/s10464-007-9156-6>

- Nost, E. (2018). *Programming adaptation: How modeling informs environmental policy in Louisiana's coastal master plan* [Unpublished doctoral dissertation]. University of Wisconsin-Madison. <https://search.library.wisc.edu/digital/ANM4WLYEMHJKON8W>
- Office of Homeland Security and Emergency Preparedness. (2021). *Hazard mitigation plan: City of New Orleans*. <https://ready.nola.gov/NOLAReady/media/Assets/Hazard%20Mitigation%20Plan/2020-City-of-New-Orleans-Hazard-Mitigation-Plan.pdf>
- Omoeva, B. (2022, June 16). Boston's climate initiative and its obstacles to implementation. *The Scope*. <https://thescopeboston.org/8054/news-and-features/features/bostons-climate-initiative-and-its-obstacles-to-implementation>
- Othering & Belonging Institute. (n.d.). *Most to least segregated cities in 2020*. <https://belonging.berkeley.edu/most-least-segregated-cities-in-2020>
- Penna, A. N., & Wright, C. E. (2009). *Remaking Boston: An environmental history of the city and its surroundings*. University of Pittsburgh Press.
- Plastrik, P. (2023). *Our shared history report: Using Boston's climate opportunities to address systemic racism*. Boston Green Ribbon Commission; Embrace Boston. <https://greenribboncommission.org/document/boston-green-ribbon-commission-and-embrace-boston-our-shared-history-report>
- Raciti, A., Negron, R., & Herst, R. (2023). Social resilience in the face of the unexpected. In D. Gamble (Ed.), *Idea city* (pp. 117–136). University of Massachusetts Press.
- Resilient Cities Network. (n.d.). *What is urban resilience?* <https://resilientcitiesnetwork.org/what-is-urban-resilience>
- Resilient Norfolk. (2025). *Project updates*. <https://www.resilientnorfolk.com/pages/project-updates>
- Rickley, L. (2024). *What happened to climate ready Boston?* Conservation Law Foundation. <https://www.clf.org/blog/what-happened-to-climate-ready-boston>
- Rios, S. (2019, May 2). As Boston pursues climate resilience, some warn efforts could make inequality worse. *WBUR*. <https://www.wbur.org/news/2019/05/02/moakley-park-east-boston-climate-resiliency>
- Ruckert, K. L., Srikrishnan, V., & Keller, K. (2019). Characterizing the deep uncertainties surrounding coastal flood hazard projections: A case study for Norfolk, VA. *Nature Research: Scientific Reports*, 9(1), Article 11373. <https://doi.org/10.1038/s41598-019-47587-6>
- Rumson, A. G., Hallett, S. H., & Brewer, T. R. (2017). Coastal risk adaptation: The potential role of accessible geospatial Big Data. *Marine Policy*, 83, 100–110. <https://doi.org/10.1016/j.marpol.2017.05.032>
- Seasholes, N. S. (2018). *Gaining ground: A history of landmaking in Boston*. MIT Press.
- Talke, S. A., Kemp, A. C., & Woodruff, J. (2018). Relative sea level, tides, and extreme water levels in Boston harbor from 1825 to 2018. *Journal of Geophysical Research: Oceans*, 123(6), 3895–3914. <https://doi.org/10.1029/2017JC013645>
- The Data Center. (n.d.). *The coastal index dashboard*. <https://www.datacenterresearch.org/coastal-dashboard/index.html>
- The Rockefeller Foundation. (n.d.). *100 Resilient cities*. <https://www.rockefellerfoundation.org/100-resilient-cities>
- Trust for Public Land. (2023). *Eco-social and economic benefits of parks and green infrastructure in New Orleans: Literature review*. [https://nola.gov/nola/media/Stormwater/Ecosocial-and-Economic-Benefits-of-Green-Infrastructure-in-New-Orleans-TPL-Literature-Review-\(Final\).pdf](https://nola.gov/nola/media/Stormwater/Ecosocial-and-Economic-Benefits-of-Green-Infrastructure-in-New-Orleans-TPL-Literature-Review-(Final).pdf)
- UN Environment Programme. (2021). *The gathering storm: Adapting to climate change in a post-pandemic world*. <https://www.unep.org/resources/adaptation-gap-report-2021>
- Ungar, M. (2011). The social ecology of resilience: Addressing contextual and cultural ambiguity of a nascent

construct. *The American Journal of Orthopsychiatry*, 81(1), 1–17. <https://doi.org/10.1111/j.1939-0025.2010.01067.x>

Urban Harbors Institute. (2023). *Perspectives on managed retreat in Massachusetts coastal communities: Results of a survey of municipal representatives*. UMass Boston. https://www.umb.edu/media/umassboston/content-assets/urban-harbor-institute/Perspectives_on_Managed_Retreat_in_Coastal_Communities_FINAL.pdf?utm_source=chatgpt.com

US Department of Housing and Urban Development. (2024). *After more than 6 years, the city of New Orleans' national disaster resilience project activities had made little impact on resilience*. Office of Inspector General; US Department of Housing and Urban Development. <https://www.hudoig.gov/reports-publications/report/after-more-6-years-city-new-orleans-national-disaster-resilience>

Wasser, M. (2024, August 5). Boston announces a new climate resilience office. *WBUR*. <https://www.wbur.org/news/2024/08/05/boston-climate-change-resiliency-osgood>

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Enhancing Sustainable and Resilient Water Infrastructure in South Africa in the Face of Climate Change

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Abstract

In the context of climate change, ensuring the sustainability and resilience of urban water infrastructure in South Africa remains a critical challenge. This study investigates the barriers hindering effective water infrastructure delivery and identifies the factors contributing to inefficiencies. It also evaluates strategies to enhance the resilience and sustainability of water infrastructure projects, focusing on water utility agencies across the country. Key research questions include: What are the barriers to the delivery of sustainable and resilient water infrastructure in South Africa? What strategies can enable the delivery of sustainable and resilient water infrastructure in South Africa? Using survey research, statistical modelling, and case study analysis, the study highlights significant challenges such as ageing infrastructure, poor maintenance, financial constraints, climate change impacts, governance issues, inefficient project management, and water resource scarcity. These challenges were found to stem from four core dimensions: inadequate project management practices, organisational and managerial limitations, operational and maintenance deficiencies, and socio-political factors. In response, the study proposes a five-pronged strategic framework to strengthen water infrastructure delivery. Recommended strategies include upgrading and maintaining ageing systems, improving funding mechanisms and financial oversight, adopting climate-resilient technologies, enhancing project management capacity, and reinforcing governance and accountability structures. Implementing these strategies is essential for ensuring South African cities are better prepared to withstand climate-related disruptions and maintain reliable access to water resources. Ultimately, integrating sustainability and resilience into water infrastructure planning and management is vital for securing long-term water security and supporting urban development under changing environmental conditions.

Keywords

barriers; climate change; resiliency; South Africa; strategies; sustainability; water infrastructure

1. Introduction

Infrastructure is widely recognised as the backbone of socio-economic development, facilitating growth and improving quality of life. Over the past two decades, developing countries such as South Africa, China, India, Vietnam, and Thailand have prioritised significant investments in both physical and digital infrastructure, including transportation, energy, water, housing, and information and communication technology. These efforts aim to stimulate economic progress and deliver substantial social benefits (Calderon & Serven, 2014; World Bank, 2020).

In South Africa, large-scale infrastructure development was at the peak during the 1960s and 1970s, driven by significant public investment that are aimed at establishing efficient systems to support socio-economic growth. Public sector water utility agencies, affiliated with the South African Association of Water Utilities (SAAWU)—a Section 21 company established in March 2001—play a key role in this effort. Formerly known as the South African Association of Water Boards, SAAWU represents and coordinates the interests of state-owned water service providers. Its membership includes nine agencies: Amatola Water, Bloem Water, Magalies Water, Mhlathuze Water, Midvaal Water Company, Lepelle Northern Water, Rand Water, Sedibeng Water, and Umgeni Water.

These agencies are responsible for developing critical infrastructure such as dams, pump stations, pipelines, reservoirs, and water and wastewater treatment works. Their projects follow standard project management practices based on the PMBOK framework, progressing through the phases of initiation, planning, design, execution, and closure. Despite these structured approaches, many agencies encounter challenges in delivering projects on time and have implemented remedial measures to address delays. For instance, Umgeni Water introduced its project management plan in 2012 to improve project execution and ensure consistent delivery. This plan aligns with PMBOK principles and incorporates additional procedures tailored to the agency's specific operational needs (Umgeni Water Project Management Plan, 2012).

However, the country has faced persistent challenges in recent years due to ageing and inadequate infrastructure, which have hindered development in various regions. Recognising the critical link between infrastructure development and economic progress (Chakamera & Alagidede, 2018; Coetzee & Kleynhans, 2017; McGaffin et al., 2019; More & Aye, 2017), the South African government has undertaken extensive efforts since the early 2000s to modernise and expand infrastructure across key sectors, including transportation, energy, and water (Cartwright et al., 2024; Fedderke & Garlick, 2008; Fourie, 2006; Marais, 2013).

Despite these efforts, the delivery of infrastructure projects has been plagued by delays, cost overruns, and inefficiencies. The public sector's infrastructure spending, which exceeded ZAR 2.2 trillion (122 billion USD) between 1998 and 1999 and 2014 and 2015, has not yielded the desired outcomes (National Treasury Budget Review, 2016). For example, large-scale water infrastructure projects have seen a 30% decline in delivery over recent years (Aiyetan & Das, 2021; Naidoo, 2016; Watermeyer & Phillips, 2020). Key challenges include inappropriate procurement practices, inadequate project management capacity, poor stakeholder engagement, and political interference (Watermeyer & Phillips, 2020). These issues highlight the need for improved governance, strategic planning, and innovative management approaches to enhance project delivery.

Water infrastructure, in particular, is under immense pressure due to climate change, population growth, and economic demands. South Africa's water security is increasingly at risk, necessitating a shift towards sustainable and resilient water infrastructure. The integration of frameworks such as the water-energy-food-health (WEF-H) nexus offers an opportunity to address the interdependencies between these critical sectors and promote holistic resource management (Mutanga et al., 2024). Moreover, climate-resilient strategies, such as leveraging nature-based solutions and improving governance structures, are essential to address systemic challenges and ensure long-term sustainability (Cartwright et al., 2024; Vinke-De Kruijf et al., 2024).

Despite significant progress in infrastructure development, the absence of comprehensive legal and institutional frameworks continues to impede effective climate adaptation in South Africa's water infrastructure sector (Odeku & Meyer, 2010). Many local municipalities lack dedicated climate change strategies and insufficient integration between adaptation initiatives and disaster risk reduction plans, resulting in fragmented and ineffective policy implementation (Matikinca et al., 2024). Furthermore, resource management challenges persist, particularly the lack of integrated water management systems and targeted capacity-building initiatives that address the specific needs of both urban and rural communities (Vushe, 2021). Institutional constraints and deep-rooted socioeconomic inequalities contribute to unreliable water systems, especially in sparsely populated or agriculturally intensive regions (Dlamini et al., 2024).

The impacts of climate change—most notably water scarcity—further intensify environmental degradation and heighten social vulnerability. While research highlights the urgent need for tools and strategies to support community-level adaptation (Thorn, 2010), local government responses have largely prioritised physical infrastructure investments, often overlooking the social dimensions of vulnerability and resilience (Matikinca et al., 2024). This reveals a critical research gap: the need for a holistic and balanced approach that integrates technical infrastructure development with broader social and environmental resilience measures.

To address this gap, this study aims to investigate the barriers that hinder the effective delivery of sustainable and resilient water infrastructure in South Africa and identify the underlying factors driving these challenges. Additionally, the study evaluates strategic interventions to deliver sustainable and climate-resilient water infrastructure systems. Accordingly, the research questions proposed for this study are:

RQ1: What are the barriers to the delivery of sustainable and resilient water infrastructure in South Africa?

RQ2: What strategies can enable the delivery of sustainable and resilient water infrastructure in South Africa?

2. Literature Review

Infrastructure development serves as the backbone of a nation's socio-economic growth, enabling critical functions such as transportation, communication, and access to resources like water and energy (Dithebe et al., 2019; Ngowi et al., 2006). However, these benefits are contingent upon the adequacy and reliability of infrastructure provision (Babbie, 2010). South Africa faces significant challenges in delivering sustainable

water infrastructure, compounded by climate change. The following review explores current research findings and identifies gaps in this critical area.

2.1. Impacts of Climate Change on Water Infrastructure

Climate change presents serious challenges to the design, operation, and maintenance of water infrastructure worldwide. Rising sea levels, more frequent extreme weather events, and shifting precipitation patterns increasingly compromise the integrity and performance of water systems. Coastal infrastructure is especially at risk from marine and groundwater inundation, which can bypass conventional defences such as sea walls, necessitating more innovative and adaptive management approaches (Maliva, 2021). Water supply systems are similarly vulnerable; climatic variations influence pipe failure rates, potentially reducing breaks in colder regions but accelerating corrosion in hotter, drier areas—thereby requiring context-specific adaptation strategies (Fan et al., 2023; Żywiec et al., 2024). Infrastructure such as dams, levees, and reservoirs face heightened risks from floods and droughts, underscoring the need for flexible designs and resilient construction materials. Climate-induced water quality deterioration, exacerbated by rising temperatures and altered rainfall, increases pollution risks and operational burdens on treatment systems (Quevauviller, 2010a, 2010b). Consequently, climate projections must be embedded in infrastructure planning, using advanced modelling techniques to anticipate future conditions (Nguyen, 2023; O'Neill, 2010).

In South Africa, one of the world's driest countries, climate change has intensified water scarcity. Prolonged droughts, erratic rainfall, and rising evaporation rates are depleting both surface and groundwater sources, straining infrastructure already operating near or beyond capacity (Mukheibir, 2008; Nhemachena et al., 2020; Thorn, 2010). These pressures are especially acute in rural regions, where competition between agriculture and domestic use is high. Additionally, increased frequency of extreme events such as floods and storms has damaged essential infrastructure—including pipelines, treatment plants, and dams—disrupting water supply and inflating repair and maintenance costs (Schulze, 2011). Urban stormwater systems, often outdated or undersized, are overwhelmed during intense rainfall, compounding water management challenges. Climate variability has also degraded water quality: reduced river flows lead to higher pollutant concentrations, while flood events contaminate supplies, jeopardising public health and increasing treatment demands (Vushe, 2021). Moreover, much of South Africa's water infrastructure is ageing and was not built to withstand current climate extremes, rendering it to maintenance needs, operational inefficiencies, and reduced resilience to future climate variability (Edokpayi et al., 2020, pp. 83–115).

2.2. Sustainability and Resilience of Water Infrastructure

Sustainability and resilience are fundamental concepts in water infrastructure management, as they address both long-term viability and the capacity to withstand and recover from disruptions. Sustainability emphasises the efficient use of resources to meet present needs without compromising the ability of future generations to meet theirs. It involves practices such as rainwater harvesting and graywater recycling to optimise resource use and reduce environmental impact (George-Williams et al., 2024; Lee et al., 2022), as well as life cycle thinking to ensure infrastructure remains functional over time (Mortula et al., 2021). In regions like Sub-Saharan Africa, sustainable water infrastructure must also contend with complex societal, technological, economic, environmental, and political challenges to ensure water availability and quality (George-Williams et al., 2024).

On the other hand, resilience focuses on the robustness of water infrastructure systems—their ability to endure and quickly recover from adverse events such as natural disasters or system failures (Mortula et al., 2021). This includes using innovative engineering solutions and nature-based approaches to adapt to evolving conditions like climate change and population growth (Wallis-Lage & Kisoglu Erdal, 2022). Governance plays a critical role in resilience by establishing policies and frameworks necessary for risk mitigation and effective infrastructure management (Atkinson et al., 2022).

Although often discussed separately, sustainability and resilience are increasingly seen as complementary. Sustainability ensures long-term resource stewardship, while resilience addresses short-term responsiveness to disruptions. When integrated, they form a holistic approach to water infrastructure management, enabling systems that are both robust and adaptable (Chambers et al., 2019). Conceptual models that merge these frameworks aid decision-making by evaluating trade-offs and synergies (Mortula et al., 2021), while performance indicators help quantify and guide system design and planning (Kang et al., 2013). However, integrating these concepts is not without challenges—it demands comprehensive governance frameworks and the alignment of sustainability and resilience goals with existing management practices.

2.3. Barriers to Sustainable and Resilient Water Infrastructure

The lack of integrated policy frameworks remains a critical barrier to addressing climate change impacts on water infrastructure. In South Africa, institutional responsibilities are often fragmented across national, provincial, and local levels, leading to duplication of efforts and gaps in implementation. This fragmentation, coupled with inadequate coordination between climate adaptation and disaster risk reduction strategies, impedes effective, unified responses to emerging climate threats (Odeku & Meyer, 2010). Local municipalities—particularly in rural and under-resourced areas—frequently lack dedicated climate change adaptation strategies, which limits their ability to respond proactively to climate-related risks (Matikinca et al., 2024).

Inadequate funding is another pervasive issue, severely constraining the ability of municipalities to upgrade ageing water infrastructure or expand services to underserved communities. Many South African municipalities struggle with insufficient revenue collection from user tariffs and face restricted access to external funding sources due to low creditworthiness and limited technical capacity (Dithebe et al., 2019). These financial challenges are often compounded by procurement, project planning, and implementation inefficiencies, resulting in delayed delivery and escalating costs.

Moreover, a shortage of technical expertise and operational capacity undermines the ability of local governments and water service authorities to plan, execute, and maintain infrastructure projects effectively. This is especially problematic in historically disadvantaged and rural regions of South Africa, where engineering skills and institutional capacity are limited (Dlamini et al., 2024; Kudumela, 2015).

Finally, social inequities and environmental degradation further complicate the delivery of sustainable and resilient water infrastructure. Marginalised communities—often located in informal settlements or peri-urban areas—frequently lack reliable access to clean water and sanitation. Inadequate stakeholder coordination, weak community engagement, and the exclusion of vulnerable groups from planning processes reduce the effectiveness of resilience-building initiatives (Ruiters & Matji, 2015).

2.4. Strategies for Enhancing Water Infrastructure Resilience

Developing integrated policy frameworks that consider the interdependencies of water, energy, food, and health is increasingly recognised as essential for addressing the complex impacts of climate change. The WEF-H nexus provides a strategic model for aligning sectoral policies and promoting sustainable resource management (Adom et al., 2022; Mathetsa et al., 2022; Mutanga et al., 2024). Such frameworks should explicitly incorporate climate adaptation and disaster risk reduction to enhance systemic resilience (Odoh & Ezealaji, 2024).

Financial constraints remain a significant barrier to implementing climate-resilient infrastructure. Innovative financing mechanisms—including public-private partnerships (PPPs) and international climate funds—have been identified as effective tools for mobilising additional resources for water infrastructure while ensuring cost-effectiveness (Pot, 2023). Further, reforms to municipal revenue systems and improved access to credit can support long-term sustainability. Adaptive management strategies, such as floodwater harvesting, wastewater reuse, and smart water technologies, are also central to building resilience in the water sector by increasing resource efficiency and reducing vulnerabilities (Vushe, 2021). Moreover, infrastructure planning must integrate early warning systems and climate-resilient design standards to mitigate the impacts of extreme weather events (Schulze, 2011).

Capacity building is another critical element. Investing in training for municipal staff and water service authorities can strengthen technical and operational competencies. Focused programmes on climate-resilient planning, implementation, and maintenance are essential (Cagliano et al., 2015). Collaborations with academic institutions and international organisations can further enhance knowledge transfer and promote innovation related to sustainable and resilient water infrastructure. In addition, community engagement in planning and managing water infrastructure enhances social resilience and ensures that adaptation strategies are locally relevant. Empowering communities with tools and knowledge for climate adaptation can help address socioeconomic vulnerabilities (Thorn, 2010). Prioritising equity in infrastructure development is key to achieving inclusive and sustainable outcomes.

Furthermore, blue-green infrastructure (BGI) is increasingly recognised as a nature-based solution that supports sustainable urban development and climate resilience. By integrating natural and semi-natural systems—such as rivers, wetlands, green roofs, and urban forests—BGI delivers vital ecosystem services while enhancing urban resilience. It employs natural processes to mitigate flood risks, improve water quality, and support biodiversity, making it a cornerstone of climate-resilient infrastructure. BGI is particularly effective in urban stormwater management. By increasing permeable surfaces and enhancing rainwater retention, it helps restore disrupted urban hydrological cycles (Afata et al., 2022; Pochodyła et al., 2021). Features like rain gardens, bioswales, and constructed wetlands reduce runoff volumes and peak flow rates (Liao et al., 2017; Wu et al., 2024). Wetlands and swales, for instance, address both flooding and water scarcity, showcasing the multifunctional value of BGI systems (Ahmad & Hassan, 2023). Additionally, BGI supports biodiversity by creating habitats and fostering ecological connectivity, aligning with ecological engineering approaches that enhance infrastructure performance and resilience (Perrelet et al., 2024). Socio-economically, BGI offers cost-effective, lower-maintenance alternatives to grey infrastructure. It promotes social interaction, community cohesion, and public health benefits (Afata et al., 2022; Gündel & Kalaycı Önaç, 2023). Technological advances—including machine learning and smart city tools—further

improve BGI design, monitoring, and performance, reinforcing its role in sustainable urban water management (Nagal & Prabhakar, 2025). Thought leaders such as Kongjian Yu emphasise water as central to climate action, advocating for BGI and sponge city models that replicate natural water cycles to manage flooding, enhance water quality, and build urban resilience (Green, 2025). Similarly, de Meulder and Kelly Shannon highlight the role of water urbanism in integrating water-sensitive strategies into urban planning. Their research advocates reviving traditional, water-based practices to foster adaptive and sustainable urban design (de Meulder & Shannon, 2013). Despite its benefits, BGI implementation faces challenges. These include the need for interdisciplinary collaboration, integration of ecological principles into conventional engineering, policy and institutional barriers, funding constraints, and limited public awareness. Nevertheless, the potential of BGI to transform cities and develop sustainable and resilient water infrastructure is widely acknowledged. Continued empirical research and case-based studies are essential to advance its implementation and inform policy (Liao et al., 2017; Perrelet et al., 2024).

The literature thus suggests that the barriers to resilient and sustainable water infrastructure are multifaceted, spanning policy, financial, technical, natural, and social dimensions. Addressing these challenges requires a holistic and context-sensitive approach that integrates innovative financing, adaptive management, capacity building, and community involvement. Cross-sectoral collaboration and aligned policies are critical to enhancing sustainable and resilient water infrastructure. However, it remains necessary to identify and respond to localised, context-specific barriers to support the long-term functionality and equity of water infrastructure systems.

3. Research Methods

The study aimed to identify barriers to water infrastructure project delivery and assess strategic measures to support the development of sustainable and resilient infrastructure in South Africa. To achieve this objective, a survey research methodology was employed. Data collection was carried out through a structured survey, and the analysis was conducted using both descriptive and inferential statistical techniques.

3.1. Data Collection

A stakeholder perception survey was conducted as no structured statistical data was available to evaluate the challenges and influencing factors in water infrastructure project delivery. The survey relied on insights from stakeholders actively involved in the water infrastructure delivery system in South Africa.

To prepare for the survey, a list of stakeholders was compiled based on criteria such as professional engagement, involvement in water-related projects, and relevant education and experience. Stakeholders were selected from the KwaZulu-Natal, Free State, and Eastern Cape provinces of South Africa. These regions were selected for their geographical diversity—KwaZulu-Natal in the east, Free State in the centre, and Eastern Cape in the southeast—as well as the presence of significant water utility agencies, access to ongoing infrastructure projects, and the willingness of potential participants. Given the scale and significance of water infrastructure initiatives in these provinces, they were considered representative of broader national trends. Once the list was finalised, stakeholders were invited to participate via email, telephone, or personal networks. The final sample was based on availability and willingness to participate.

Efforts were made to ensure inclusivity and avoid discrimination based on race, gender, nationality, or age, thereby minimising potential bias in the responses.

The final survey included 145 stakeholders, with 120 valid responses received, yielding a response rate of over 82%, which was considered adequate. The respondents comprised a diverse group of professionals involved in water infrastructure, including project managers, civil and planning engineers, quantity surveyors, environmental project managers, and servitude administrators. The group also included technical staff and civil society professionals such as water quality technologists, hydrologists, geologists, mechanical and electrical engineers, information and communication technology specialists, architects, as well as policy-makers and decision-makers.

A pre-tested questionnaire was used for data collection, containing questions on key challenges, influencing factors, and strategic measures to improve project delivery. Respondents rated their perceptions on a five-point Likert scale (1 = *very low*; 2 = *low*; 3 = *average*, 4 = *high*; 5 = *very high*).

The questionnaire was distributed via email, and responses were collected using the same platform.

3.2. Data Analysis

A quantitative approach was used to analyse the survey data, employing both descriptive and inferential statistical techniques. Prior to analysis, the dataset was examined for missing values and outliers to ensure its validity and reliability. The data, collected on an ordinal scale ranging from 1 to 5, showed no issues related to missing entries, outliers, or inconsistencies. Given the non-normal distribution of the data, a non-parametric test was considered suitable for the analysis. The collected data were analysed using IBM SPSS (version 30).

Barriers and strategies were analysed using metrics such as the perception index (*PI*), standard deviation (*SD*), interquartile range (*IQR*), coefficient of variation (*CoV*), and a one-sample Chi-square test. The *PI* reflected the average ratings assigned by experts for each barrier and strategy, with a $PI \geq 3$ indicating an average or higher rating. In contrast, a $PI < 3$ suggested a lower-than-acceptable rating. The *SD* measured the consistency of responses, with values ≤ 1.0 signifying high consistency. Similarly, an $IQR \leq 1.0$ and $CoV < 30\%$ indicated a strong consensus among respondents (Geh et al., 2022; von der Gracht, 2012). The non-parametric one-sample Chi-square test was used to determine the statistical significance of the responses, with significance set at $\alpha \leq 0.05$ and $p \leq 0.05$.

4. Results and Discussions

4.1. Profile of Respondents

The demographic characteristics of the respondents are outlined in Table 1, which includes details such as professional roles, years of experience, and involvement in water projects. This information was essential to assess the adequacy and reliability of the responses. As shown in Table 1, the distribution of professional roles ranges from 3.33% (environmental project manager) to 19.17% (other professionals). Key stakeholders such as project managers, contractors, consultants, civil engineers, quantity surveyors, and planning engineers

are well-represented, indicating a balanced participation of relevant stakeholders in the survey. The others included professionals such as water quality technologists, hydrologists, geologists, mechanical and electrical engineers, information and communication technologists, architects, policy makers, and decision makers.

A significant portion of the respondents (39.17%) have five to 10 years of professional experience, while over 19.17% have 11 to 15 years of experience. Additionally, 15% of the respondents possess more than 15 years of experience, meaning over 74% of the participants have substantial professional expertise. Furthermore, more than 84% of the respondents reported direct or indirect involvement in water projects, while approximately 16% lacked specific water infrastructure project experience but had relevant expertise in other infrastructure domains. These findings indicate that the respondent pool is diverse and representative, making it suitable for the study.

Table 1. Demographic profile of respondents.

Respondents	Frequency	%
Professional engagement		
Project managers	11	9.17
Civil engineers	10	8.33
Planning engineers	9	7.50
Quantity surveyors	11	9.17
Environmental project manager	4	3.33
Servitude administrators	8	6.67
Technical staff	19	15.83
Contractors	16	13.33
Consultants	9	7.50
Other related professionals	23	19.17
Years of experience		
< 5 years	32	26.67
5–10 years	47	39.17
11–15 years	23	19.17
> 15 years	18	15.00
Participation in water projects		
Directly participated in water projects	64	53.33
Indirect association with water projects	37	30.83
Not associated with water projects, but experience in other infrastructure projects	19	15.83

4.2. Perception of Stakeholders on the Barriers to Sustainable and Resilient Water Infrastructure

The analysis of stakeholder perceptions regarding various barriers (Table 2) reveals that ageing infrastructure and poor maintenance ($PI = 4.17$) are the most significant concerns, with the lowest variability ($IQR = 1.0$, $CoV = 13.3\%$), indicating a strong agreement among respondents. Funding and financial constraints ($PI = 3.89$, $IQR = 1.0$, $CoV = 21.5\%$), inefficiencies in project management ($PI = 3.64$, $IQR = 1.0$, $CoV = 21.6\%$) and water resource scarcity ($PI = 3.62$, $IQR = 1.0$, $CoV = 22.7\%$), technological and innovation barriers

($PI = 3.53$), emerge as high-level or critical barriers, highlighting the financial limitations that hinder progress. Additionally, environmental degradation ($PI = 3.12$) is perceived as a moderate challenge, reflecting concerns about resource allocation and operational effectiveness.

On the lower end of the scale, governance and management issues ($PI = 2.98$), political and policy barriers ($PI = 2.85$), climate change uncertainties ($PI = 2.76$), and social and community challenges ($PI = 1.78$) are perceived as less significant barriers. However, the high Coefficient of Variation ($CoV = 47.0\%$) for social and community challenges suggests considerable disagreement among stakeholders, indicating varying perspectives on the importance of social engagement in addressing these issues.

Further, all barriers have p -values <0.001 (Table 2), confirming that the differences in stakeholder perceptions are statistically significant. This suggests that addressing the most critical barriers, such as infrastructure deficiencies, financial constraints, and project management inefficiencies, could lead to meaningful improvements. Meanwhile, the variability in perceptions of social challenges highlights the need for targeted stakeholder engagement to bridge differing viewpoints. Overall, the findings underscore the importance of strategic interventions to enhance infrastructure resilience, financial sustainability, and governance efficiency while considering the diverse perspectives of stakeholders.

Table 2. Perception of stakeholders on the barriers to sustainable and resilient water infrastructure.

Barriers	Perception of stakeholders				
	PI	SD	IQR	$CoV(\%)$	p -values
Ageing infrastructure and poor maintenance	4.17	0.555	1.0	13.3	<0.001
Funding and financial constraints	3.89	0.848	1.0	21.5	<0.001
Climate change uncertainties	2.76	1.04	1.0	36.4	<0.001
Governance and management issues	2.98	1.115	2.0	37.4	<0.001
Inefficiencies in project management	3.64	0.786	1.0	21.6	<0.001
Water resource scarcity	3.62	0.822	1.0	22.7	<0.001
Political and policy barriers	2.85	0.885	1.0	31.1	<0.001
Social and community challenges	1.78	0.835	1.0	47.0	<0.001
Technological and innovation barriers	3.53	1.004	1.0	28.5	<0.001
Environmental degradation	3.12	1.014	2.0	32.5	<0.001

4.3. Perception of Stakeholders on the Strategies for Sustainable and Resilient Water Infrastructure

Table 3 presents the perception of stakeholders on the strategies for sustainable and resilient water infrastructure. The analysis of stakeholder perceptions regarding strategies to address key challenges indicates that upgrading and maintaining infrastructure ($PI = 4.36$) is perceived as the most significant (very high) strategy. This suggests a strong consensus on the need for infrastructure improvements, with relatively low variability ($CoV = 15.1\%$). Similarly, increasing funding and financial management ($PI = 3.92$) is rated High, highlighting financial sustainability as a crucial factor in overcoming barriers.

Other highly rated strategies include enhancing governance and accountability ($PI = 3.71$). The resilience to extreme weather events ($PI = 3.25$), strengthening project management and capacity building ($PI = 3.13$),

and integrating climate-resilient technologies ($PI = 3.06$) fall within the Moderate range, indicating their importance in improving system efficiency and adaptability and reflecting the need for long-term investment in human and technological resource as well as the development of institutional frameworks that support sustained capacity enhancement.

In contrast, policy and regulatory reforms ($PI = 2.82$) are rated Low, suggesting that while governance adjustments are necessary, they are not seen as an immediate priority. Community engagement and awareness ($PI = 2.45$) is the least prioritised strategy, categorised as Very Low, with a high CoV (50.2%), indicating significant stakeholder disagreement.

Overall, the findings emphasise that infrastructure development and financial investment are seen as the most effective strategies, while policy changes and community involvement are perceived as less urgent, despite their potential long-term benefits. The statistical significance ($p < 0.001$) across all strategies confirms substantial differences in stakeholder perceptions (Table 3), thus necessitating strategic priorities for effective implementation.

Table 3. Perception of stakeholders on the strategies for sustainable and resilient water infrastructure.

Strategies	Perception of stakeholders				
	<i>PI</i>	<i>SD</i>	<i>IQR</i>	<i>CoV(%)</i>	<i>p-values</i>
Upgrading and maintaining infrastructure	4.36	0.658	1.0	15.1	<0.001
Increasing funding and financial management	3.92	0.693	1.0	17.7	<0.001
Integrating climate-resilient technologies	3.06	0.836	0	27.1	<0.001
Strengthening project management and capacity building	3.13	0.826	1.0	26.4	<0.001
Enhancing governance and accountability	3.71	0.691	1.0	18.6	<0.001
Resilience to extreme weather events	3.25	0.781	1.0	24.0	<0.001
Policy and regulatory reforms	2.82	1.108	2.0	39.3	<0.001
Community engagement and awareness	2.45	1.229	2.0	50.2	<0.001

4.4. Discussion

South Africa faces significant challenges in delivering sustainable and resilient water infrastructure, compounded by the effects of climate change, ageing infrastructure, financial limitations, and systemic governance inefficiencies. These barriers are deeply embedded in the country's historical, institutional, and socio-political context, influencing both policy and implementation outcomes.

Ageing infrastructure and poor maintenance emerged as the most pressing barrier. This reflects the deterioration of water systems built decades ago, often without consideration for the intensifying impacts of climate variability. These systems were designed for historical hydrological conditions, not the prolonged droughts and extreme weather events experienced today. Infrastructure degradation leads to operational inefficiencies, water losses, and inflated maintenance costs, especially in municipalities with limited technical capacity and budget (Emily & Muyengwa, 2021; Ruiters & Amadi-Echendu, 2020).

Financial constraints also pose a significant barrier. Many local governments struggle with revenue generation (Ruiters & Amadi-Echendu, 2020) due to limited tax bases, low water tariff collection rates, and poor billing systems. These factors, combined with constrained access to external funding and inefficient procurement practices, result in chronic underinvestment and delays (Dithebe et al., 2019). Additionally, political interference in budgeting and infrastructure planning often diverts funds from priority areas.

Project management inefficiencies and water resource scarcity highlight systemic issues in infrastructure project delivery, such as poor planning, lack of technical expertise, and fragmented coordination among stakeholders. Vushe (2021) underscores the absence of integrated water resource management, which is essential for balancing competing water demands and promoting long-term sustainability.

Barriers related to technology and innovation reflect the reliance on outdated infrastructure that cannot accommodate rapid urbanisation or fluctuating climate patterns. Moreover, limited uptake of smart water technologies is often due to cost, lack of technical skills, and risk aversion in public institutions. Governance and institutional fragmentation remain persistent challenges. Odeku and Meyer (2010) argue that unclear mandates, overlapping responsibilities, and insufficient legal frameworks hinder coherent climate adaptation responses. This is especially evident in the weak alignment between national strategies and municipal implementation, where local policies often lack enforceability or integration with disaster risk management plans (Matikinca et al., 2024).

Barriers such as climate change uncertainties and social/community challenges were ranked lower, possibly due to a technocratic bias among stakeholders prioritising infrastructure over softer, less tangible dimensions. However, high CoV for social issues signals divergent views, pointing to a lack of consensus on the importance of community engagement. This reflects a broader tendency to undervalue social vulnerability in infrastructure planning (Thorn, 2010).

In response, the study identified key strategies. Upgrading and maintaining infrastructure emerged as the top priority, indicating broad agreement on the urgency of modernising systems to withstand current and future climate threats. Schulze (2011) highlights the need for climate-resilient design standards, including flood-resistant infrastructure and drought-adaptive water supply systems.

Enhanced financial mechanisms, including PPPs, green bonds, and international climate financing, are critical to overcoming funding gaps. Dithebe et al. (2019) support innovative financing models that diversify revenue streams and improve creditworthiness, especially for financially struggling municipalities.

Strengthening governance and accountability is recognised as essential for enabling integrated and transparent decision-making. Mutanga et al. (2024) advocate for the WEF-H nexus framework to align multisectoral policies and foster resilient systems.

Moderately ranked strategies such as adopting climate-resilient technologies, investing in project management capacity, and promoting resilience to extreme weather highlight the long-term nature of adaptation. Vushe (2021) points to adaptive management approaches, like floodwater harvesting and decentralised systems, as cost-effective, scalable solutions.

Although policy and regulatory reforms and community engagement ranked lower, literature suggests they are critical for sustained progress. Legal frameworks provide the enabling environment for other strategies, while community involvement ensures relevance, ownership, and local adaptation capacity (Odeku & Meyer, 2010; Thorn, 2010). The undervaluation of these areas in practice suggests a gap between technical planning and socio-environmental needs.

Overall, the study revealed that while infrastructure and financial reforms are widely prioritised, deeper integration of social, governance, and environmental dimensions is essential for achieving sustainable and climate-resilient water infrastructure systems. The findings reinforce the need for a multi-dimensional, integrated approach to overcome entrenched barriers and develop sustainable and resilient water infrastructure to ensure water security in the face of climate change.

5. Conclusions

This study highlights the critical barriers and strategies for achieving sustainable and resilient water infrastructure in South Africa. The findings reveal that ageing infrastructure, financial constraints, inefficiencies in project management, and water resource scarcity are the most pressing challenges. Governance and policy barriers, along with social and community engagement, are perceived as less immediate but still relevant concerns. These insights align with existing literature, which emphasises the need for integrated water management, improved institutional coordination, and enhanced financial mechanisms to address these challenges effectively.

The implications of these findings are particularly significant for South African policymakers, municipal authorities, and water service providers operating within a context of growing climate risks, infrastructure backlogs, and socio-economic inequalities. Addressing ageing infrastructure and chronic maintenance deficits should be a national priority, especially in historically under-served areas such as rural provinces and peri-urban informal settlements. To overcome persistent financial constraints, municipalities must explore innovative funding mechanisms, including PPPs, municipal green bonds, and access to international climate finance through instruments like the Green Climate Fund. Strengthening governance structures—particularly at the municipal level—requires clearer institutional mandates, enhanced regulatory oversight, and reduced political interference in budgeting and procurement processes. Building technical and managerial capacity within local government is also essential to improve project planning, implementation, and monitoring. Additionally, integrating climate-resilient technologies, such as smart water metering, leak detection systems, and decentralised water reuse, can improve efficiency and adaptability. Importantly, although community engagement is currently undervalued in infrastructure planning, promoting public participation and local ownership is critical in South Africa's diverse and unequal society. Strengthening citizen awareness and involving communities, particularly in vulnerable regions, can improve accountability, foster behavioural change, and lead to sustainable and resilient water infrastructure and more equitable and sustainable water management strategies.

This study contributes to the growing body of research on water infrastructure sustainability and resilience by providing an empirical assessment of stakeholder perceptions. It underscores the importance of a multi-faceted approach that integrates technical, financial, and social dimensions to enhance water security

in the face of climate change. By aligning these strategies with global best practices, South Africa can improve its adaptive capacity and resilience in water infrastructure development and management.

However, the study has certain limitations. The reliance on stakeholder perceptions may introduce biases that do not fully capture the complexity of water infrastructure challenges. Additionally, the study does not account for regional variations in water infrastructure needs, which may require tailored solutions. Furthermore, social issues such as corruption, including fraud, bribery, and misappropriation of funds, were not addressed, as they require dedicated investigation. Future research should incorporate quantitative performance evaluations, explore region-specific adaptation strategies, and examine social challenges to provide a more comprehensive understanding of sustainable and resilient water infrastructure development and management.

Conflict of Interests

The author declares no conflict of interests.

Data Availability

The data is available from the corresponding author upon reasonable request.

References

- Adom, R. K., Simatele, M. D., & Reid, M. (2022). Addressing the challenges of water-energy-food nexus programme in the context of sustainable development and climate change in South Africa. *Journal of Water and Climate Change*, 13(7), 2761–2779. <https://doi.org/10.2166/wcc.2022.099>
- Afata, T. N., Derib, S., & Nemo, R. (2022). Review of blue-green infrastructure in some selected countries. *American Journal of Environmental Sciences*, 18(4), 81–88. <https://doi.org/10.3844/ajessp.2022.81.88>
- Ahmad, N., & Hassan, Q. (2025). Ecosystem services linked to nature-based solutions for resilient and sustainable cities in India. *Frontiers in Water*, 6, Article 1504492. <https://doi.org/10.3389/frwa.2024.1504492>
- Aiyetan, A. O., Das, D.K. (2021). Evaluation of the factors and strategies for water infrastructure project delivery in South Africa. *Infrastructures*, 6(5), Article 65. <https://doi.org/10.3390/infrastructures6050065>
- Atkinson, C., Curnin, S., & Murphy-Gregory, H. (2022). Resilient and sustainable water infrastructure: A systematic literature review protocol. *Social Science Protocols*, 5(1), 1–12. <https://doi.org/10.7554/ssp.v5.6966>
- Babbie, E. R. (2010). *The practice of social research* (12th ed.). Wadsworth Cengage.
- Cagliano, A. C., Grimaldi, S., & Rafele, C. (2015). Choosing project risk management techniques. A theoretical framework. *Journal of Risk Research*, 18(2), 232–248.
- Calderon, C., & Serven, L. (2014). *Infrastructure, growth, and inequality: An overview* (WPS 7034). World Bank Group. <http://documents.worldbank.org/curated/en/322761468183548075>
- Cartwright, A., Swilling, M., Cullis, J., Walsh, K. J., & Gcanga, A. (2024). ‘Some for all, forever’: Investing in universal access to water services in a warming world—The case of South Africa. Preprints. <https://doi.org/10.20944/preprints202407.0311.v1>
- Chakamera, C., & Alagidede, P. (2018). The nexus between infrastructure (quantity and quality) and economic growth in Sub-Saharan Africa. *International Review of Applied Economics*, 32(5), 641–672. <https://doi.org/10.1080/02692171.2017.1355356>
- Chambers, K., Baker, A. C., McKay, S. K., & Morgan, H. (2019). *Retrospective sustainability and resilience:*

- Complementary concepts for managing systems. Coastal and Hydraulics Laboratory. <https://erdc-library.erdc.dren.mil/jspui/bitstream/11681/32407/1/ERDC-TN%20EMRRP-SR-86.pdf>
- Coetzee, C. E., & Kleynhans, E. P. J. (2017). The contribution of public capital towards economic growth: A KwaZulu-Natal case study. *South African Journal of Economic and Management Sciences*, 20(1), 1–10.
- de Meulder, B., & Shannon, K. (2013). *Water urbanisms: East*. Park Books.
- Dithebe, K., Clinton, O. A., Thwala, W. D., & Oke, A. E. (2019). Analysis on the perceived occurrence of challenges delaying the delivery of water infrastructure assets in South Africa. *Journal of Engineering, Design and Technology*, 17(3), 554–571. <https://doi.org/10.1108/JEDT-10-2017-0101>
- Dithebe, K., Aigbavboa, C., & Thwala, D. W. (2019). An appraisal of water infrastructure projects financing challenges in South Africa. In I. Lill & E. Witt (Eds.), *10th Nordic conference on construction economics and organisation* (Vol. 2, pp. 103–110). Emerald Publishing. <https://doi.org/10.1108/S2516-285320190000002022>
- Dlamini, N., Senzanje, A., & Mabhaudhi, T. (2024). Modelling the water supply-demand relationship under climate change in the Buffalo River catchment, South Africa. *PLOS Climate*, 3(8), Article 0000464. <https://doi.org/10.1371/journal.pclm.0000464>
- Edokpayi, J. N., Makungo, R., Mathivha, F. I., Rivers, N., Volenzo, T., & Odiyo, J. O. (2020). *Influence of global climate change on water resources in South Africa: Toward an adaptive management approach*. Elsevier. <https://doi.org/10.1016/B978-0-12-818339-7.00005-9>
- Emily, M., & Muyengwa, G. (2021). Maintenance of municipality infrastructure: A case study on service delivery in limpopo province at South Africa. *American Journal of Operations Research*, 11, 309–323. <https://doi.org/10.4236/ajor.2021.116019>
- Fan, X., Zhang, X., & Yu, X. (2023). Assessment of the impacts of climate change on water supply system pipe failures. *Dental Science Reports*, 13(1), Article 7349. <https://doi.org/10.1038/s41598-023-33548-7>
- Fedderke, J., & Garlick, R. (2008). *Infrastructure development and economic growth in South Africa: A review of the accumulated evidence* (Policy Paper No. 12). University of Cape Town. https://econrsa.org/system/files/publications/policy_papers/pp12.pdf
- Fourie, J. (2006). Economic infrastructure: A review of definitions, theory and empirics. *South African Journal of Economics*, 74(3), 530–556. <https://doi.org/10.1111/j.1813-6982.2006.00086.x>
- Geh, N., Emuze, F., & Das, D. K. (2022). Barriers to the deployment of solar photovoltaic in public universities in South Africa: A delphi study. *International Journal of Building Pathology and Adaptation*, 42(5), 957–981. <https://doi.org/10.1108/IJBPA-11-2021-0147>
- George-Williams, H. E. M., Hunt, D. V. L., & Rogers, C. D. F. (2024). Sustainable water infrastructure: Visions and options for Sub-Saharan Africa. *Sustainability*, 16(4), Article 1592. <https://doi.org/10.3390/su16041592>
- Green, J. (2025). *Kongjian Yu: Water is key to climate action*. The Dirt: Uniting the Built and Natural Environments. <https://dirt.asla.org/2025/01/30/kongjian-yu-water-is-key-to-climate-action>
- Gündel, H., & Kalaycı Önaç, A. (2023). *Sponge city based on blue-green urbanism*. International Students Science Congress. <https://doi.org/10.52460/issc.2023.053>
- Kang, D., Kim, T.-W., & Ahn, J.-H. (2013). Water resources infrastructure: Sustainability and resilience. *Journal of the Korean Society of Hazard Mitigation*, 13(1), 309–315. <https://doi.org/10.9798/KOSHAM.2013.13.1.309>
- Kudumela, F. P. (2015). *Risks and mitigations associated with infrastructure development projects in South Africa* [Unpublished master's thesis]. University of Johannesburg.
- Lee, J., Younos, T., & Parece, T. E. (2022). Decentralised green water-infrastructure systems: Resilient and sustainable management strategies for building water systems. In T. Younos, J. Lee, T. E. Parece (Eds.),

- Resilient water management strategies in urban settings* (pp. 1–20). Springer. https://doi.org/10.1007/978-3-030-95844-2_1
- Liao, K.-H., Deng, S., & Tan, P. Y. (2017). Blue-green infrastructure: New frontier for sustainable urban stormwater management. In P. Yok Tan & C. Yung Jim (Eds.), *Greening cities: Forms and functions* (pp. 203–226). Springer. https://doi.org/10.1007/978-981-10-4113-6_10
- Maliva, R. (2021). *Groundwater related impacts of climate change on infrastructure*. In R. Maliva (Ed.), *Climate change and groundwater: Planning and adaptations for a changing and uncertain future* (pp. 177–195). Springer. https://doi.org/10.1007/978-3-030-66813-6_8
- Marais, E. (2013). *Infrastructure development key to economic development*. Parliamentary Monitoring Group, South Africa. <http://www.da.org.za/2015/05/infrastructure-development-is-key-to-economic-growth>
- Mathetsa, S. M., Simatele, M. D., & Rampedi, I. T. (2022). A water-centric approach in the assessment and governance of the water-energy-climate change nexus in South Africa. *Frontiers in Sustainable Food Systems*, 6. <https://doi.org/10.3389/fsufs.2022.691704>
- Matikinca, P., Nyamakura, B., & Shackleton, S. (2024). Climate change adaptation and disaster risk reduction in South Africa's local municipal plans. *South African Journal of Science*, 120(7/8). <https://doi.org/10.17159/sajs.2024/15797>
- McGaffin, R., Viruly, F., & Boyle, L. (2019). An investigation into the use of land-based financing to fund infrastructure in South Africa. *Journal of Property Investment & Finance*, 17(3), 554–571. <https://doi.org/10.1108/JEDT-10-2017-0101>
- More, I., & Aye, G. (2017). Effect of social infrastructure investment on economic growth and inequality in South Africa: a SEM approach. *International Journal of Economics and Business Research*, 13, 95–109.
- Mortula, M., Ahmad, I., Sadiq, R., & Beheiry, S. (2021). A conceptual unified model for assessing improvements in sustainability and resilience in water distribution systems. In S. Eslamian & F. Eslamian (Eds.), *Handbook of disaster risk reduction for resilience: New frameworks for building resilience to disasters* (pp. 341–359). Springer. https://doi.org/10.1007/978-3-030-61278-8_15
- Mukheibir, P. (2008). Water resources management strategies for adaptation to climate-induced impacts in South Africa. *Water Resources Management*, 22(9), 1259–1276. <https://doi.org/10.1007/S11269-007-9224-6>
- Mutanga, S. S., Mantlana, B. K., Mudavanhu, S., Muthige, M., Skhosana, F. V., Lumsden, T., Naidoo, S., Thambiran, T., & John, J. (2024). Implementation of water energy food-health nexus in a climate-constrained world: A review for South Africa. *Frontiers in Environmental Science*, 12. <https://doi.org/10.3389/fenvs.2024.1307972>
- Nagal, B., & Prabhakar, A. K. (2025). Sustainable water management in the digital age: Intelligent solutions for a precious resource. In S. Pathak, A. K. Shukla, S. Sharma, & V. P. Singh (Eds.), *Intelligent infrastructure and smart materials* (pp. 91–114). Springer. https://doi.org/10.1007/978-3-031-92421-7_6
- Naidoo, R. (2016, December 12). Water construction projects take a dive in 2016. *Infrastructure News and Service Delivery*. <https://infrastructurenews.co.za/2016/12/12/water-construction-projects-take-a-dive-in-2016>
- National Treasury Budget Review. (2016). *National treasury budget review*.
- Ngowi, A. B., Pienaar, E., Akindele, O., & Iwisi, D. (2006). Globalisation of the construction industry: A review of infrastructure financing. *Journal of Financial Management of Property and Construction*, 11(1), 45–58.
- Nguyen, V. T. V. (2023). Urban water infrastructure design in climate change context: Advances and challenges in developing engineering practice guidelines. In *World Environmental and Water Resources Congress 2023* (pp. 399–404). American Society of Civil Engineers. <https://doi.org/10.1061/9780784484852.038>

- Nhemachena, C., Nhamo, L., Matchaya, G., Nhemachena, C., Muchara, B., Karuaihe, S., & Mpandeli, S. (2020). Climate change impacts on water and agriculture sectors in Southern Africa: Threats and opportunities for sustainable development. *Water*, 12(10), Article 2673. <https://doi.org/10.3390/W12102673>
- O'Neill, J. A. (2010). *Climate change's impact on the design of water, wastewater, and stormwater infrastructure*. Colorado State University. <https://doi.org/10.25675/10217/200817>
- Odeku, K., & Meyer, E. (2010). Climate change surge: implementing stringent mitigation and adaptation strategies in South Africa. *Journal of African Law*, 54(2), 159–183. <https://doi.org/10.1017/S0021855310000033>
- Odoh, B. I., & Ezealaji, I. P. (2024). From scarcity to abundance: Innovative solutions for Africa's water crisis. *International Journal of Science and Research Archive*, 13(1), 398–406. <https://doi.org/10.30574/ijrsra.2024.13.1.1620>
- Perrelet, K., Moretti, M., Dietzel, A., Altermatt, F., & Cook, L. M. (2024). Engineering blue-green infrastructure for and with biodiversity in cities. *Npj: Urban Sustainability*, 4, 1–11. <https://doi.org/10.1038/s42949-024-00163-y>
- Pochodyła, E., Glińska-Lewczuk, K., & Jaszczak, A. (2021). Blue-green infrastructure as a new trend and an effective tool for water management in urban areas. *Landscape Online*, 92. <https://doi.org/10.3097/LO.202192>
- Pot, W. D. (2023). Deciding for resilience: Utilising water infrastructure investments to prepare for the future. *WIREs Water*, 10(5), Article e1661. <https://doi.org/10.1002/wat2.1661>
- Quevauviller, P. (2010a). A snapshot of policy and research considerations about water and climate change. *Aqua Mundi*, 1, 23–28. <https://doi.org/10.4409/Am-008-10-0004>
- Quevauviller, P. (2010b). Water Sustainability and Climate Change in the EU and Global Context—Policy and Research Responses. In R. E. Hester & R. M. Harrison (Eds.), *Issues in environmental science and technology: Sustainable water* (pp. 1–24). Royal Society of Chemistry. <https://doi.org/10.1039/9781849732253-00001>
- Ruiters, C., & Amadi-Echendu, J. (2020). Engineering and financial realities of water infrastructure in South Africa. In J. P. Liyanage, J. Amadi-Echendu, & J. Mathew (Eds.), *Engineering assets and public infrastructures in the age of digitalization: Proceedings of the 13th world congress on engineering asset management* (pp. 174–182). Springer. https://doi.org/10.1007/978-3-030-48021-9_20
- Ruiters, C., & Matji, M. P. (2015). Water institutions and governance models for the funding, financing and management of water infrastructure in South Africa. *Water SA*, 41(5), 660–676. <https://doi.org/10.4314/wsa.v41i5.09>
- Schulze, R. (2011). Approaches towards practical adaptive management options for selected water-related sectors in South Africa in a context of climate change. *Water SA*, 37(5), 621–645. <https://doi.org/10.4314/WSA.V37I5.1>
- Thorn, J. (2010). Water scarcity and climate change in South Africa. *Veld & Flora*, 96(2), Article 66.
- Umgeni Water Project Management Plan. (2012). *Umgeni Water, Durban, South Africa*, 2012.
- Wu, J., Liu, Q., Liang, L., Li, S., Gan, L., & Wu, H. (2024). Alteration of wetland resilience for the intermittently and permanently inundated wetland. *Environmental Research Letters*, 19(12), Article 124077. <https://doi.org/10.1088/1748-9326/ad7f71>
- Vinke-De Kruijf, J., Heim LaFrombois, M. E., Warbroek, B., Morris, J. C., & Kuks, S. M. M. (2024). Climate-resilient water infrastructure: A call to action. *The Journal of Critical Infrastructure Policy*, 5(1), 17–29. <https://doi.org/10.1002/jci3.12017>
- von der Gracht, H. A. (2012). Consensus measurement in Delphi studies: Review and implications for future

quality assurance. *Technological Forecasting and Social Change*, 79(8), 1525–1536. <https://doi.org/10.1016/j.techfore.2012.04.013>

Vushe, A. (2021). Proposed research, science, technology, and innovation to address current and future challenges of climate change and water resource management in Africa. In S. Diop, P. Scheren, & A. Niang (Eds.), *Climate change and water resources in Africa: Perspectives and solutions towards an imminent water crisis* (pp. 489–518). Springer. https://doi.org/10.1007/978-3-030-61225-2_21

Wallis-Lage, C., & Kisoglu Erdal, Z. (2022). Resilience through systems thinking for water infrastructure. In A. K. Biswas & C. Tortajada (Eds.), *Water security under climate change* (pp. 41–67). Springer. https://doi.org/10.1007/978-981-16-5493-0_4

Watermeyer, R., & Phillips, S. (2020). *Public infrastructure delivery and construction sector dynamism in the South African economy*. Department of Planning, Monitoring and Evaluation.

World Bank. (2020). *Infrastructure in Asia and the Pacific: Toward a sustainable future*. World Bank Group. <https://www.worldbank.org/en/topic/infrastructure/publication/infrastructure-in-asia-and-the-pacific>

Żywiec, J., Szpak, D., Wartalska, K., & Grzegorzec, M. (2024). The impact of climate change on the failure of water supply infrastructure: A bibliometric analysis of the current state of knowledge. *Water*, 16(7), Article 1043. <https://doi.org/10.3390/w16071043>

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Enhancing Water Infrastructure Resilience in Response to Climate Change: Evidence From South Africa

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Abstract

Climate change is intensifying extreme weather events worldwide, placing unprecedented stress on water infrastructure systems. As climate variability increases, water utilities face mounting challenges in maintaining infrastructure integrity. This study, conducted in South Africa, quantifies the relationship between climate variability and water infrastructure resilience through empirical analysis of 43 years of historical data spanning 1980 to 2023. The article uses correlation, regression, and time-series forecasting techniques to examine how extreme weather events, specifically floods and droughts, impact pipeline infrastructure performance metrics, including pipe failures, supply interruptions, and economic losses. The analysis reveals strong correlations between climate events and pipeline failures (flood-pipe failure $r = 0.78$; drought-pipe failure $r = 0.64$), with regression modelling showing that drought events have a 47% greater impact on pipe failures than flood incidents (coefficients 6.19 vs 4.21). Autoregressive integrated moving average (ARIMA) forecasting indicates an annual increase of approximately 4.5 pipe failures over the next two decades, indicating growing infrastructure vulnerability without intervention. The study concludes that enhancing resilience requires an integrated approach combining structural improvements with distributed systems and nature-based solutions, with implementation priorities guided by the vulnerability of infrastructure components to specific climate stressors. These findings provide water managers with a quantitative basis for resilience planning that addresses immediate climate threats and long-term adaptation needs.

Keywords

climate change; extreme weather events; flood incidence; resilient water infrastructure

1. Introduction

Resilience of water infrastructure has emerged as a defining priority in the face of climate change, which amplifies global water challenges, intensifies scarcity, and exposes the vulnerabilities of infrastructure systems (Amparo-Salcedo et al., 2025; Karimi et al., 2024; Olawuyi & Mushunje, 2024). Rapid urbanisation, ageing water systems, and climate-induced variability place increasing pressure on distribution and drainage networks. These pressures are particularly acute in semi-arid and arid regions, where climate variability interacts with existing supply constraints to threaten water security (Karimi et al., 2024). Water infrastructure encompasses collection, treatment, distribution, and drainage systems (Taiwo et al., 2023), but pipeline networks represent the most extensive and vulnerable of distribution systems, with pipe failures causing substantial service disruptions and economic losses (Serafeim et al., 2024; Vinke-De Kruijf et al., 2024). Extreme weather events such as droughts and floods magnify these vulnerabilities, with floodwaters damaging buried assets through hydraulic loading and erosion, and droughts triggering soil shrinkage, subsidence, and stress fractures (Ferdowsi et al., 2024). In this study, floods refer to inland flooding events, excluding coastal storm surges.

Resilience, defined broadly as the capacity to withstand shocks, adapt to change, and recover effectively, has become a central concept in climate adaptation planning (Kapucu et al., 2024). Within resilience theory, two perspectives dominate: engineering resilience, which emphasises the speed and extent of recovery to a functional state, and ecological resilience, which highlights adaptability, transformation, and the ability to maintain function under persistent chronic stressors (Folke et al., 2010). In the context of water infrastructure, engineering resilience is critical for rapid restoration after sudden shocks such as floods, while ecological resilience underpins adaptive responses to gradual, chronic stresses such as drought. Both perspectives are vital for water infrastructure, yet empirical evidence quantifying how specific climate stressors influence infrastructure performance remains limited. Many studies adopt conceptual frameworks or develop resilience indices without directly linking them to long-term performance (Mehvar et al., 2021; Vinke-De Kruijf et al., 2024). Predictive models often exclude climate variability parameters, limiting their usefulness for forward-looking adaptation strategies (Serafeim et al., 2024). Furthermore, while resilience strategies such as material upgrades, decentralised systems, and nature-based solutions are widely discussed, there is limited empirical assessment of their relative importance for different failures and climate conditions. This article addresses these gaps by combining 43 years of climate and infrastructure performance data for South Africa to evaluate the statistical relationships between extreme weather events and infrastructure failures. Regression and time-series forecasting models are developed to anticipate future failure patterns under projected climate scenarios. Drawing from these empirical insights, the study proposes targeted strategies for strengthening the resilience of urban water distribution and drainage systems, aligning both engineering and ecological resilience principles with practical adaptation planning.

2. Climate Change and Water Infrastructure Resilience

The frequency and intensity of climate-related events place immense pressure on urban water distribution systems, with significant implications for long-term sustainability and resilience (Ferdowsi et al., 2024). Rising global temperatures, shifting precipitation patterns, and weather events such as droughts and floods increase infrastructure vulnerability and threaten water security (Arias et al., 2021; Ferdowsi et al., 2024). Analysis of global climate data reveals that between 1980 and 2023, extreme weather events affecting

urban water distribution and drainage infrastructure have increased drastically, with drought durations extending significantly in arid regions (World Meteorological Organization, 2023). This trend underscores the critical need for infrastructure systems capable of withstanding acute shocks and chronic stresses. The impacts of climate change on urban water distribution systems vary significantly across regions, depending on geographical, climatic, and socio-economic factors. Prolonged droughts exacerbate groundwater depletion in arid and semi-arid regions, leading to aquifer over-pumping and subsequent land subsidence due to sediment compaction. The drying and shrinkage of soils create localised ground movement and cracking. These processes induce stress on pipelines, potentially causing failure through bending, joint displacement, or fracture (Kundzewicz et al., 2018). In regions vulnerable to extreme rainfall and flooding, overwhelmed drainage networks, rapid reservoir sedimentation, and infrastructure failures from extreme water loads are now major challenges (Madonsela et al., 2019; Nhamo et al., 2025). Studies by Kuzma et al. (2023) and Urquiza and Billi (2020) state that regions that experience high levels of water stress tend to have less resilient infrastructure. This relationship between water stress and infrastructure resilience creates a challenging dynamic. The interconnected challenges climate change poses call for a broader approach to resilience. Solutions that combine technological innovation and nature-based systems are proving to be more effective in building long-term infrastructure resilience (Adom et al., 2022; Akamani, 2023; Mehvar et al., 2021; Vinke-De Kruijf et al., 2024).

South Africa has, in recent years, faced increasing weather-related disasters. While the country's climate varies due to its geography, climate change intensifies these extremes, with rising temperatures, shifting rainfall patterns, and increasing frequency and severity of floods and droughts representing a clear departure from historical norms (Adom et al., 2022; Arias et al., 2021; Bopape et al., 2025; Henchiri et al., 2024). These shifts place considerable strain on fragile water supply infrastructure, much of which is ageing, poorly maintained, or structurally vulnerable (National Research Foundation's South African Environmental Observation Network, n.d.). Notably, this vulnerability is uneven across the country. For example, the Western Cape provinces have endured multi-year droughts, while the Eastern and Western Cape and KwaZulu-Natal provinces have experienced increasingly frequent and intense flood events. The resulting infrastructure stress is multifaceted, ranging from pipe bursts, leakages, and pressure losses to widespread service outages (Steyn et al., 2018). These failures cause physical and operational damage and have wider financial, environmental, and public health consequences. Data from the Emergency Events Database (n.d.) highlights this contrast: While floods remain the most frequent natural hazard, droughts have also imposed substantial economic costs. For instance, the 2015–2018 drought in the Western Cape resulted in losses exceeding 1 billion US Dollars, with distribution systems compromised by subsidence-induced fractures (Mahlalela et al., 2019; Visser, 2018). In contrast, the April 2022 floods in KwaZulu-Natal damaged more than 600 km of water mains in a single day, causing total infrastructure and business losses of approximately 2 billion US Dollars (Department of Water and Sanitation, 2022, 2023; Grab & Nash, 2024). Collectively, these events underscore the vulnerability of South Africa's water infrastructure to climate extremes and highlight the urgent need for resilient, adaptive infrastructure planning and investment.

Building resilient urban water distribution infrastructure is essential for mitigating the impacts of climate change and ensuring sustainable water availability (Ferdowsi et al., 2024; Morris & Little, 2019). An approach that integrates technological innovation and nature-based solutions can significantly enhance the adaptability and longevity of water systems. While these strategies offer promising pathways to resilience, their effectiveness varies considerably across different contexts, and each approach carries

distinct limitations and implementation challenges (Akamani, 2023; Crozier et al., 2024). Nature-based solutions have gained recognition as effective strategies for enhancing urban water distribution resilience. Wetland restoration is vital in flood mitigation, water purification, and biodiversity conservation. Further, permeable pavements, urban forests, and rain gardens absorb and store stormwater, reducing overland flows and floods (Addo-Bankas et al., 2024; Fisk et al., 2024; Vinke-De Kruijf et al., 2024). Ecosystem-based water management, which integrates natural systems with engineered infrastructure, provides long-term, sustainable solutions to hydrological challenges (Addo-Bankas et al., 2024; Cohen-Shacham et al., 2016; Vinke-De Kruijf et al., 2024). Despite these benefits, nature-based solutions face significant implementation challenges that limit their widespread adoption, especially during extended drought periods followed by intense rainfall (Boogaard, 2022; Castelo et al., 2023). These solutions also face temporal limitations as many nature-based interventions require an extensive period to function fully, creating a mismatch with the immediate resilience needs as climate impacts intensify. Further, while often promoted as low-maintenance alternatives, evidence from long-term implementations depicts that nature-based solutions require consistent, specialised maintenance to maintain performance, without which efficiency may decline by 15–30% within 3–5 years of installation (Nelson et al., 2020). However, limited empirical evidence connects these strategies to specific, quantified performance outcomes under real climate variability. This study addresses this gap by linking historical climate and infrastructure failure records to targeted adaptation recommendations.

3. Methodology

This study adopts a quantitative approach to investigate the relationship between climate variability and the resilience of urban water distribution and drainage infrastructure in South Africa. The methodological framework integrates long-term climate and infrastructure failure data with statistical modelling techniques, specifically multiple regression and autoregressive integrated moving average (ARIMA) forecasting. The approach enables both the identification of historical relationships and the projection of future infrastructure performance under continued climate variability.

3.1. Data Collection and Processing

The dataset used spans the period from 1980 to 2023 and synthesises information from multiple reputable sources. International datasets were drawn from the IPCC Climate Data Archive (Arias et al., 2021), the Emergency Events Database, and Our World in Data (Ritchie et al., 2022). While regional and national datasets were obtained from the South African Department of Water and Sanitation, the National Research Foundation's South African Environmental Observation Network, and published infrastructure damage assessment reports, although some datasets originate from global repositories, the analysis focuses exclusively on South Africa. Where possible, records from international databases were filtered to extract only national-level entries. In cases where multiple data sources overlapped for the same variable, a standardisation protocol was applied to ensure temporal and definitional consistency. Units of measurement were harmonised across sources: extreme weather events were expressed as the annual count of officially recorded incidents, pipe failures as the number of documented ruptures and leaks per 100 km of pipeline per year, supply interruptions as the annual number of recorded service outages, and economic losses as millions of United States dollars per year, adjusted for inflation using historical exchange rates and price indices. Data quality assurance involved three main steps. First, temporal alignment ensured that all variables

were consistently recorded annually over the 43-year study period. Second, definitional harmonisation ensured that drought events reflected official declarations and that flood incidents excluded coastal storm surges. Third, completeness checks addressed data gaps representing less than 2% of the dataset by interpolating weighted averages from adjacent years. Although interpolation preserves trend continuity, it may also smooth out short-term variability. Sensitivity tests excluding interpolated years could be conducted in future work to assess robustness. This pre-processing preserved the integrity of long-term trends while maintaining statistical robustness for subsequent analyses.

3.2. Statistical Analysis

3.2.1. Descriptive Statistics

Descriptive statistics were computed for all variables to characterise infrastructure failure trends. Pearson correlation coefficients assessed the relationships between climate events (flood and drought) and infrastructure failures (pipe bursts). The multiple regression and ARIMA models were applied to quantify the impact of climate events on infrastructure failures and to forecast future trends in infrastructure failures, focusing on the impact of climate variability over the next two decades (Box et al., 2015). Descriptive statistics were computed to characterise the distribution of climate events and infrastructure failures over the study period. The mean (μ) and standard deviation (σ) for each variable were calculated following Equations (1) and (2), where n represents the number of observations and X_i the observed values for each variable:

$$\mu = \frac{1}{n} \sum_{i=1}^n X_i \quad (1)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (X_i - \mu)^2} \quad (2)$$

These descriptive measures provided a baseline for understanding central tendency and variability for flood incidents, drought incidents, pipe failures, supply interruptions, and economic losses. Additional measures included minimum and maximum values to establish ranges and interquartile ranges for distribution analysis. This statistical profiling established the foundation for subsequent correlation and regression analyses by characterising the fundamental properties of each variable.

3.2.2. Correlation Analysis

Pearson correlation coefficient was employed to assess relationships between climate events and infrastructure failures (Kakoudakis et al., 2018). The correlation coefficient (r) was calculated using Equation (3), where Z_i and Y_i represent paired observations of climate events and infrastructure metrics, while $\bar{Z}$ and $\bar{Y}$ represent their respective means:

$$r = \frac{\sum_{i=1}^n (Z_i - \bar{Z})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^n (Z_i - \bar{Z})^2} \sqrt{\sum_{i=1}^n (Y_i - \bar{Y})^2}} \quad (3)$$

This analysis quantified the strength and direction of the relationship between climate events and pipe failures, supply interruptions, and economic losses. Statistical significance was determined using t -tests for correlation coefficients, with significance thresholds established at $p < 0.05$ and $p < 0.01$. This enabled determining whether observed correlations represented genuine relationships or could reasonably be attributed to random variation (Taiwo et al., 2024, 2025).

3.2.3. Multiple Regression Analysis

A multiple linear regression model was applied to quantify the influence of extreme weather events on infrastructure failures. The general form of the model, as shown in Equation (4), expresses infrastructure failures Y as a function of flood incidents X_1 and drought incidents X_2 :

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon \quad (4)$$

Here, Y denotes the number of pipe failures per 100 km per year, β_0 is the intercept, β_1 and β_2 are the regression coefficients, and ε is the error term. A second model of identical form was developed to estimate annual economic loss as a function of climate exposure and infrastructure vulnerability. While robust, this approach does not capture indirect or long-term costs such as health impacts, environmental damages or business losses, which means estimates likely understate the actual economic burden. Model parameters were estimated using ordinary least squares estimation, as expressed in Equation (5), where $\hat{\beta}$ is the vector of estimated coefficients, X is the matrix of independent variables, and Y is the dependent variable vector:

$$\hat{\beta} = (X^T X)^{-1} X^T Y \quad (5)$$

Model performance was evaluated using the coefficient of determination (R^2) and tested for multicollinearity, residual normality, and homoscedasticity using standard diagnostic plots. Multicollinearity was assessed using the variance inflation factor, with values below 5 indicating acceptable levels. Residuals were tested for autocorrelation using the Durbin–Watson statistic, normality using the Shapiro–Wilk test, and homoscedasticity using the Breusch–Pagan test. Where necessary, corrective measures such as variable transformation were considered.

3.2.4. ARIMA Time-Series Forecasting

An ARIMA model was employed to forecast future trends in pipe failures over 20 years (2024–2044). The ARIMA model, represented in Equation (6), captures both short-term autocorrelation structures and long-term trends (Box et al., 2015):

$$\phi(B)(1 - B)^d X_t = \theta(B)\varepsilon_t \quad (6)$$

where

$$\begin{aligned} \phi(B) &= 1 - \phi_1 B - \phi_2 B^2 - \dots - \phi_p B^p \\ \theta(B) &= 1 + \theta_1 B + \theta_2 B^2 + \dots + \theta_q B^q \end{aligned}$$

where B is the backshift operator ($BX_t = X_{t-1}$), $\phi(B)$ is the autoregressive polynomial of order p , $(1 - B)^d$ denotes differencing of order d to achieve stationarity, and $\theta(B)$ is the moving average polynomial of order q . ε_t is white noise with zero mean and constant variance σ^2 :

Model identification followed the Box–Jenkins methodology, which involved assessing autocorrelation and partial autocorrelation plots to determine the orders p , d , and q . Stationarity of the series was confirmed through the Augmented Dickey–Fuller test. The Ljung–Box test was applied to verify the absence of autocorrelation in residuals, while normality was assessed using the Shapiro–Wilk test. Model selection was guided by minimising the Akaike Information Criterion (AIC) and the Bayesian Information Criterion (BIC). Forecasts were generated with 95% confidence intervals using Equation (7), where $\hat{Y}_{t+h}$ is the point forecast for the time series at $t + h$ and $\hat{V}_{t+h}$ is the forecast error variance:

$$CI_{t+h} = \hat{Y}_{t+h} \pm 1.96 \times \sqrt{\hat{V}_{t+h}} \quad (7)$$

This approach explicitly accounts for both parameter and innovation uncertainties, providing realistic bounds for future infrastructure failure projections under continuing climate variability.

4. Results

4.1. Descriptive Statistics

The descriptive statistics in Table 1 summarise climate events and infrastructure performance metrics from 1980 to 2023. These results reflect significant variability in climate and infrastructure performance over time, with evidence of a clear upward trend in failures and water loss. Annual flood ranged from 9 to 22 incidents (mean = 15.4, SD = 3.2), while drought incidents varied between 4 and 13 (mean = 8.7, SD = 2.8). The rate of pipe failures ranged from 85 to 180 per 100 km annually (mean = 125, SD = 24), with supply interruptions between 65 and 140 events per year (mean = 98, SD = 18). Economic losses ranged from USD 1.1 million to USD 4.2 million per year, with a mean of USD 2.4 million (SD = 0.9).

Table 1. Descriptive statistics of climate events and infrastructure failures (1980–2023).

Variable	Mean	SD	Min	Max
Flood Events	15.4	3.2	9	22
Drought Events	8.7	2.8	4	13
Total Pipe Failures/100 km	125	24	85	180
Supply Interruptions	98	18	65	140
Economic Loss (Million USD/year)	2.4	0.9	1.1	4.2

These statistics provide the baseline for assessing relationships between extreme weather events and infrastructure performance.

4.2. Correlation Analysis

Pearson correlation coefficients were calculated to highlight the relationship between climate events (floods and droughts), infrastructure failures, and economic loss. Table 2 shows these associations.

The results show strong positive correlations, all statistically significant ($p < 0.05$ or $p < 0.01$). The strongest correlation exists between flood incidents and economic losses ($r = 0.81$, $p < 0.01$), indicating that flooding events have substantial financial implications. While these results demonstrate strong statistical associations, they do not establish causality. Factors such as ageing infrastructure and governance quality may also influence

Table 2. Correlation between weather events and infrastructure failures.

Variable	Pipe Failures	Supply Interruptions	Economic Loss
Flood Incidents	0.78 ($p < 0.01$)	0.72 ($p < 0.01$)	0.81 ($p < 0.01$)
Drought Incidents	0.64 ($p < 0.05$)	0.69 ($p < 0.01$)	0.74 ($p < 0.01$)

failure rates and economic losses. The relationship between floods and pipe failures is similarly robust ($r = 0.78$, $p < 0.01$), suggesting that flooding significantly increases the likelihood of physical infrastructure breakdowns. Supply interruptions show slightly lower, though still strong, correlations with both flood ($r = 0.72$, $p < 0.01$) and drought incidents ($r = 0.69$, $p < 0.01$), reflecting the dual impact of both extreme weather types on service continuity.

Drought incidents demonstrate consistently positive correlations with all infrastructure performance metrics, though generally at slightly lower magnitudes than flood correlations. The strongest drought-related correlation is with economic losses ($r = 0.74$, $p < 0.01$), highlighting the significant financial impact of water scarcity. While still significant, the correlation between droughts and pipe failures ($r = 0.64$, $p < 0.05$) is the lowest among the examined relationships, suggesting that flooding events may have more immediate and pronounced effects on physical infrastructure integrity than drought conditions. These results indicate that floods and droughts exert measurable and statistically significant pressure on urban water distribution and drainage systems, although the nature and magnitude of impacts differ.

4.3. Multiple Regression Analysis

Regression analysis allowed us to estimate how much additional pipe failure is expected for each extra drought or flood event. At the same time, ARIMA forecasting projected these failures into the future under current climate trends.

The multiple regression analysis quantified the relationship between climate variability (floods and droughts) and pipe failures from 1980 to 2023. The regression model estimating pipe failures as a function of flood and drought incidents produced Equation (8) as formulated in Equation (4), where Y represents the predicted number of pipe failures per 100 km, X_1 is the number of annual flood incidents, and X_2 represents drought incidents:

$$Y = 72.63 + 4.21(X_1) + 6.19(X_2) \quad (8)$$

The intercept (72.63) represents the expected baseline number of pipe failures with no recorded flood or drought incidents. The coefficient for flood incidents (4.21) shows that each additional flood event is associated with approximately 4.21 additional pipe failures, holding drought incidents constant. Similarly, the coefficient for drought incidents (6.19) indicates that each additional drought event corresponds to approximately 6.19 additional pipe failures, holding flood incidents constant. The model achieved a coefficient of determination (R^2) of 0.86, indicating that floods and droughts together explain 86% of the variance in pipe failures during the study period. Both predictors were statistically significant ($p < 0.01$), confirming their strong contribution to infrastructure failures. Notably, the coefficient for drought incidents (6.19) is about 47% higher than for floods (4.21), suggesting droughts may impose greater stress on urban water systems than flooding.

4.4. ARIMA Forecasting

The ARIMA model analysis identified ARIMA (1,1,1) as the optimal specification for modelling pipe failures based on minimum AIC and BIC values compared to alternative specifications. This model incorporates a first-order autoregressive term, first-order differencing for stationarity, and a first-order moving average component. The fitted ARIMA (1,1,1) model demonstrated good historical fit with the data from 1980 to 2023. Residual diagnostics confirmed model adequacy, with the Ljung-Box test showing no significant autocorrelation in residuals ($p > 0.05$) and the Shapiro-Wilk test confirming approximate normality of residuals ($p > 0.05$). These diagnostic results validate the statistical appropriateness of the selected model for the pipe failure data. The 20-year forecast (2024–2044) suggests a steady increase in pipe failures of approximately 4.5 failures per 100 km per year. The 95% confidence intervals widen progressively with the forecast horizon, reflecting the increasing uncertainty inherent in long-term projections. This expanding uncertainty is a natural characteristic of time series forecasting, where prediction accuracy diminishes as the forecast extends further into the future, as shown in Figure 1.

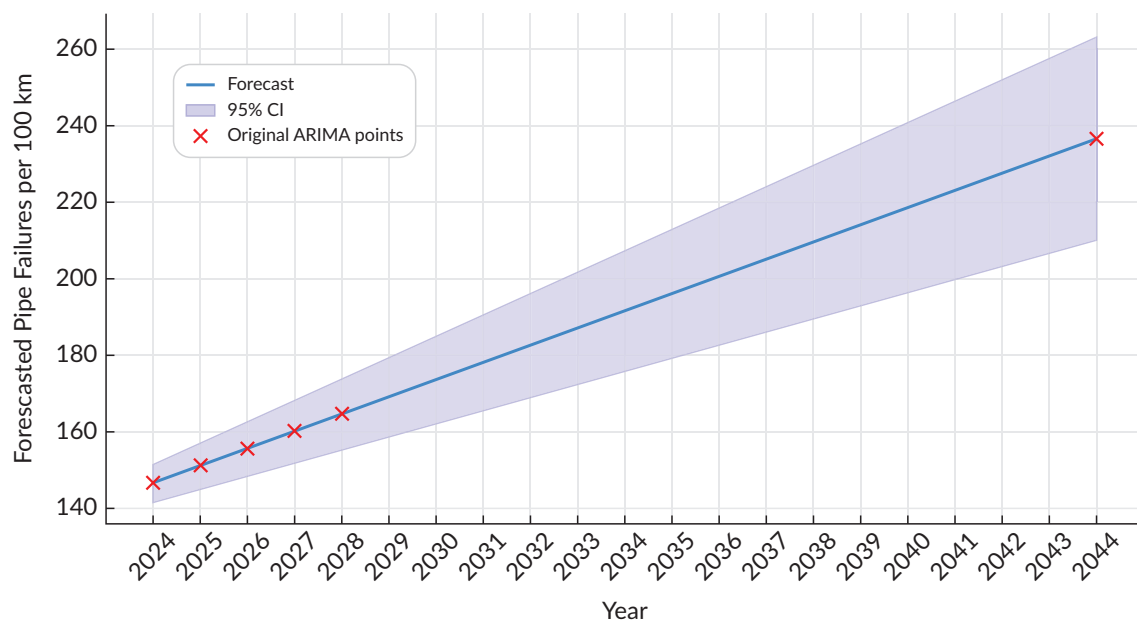


Figure 1. ARIMA (1,1,1) forecast of annual pipe failures per 100 km (2024–2044).

The projected upward trend underscores the increasing vulnerability of the existing water distribution network under current climate variability trajectories. If no adaptive interventions are implemented, the frequency and severity of failures are expected to rise significantly, with corresponding increases in economic losses and service disruptions.

5. Discussion

The findings of this study provide strong empirical evidence that climate variability manifested through floods and droughts has a measurable and statistically significant effect on the performance of urban water distribution and drainage infrastructure in South Africa. The correlation analysis demonstrated that flood incidents have the strongest relationship with economic losses ($r = 0.81$) and pipe failures ($r = 0.78$), while

droughts, although less immediately destructive, were shown through regression analysis to have a 47% greater impact on pipe failures than flooding events (regression coefficients 6.19 vs. 4.21). The ARIMA forecast indicates that, without intervention, annual pipe failures will continue to increase by approximately 4.5 failures per 100 km per year over the next two decades. These results confirm that sudden-onset and prolonged climate events can undermine infrastructure resilience, though they operate through different mechanisms and require tailored adaptation strategies.

5.1. Climate Variability and Infrastructure Resilience

The strong correlations between climate events and infrastructure failures (flood-pipe failure $r = 0.78$; drought-pipe failure $r = 0.64$) demonstrate the vulnerability of current water systems to climate variability. More significantly, the regression analysis reveals that drought incidents have a 47% greater impact on pipe failures than flood events (regression coefficients 6.19 vs. 4.21), challenging the common assumption that flooding poses the primary threat to urban water distribution and drainage infrastructure. These include pluvial flooding, riverine overflow, and in some instances, minor coastal storm surges. This study excludes coastal storm surges and sea-level rise-related flooding, focusing exclusively on inland flood hazards. These findings align with ecological and engineering resilience frameworks (Sinha et al., 2023). The time-series forecasting, which projects an annual increase of 4.5 pipe failures, on average, over the next two decades, indicates that current infrastructure lacks sufficient engineering resilience to withstand increasing climate pressures. The correlation analysis (drought-economic loss $r = 0.74$) suggests that water systems lack the adaptive capacity necessary for ecological resilience, particularly during prolonged drought conditions. The combination of high R-squared values (0.86) in the regression model and consistent upward trends in the ARIMA projections underscores the urgent need for interventions that enhance both dimensions of resilience. Without such measures, the forecast indicates infrastructure failures will continue to increase, threatening water security for millions.

5.2. Infrastructure-Specific Adaptation Strategies

For distribution networks, the regression results indicate that each additional drought event is associated with approximately 6.19 more pipe failures per 100 km. Targeted material upgrades from traditional metal and concrete to high-density polyethylene or ductile iron could reduce vulnerability to soil movement and stress fractures (Mehvar et al., 2021). Though not the primary focus of the modelling, treatment facilities are indirectly implicated in resilience planning. The correlation between drought incidents and supply interruptions ($r = 0.69$) indicates that reduced raw water availability can limit treatment capacity, a phenomenon well-documented in other semi-arid regions (Al-Saidi & Elagib, 2017; Radcliffe, 2015). Decentralised treatment solutions such as neighbourhood-scale recycling and dual reticulation systems can mitigate these effects by diversifying sources and distributing operational risks. Stormwater and drainage systems face particular challenges under intensified precipitation events. The correlation analysis revealed that floods have strong relationships with pipe failures and economic losses, consistent with evidence that drainage systems designed for historical rainfall intensities often fail under current climate extremes (Depietri & McPhearson, 2017; Nhamo et al., 2025). Failure in drainage infrastructure can lead to cascading disruptions across the water network, including backflow contamination and treatment plant overloads (Ferdowsi et al., 2024). Integrating nature-based solutions such as bioswales, permeable pavements, and constructed wetlands can reduce peak hydraulic loads while delivering ecological co-benefits. Copenhagen's

post-flood blue-green infrastructure initiative is a case in point, achieving reductions in flood-related pipe failures while enhancing urban biodiversity (Depietri & McPhearson, 2017).

5.3. Balancing Prevention, Adaptation, and Acceptance

The statistical evidence from this study suggests that neither prevention nor adaptation alone is sufficient to address the dual challenges posed by floods and droughts. Adaptive strategies that improve flexibility, redundancy, and responsiveness must complement engineering-focused prevention measures such as infrastructure hardening. At the same time, strategic acceptance of certain risks may be the most cost-effective option for non-critical infrastructure components, provided robust contingency and emergency response plans are in place (Bani et al., 2024). Given the average annual economic loss of USD 2.4 million identified in this study, cost-benefit analyses should prioritise interventions where the potential for avoided damage is most significant. For example, replacing high-risk pipeline segments in flood-prone and drought-affected areas can yield outsized benefits relative to investment costs. Similarly, diversifying water sources and enhancing localised treatment capacity can reduce dependency on vulnerable centralised infrastructure during climate extremes.

5.4. Governance and Community Engagement

Resilience planning is as much a governance challenge as an engineering one. The significant correlation between flood events and economic losses ($r = 0.81$) reflects physical vulnerability and institutional readiness. Adaptive governance structures that can mobilise resources rapidly and integrate new data into decision-making are essential for managing the evolving risks identified by this study (Akamani, 2023; Bani et al., 2024). Community engagement is also critical. Participatory planning approaches can reveal localised vulnerabilities and adaptation opportunities that may be overlooked in purely technical assessments. As demonstrated in post-flood resilience planning efforts, incorporating community knowledge into project design can enhance both legitimacy and effectiveness (McEwen & Jones, 2012). In South Africa, where service delivery protests often signal dissatisfaction with infrastructure performance, early and meaningful stakeholder involvement can help align adaptation investments with community priorities, improving both uptake and sustainability of resilience measures.

6. Conclusion

This study examined the relationship between climate variability and the resilience of urban water distribution and drainage infrastructure in South Africa by integrating 43 years of climatic and infrastructure performance data into correlation, multiple regression, and ARIMA time-series forecasting analyses. The results provide clear empirical evidence that floods and droughts exert significant pressure on water infrastructure, though their impacts differ in magnitude and mechanism. Flood incidents were found to have the strongest association with economic losses and acute infrastructure failures. In contrast, drought events, while less immediate in their damage, exerted a 47% greater influence on pipe failures than flooding. The regression model's explanatory power ($R^2 = 0.86$) and the ARIMA projection of an average increase of 4.5 pipe failures per 100 km per year over the next two decades underscore the urgency of proactive resilience planning. Without targeted interventions, the vulnerability of South Africa's water distribution network is likely to increase, resulting in escalating service disruptions and economic losses. This study

offers infrastructure managers and policymakers actionable insights by grounding resilience strategies in empirical evidence. The findings highlight the need for targeted material upgrades in drought-prone areas, decentralised treatment systems to reduce supply interruption risks, and nature-based stormwater solutions to alleviate hydraulic stress during floods. Balancing prevention, adaptation, and strategic acceptance guided by cost-benefit considerations emerges as a pragmatic approach to enhancing resilience.

Beyond its practical recommendations, the study contributes to the broader resilience literature by demonstrating that empirical, long-term, climate-linked infrastructure performance data can and should inform adaptation planning. This integrated analytical framework, combining engineering and ecological resilience perspectives with statistical modelling, offers a replicable methodology for other regions facing similar climate pressures. Future research should expand the scope to explore mechanisms linking drought stress to pipeline failures in greater detail and assess the long-term cost-effectiveness of specific adaptation measures in diverse socio-climatic contexts. Strengthening the evidence base in these areas will be critical for building urban water systems capable of withstanding the accelerating challenges of climate change. Further, while this study focused on inland flood and drought hazards, coastal storm surges and sea-level rise pose increasingly urgent risks for cities such as Durban and Cape Town. Future studies should integrate these compound risks to provide a comprehensive national resilience assessment. Addressing inland and coastal challenges will be critical for safeguarding South Africa's water infrastructure under climate change.

Conflict of Interests

The author declares no conflict of interests.

Data Availability

Data will be made available on request.

LLMs Disclosure

To prepare this work, the author used ChatGPT 4.0 and Grammarly tools strictly for grammar and editing purposes.

References

- Addo-Bankas, O., Wei, T., Zhao, Y., Bai, X., Núñez, A. E., & Stefanakis, A. (2024). Revisiting the concept, urban practices, current advances, and future prospects of green infrastructure. *Science of the Total Environment*, 954, 176473. <https://doi.org/10.1016/j.scitotenv.2024.176473>
- Adom, R. K., Simatele, M. D., & Reid, M. (2022). Addressing the challenges of water-energy-food nexus programme in the context of sustainable development and climate change in South Africa. *Journal of Water and Climate Change*, 13(7), 2761–2779.
- Akamani, K. (2023). The roles of adaptive water governance in enhancing the transition towards ecosystem-based adaptation. *Water*, 15(13), 2341. <https://doi.org/10.3390/w15132341>
- Al-Saidi, M., & Elagib, N. A. (2017). Towards understanding the integrative approach of the water, energy and food nexus. *Science of the Total Environment*, 574, 1131–1139.
- Amparo-Salcedo, M., Pérez-Gimeno, A., & Navarro-Pedreño, J. (2025). Water security under climate change: Challenges and solutions across 43 countries. *Water*, 17(5). <https://doi.org/10.3390/w17050633>
- Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., Naik, V., Palmer, M., Plattner, G.K., Rogelj, J., Rojas, M., Sillmann, J., Storelvmo, T., Thorne, P., Trewin, B., Achutarao, K., Adhikary, B., Allan, R.,

- Armour, K., . . . Zickfeld, K. (2021). Intergovernmental Panel on Climate Change (IPCC). Technical summary. In *Climate change 2021: The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 33–144). Cambridge University Press.
- Bani, M., Barendregt, E., Blom, M., Burgers, S., de Groot, C., Hordijk, R., Nobel, A., Philippen, S., & Vendel, B. (2024). *Climate change and the Dutch housing market: Insights and policy guidance based on a comprehensive literature review*. ABN AMRO. <https://library.wur.nl/WebQuery/hydrotheek/2332862>
- Boogaard, F. C. (2022). Spatial and time variable long term infiltration rates of green infrastructure under extreme climate conditions, drought and highly intensive rainfall. *Water*, 14(6), 840. <https://doi.org/10.3390/w14060840>
- Bopape, M. M., Keebine, G., Ndarana, T., Mbokodo, I. L., Hlahane, K., Motshegwa, T., Amha, Y., Ogega, O. M., Mfopa, C., Mahlobo, D. D., & Engelbrecht, F. A. (2025). Weather related disasters in South Africa from 1980 to 2023. *Environmental Development*, 56, 101254. <https://doi.org/10.1016/j.envdev.2025.101254>
- Box, G. E., Jenkins, G. M., Reinsel, G. C., & Ljung, G. M. (2015). *Time series analysis: Forecasting and control*. John Wiley & Sons.
- Castelo, S., Amado, M., & Ferreira, F. (2023). Challenges and opportunities in the use of nature-based solutions for urban adaptation. *Sustainability*, 15(9), 7243. <https://doi.org/10.3390/su15097243>
- Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (Eds.). (2016). *Nature-based solutions to address global societal challenges*. IUCN. <https://doi.org/10.2305/IUCN.CH.2016.13.en>
- Crozier, A., Lence, B. J., & Weijs, S. V. (2024). Resilience framework for urban water supply systems planning. *Sustainable and Resilient Infrastructure*, 9(4), 386–406.
- Department of Water and Sanitation. (2022). *Water, sanitation and climate data resources*. <https://opendataza.gitbook.io/toolkit/open-data-resources/water-and-climate-data-resources>
- Department of Water and Sanitation. (2023). *KwaZulu-Natal floods: Infrastructure damage assessment report* (Report No. 12/2023).
- Depietri, Y., & McPhearson, T. (2017). Integrating the grey, green, and blue in cities: Nature-based solutions for climate change adaptation and risk reduction. In N. Kabisch, H. Korn, J. Stadler, & A. Bonn (Eds.), *Nature-based solutions to climate change adaptation in urban areas: Linkages between science, policy and practice* (pp. 91–109). Springer.
- Emergency Events Database. (n.d.). *Country profile: South Africa 1980–2023*. <https://doc.emdat.be/docs/data-structure-and-content/emdat-public-table>
- Ferdowsi, A., Piadeh, F., Behzadian, K., Mousavi, S. F., & Ehteram, M. (2024). Urban water infrastructure: A critical review on climate change impacts and adaptation strategies. *Urban Climate*, 58, 102132. <https://doi.org/10.1016/j.uclim.2024.102132>
- Fisk, J. M., Harris, P. A., Kuks, S. M., Morris, J. C., & Vinke-De Kruijf, J. (2024). Framing water infrastructure for climate resilience: Governance dimensions and challenges. *Public Works Management & Policy*, 29(2), 133–145.
- Folke, C., Carpenter, S. R., Walker, B., Scheffer, M., Chapin, T., & Rockström, J. (2010). Resilience thinking: Integrating resilience, adaptability and transformability. *Ecology and Society*, 15(4).
- Grab, S. W., & Nash, D. J. (2024). A new flood chronology for KwaZulu-Natal (1836–2022): The April 2022 Durban floods in historical context. *South African Geographical Journal*, 106(4), 476–497.
- Henchiri, M., Zhang, J., Li, S., Essifi, B., & Wilson, K. (2024). Comprehensive assessment of drought vulnerability and resilience over North and West Africa during 1980–2100. *Agricultural Water Management*, 296, 108804. <https://doi.org/10.1016/j.agwat.2024.108804>
- Kakoudakis, K., Farmani, R., & Butler, D. (2018). Pipeline failure prediction in water distribution networks using weather conditions as explanatory factors. *Journal of Hydroinformatics*, 20(5), 1191–1200.

- Kapucu, N., Ge, Y., Rott, E., & Isgandar, H. (2024). Urban resilience: Multidimensional perspectives, challenges and prospects for future research. *Urban Governance*, 4(3), 162–179.
- Karimi, M., Tabiee, M., Karami, S., Karimi, V., & Karamidehkordi, E. (2024). Climate change and water scarcity impacts on sustainability in semi-arid areas: Lessons from the south of Iran. *Groundwater for Sustainable Development*, 24, 101075. <https://doi.org/10.1016/j.gsd.2023.101075>
- Kundzewicz, Z. W., Krysanova, V., Benestad, R. E., Hov, Ø., Piniewski, M., & Otto, I. M. (2018). Uncertainty in climate change impacts on water resources. *Environmental Science & Policy*, 79, 1–8.
- Kuzma, S., Saccoccia, L., & Chertock, M. (2023). 25 countries, housing one-quarter of the population, face extremely high water stress. World Resources Institute. <https://www.wri.org/insights/highest-water-stressed-countries>
- Madonsela, B., Koop, S., Van Leeuwen, K., & Carden, K. (2019). Evaluation of water governance processes required to transition towards water sensitive urban design—An indicator assessment approach for the city of Cape Town. *Water*, 11(2), 292.
- Mahlalela, P. T., Blamey, R. C., & Reason, C. J. C. (2019). Mechanisms behind early winter rainfall variability in the southwestern Cape, South Africa. *Climate Dynamics*, 53(1), 21–39.
- McEwen, L., & Jones, O. (2012). Building local/lay flood knowledges into community flood resilience planning after the July 2007 floods, Gloucestershire, UK. *Hydrology Research*, 43(5), 675–688.
- Mehvar, S., Wijnberg, K., Borsje, B., Kerle, N., Schraagen, J. M., Vinke-de Kruijf, J., Geurs, K., Hartmann, A., Hogeboom, R., & Hulscher, S. (2021). Towards resilient vital infrastructure systems—Challenges, opportunities, and future research agenda. *Natural Hazards and Earth System Sciences*, 21(5), 1383–1407.
- Morris, J. C., & Little, R. G. (2019). Symposium issue: Climate change and infrastructure—The coming challenge. *Public Works Management & Policy*, 24(1), 3–5.
- National Research Foundation's South African Environmental Observation Network. (n.d.). *Hydrological disaster records for South Africa*. <https://infogram.com/flood-vs-drought-1h0n25y7n3jnz6p>
- Nelson, D. R., Bledsoe, B. P., Ferreira, S., & Nibbelink, N. P. (2020). Challenges to realizing the potential of nature-based solutions. *Current Opinion in Environmental Sustainability*, 45, 49–55.
- Nhamo, G., Chapungu, L., & Mutanda, G. W. (2025). Trends and impacts of climate-induced extreme weather events in South Africa (1920–2023). *Environmental Development*, 55, 101183. <https://doi.org/10.1016/j.envdev.2025.101183>
- Olawuyi, S. O., & Mushunje, A. (2024). Livelihood impacts of drought: Experiences from households and business organizations in Western Cape province of South Africa. *Research on World Agricultural Economy*, 5(2), 114–130.
- Radcliffe, J. C. (2015). Water recycling in Australia—During and after the drought. *Environmental Science: Water Research & Technology*, 1(5), 554–562.
- Ritchie, H., Rosado, P., & Roser, M. (2022). *Natural disasters*. Our World in Data. <https://ourworldindata.org/natural-disasters>
- Serafeim, A. V., Fourniotis, N. T., Deidda, R., Kokosalakis, G., & Langousis, A. (2024). Leakages in water distribution networks: Estimation methods, influential factors, and mitigation strategies—A comprehensive review. *Water*, 16(11), 1534.
- Sinha, S. K., Davis, C., Gardoni, P., Babbar-Sebens, M., Stuhr, M., Huston, D., Cauffman, S., Williams, W. D., Alanis, L. G., & Anand, H. (2023). Water sector infrastructure systems resilience: A social-ecological-technical system-of-systems and whole-life approach. *Cambridge Prisms: Water*, 1, e4.
- Steyn, M., Meissner, R., Nortje, K., Funke, N., & Petersen, C. (2018). Water security and South Africa. In R. Meissner, N. Funke, K. Nortje, & M. Steyn (Eds.), *Understanding water security at local government level in South Africa* (pp. 1–44). Springer.

- Taiwo, R., Shaban, I. A., & Zayed, T. (2023). Development of sustainable urban water distribution and drainage infrastructure: A proper understanding of water pipe failure. *Journal of Cleaner Production*, 398, 136653. <https://doi.org/10.1016/j.jclepro.2023.136653>
- Taiwo, R., Zayed, T., Bakhtawar, B., & Adey, B. T. (2025). Explainable deep learning models for predicting water pipe failures. *Journal of Environmental Management*, 379, 124738. <https://doi.org/10.1016/j.jenvman.2025.124738>
- Taiwo, R., Zayed, T., & Seghier, M. E. A. B. (2024). Integrated intelligent models for predicting water pipe failure probability. *Alexandria Engineering Journal*, 86, 243–257.
- Urquiza, A., & Billi, M. (2020). Water markets and social–ecological resilience to water stress in the context of climate change: An analysis of the Limarí Basin, Chile. *Environment, Development and Sustainability*, 22(3), 1929–1951.
- Vinke-De Kruijf, J., Heim LaFrombois, M. E., Warbroek, B., Morris, J. C., & Kuks, S. M. (2024). Climate-resilient water infrastructure: A call to action. *Journal of Critical Infrastructure Policy*, 5(1), 17–29.
- Visser, W. P. (2018). A perfect storm: The ramifications of Cape Town's drought crisis. *TD: The Journal for Transdisciplinary Research in Southern Africa*, 14(1), 1–10.
- World Meteorological Organization. (2023). *State of the global climate 2022* (WMO-No. 1316). https://library.wmo.int/viewer/66214/download?file=Statement_2022.pdf&type=pdf&navigator=1

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Data-Driven Urban Digital Twins and Critical Infrastructure Under Climate Change: A Review of Frameworks and Applications

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Abstract

Urban Digital Twins (UDTs) are rapidly emerging as a transformative tool for enhancing the resilience and sustainability of critical infrastructure (CI) in smart cities, particularly in the face of climate-induced risks. They have gained significant attention in both research and real-world applications. By integrating real-time data, advanced simulations, and predictive analytics, UDTs facilitate data-driven decision-making and optimise urban systems. Given the complexity of urban environments and dynamics, addressing interdependency, interoperability, and inclusiveness is crucial for their effective implementation. This article examines the role of UDTs in managing CI, summarising key risks, technological advancements, and applications. A conceptual framework is proposed in this study to outline the resources required and the potential of UDTs in addressing climate challenges. Despite their promise, the implementation of UDTs faces multidimensional challenges: This article also explores these barriers and future directions for overcoming them through interdisciplinary collaboration, standardisation efforts, and inclusive governance frameworks. As UDTs continue to evolve, sustained innovation and equitable resource distribution will be essential to maximising their impact on the future of urban infrastructure and climate resilience.

Keywords

critical infrastructure resilience; smart cities; urban analytics; urban digital twins; urban management; urban planning

1. Introduction

Critical infrastructure (CI) refers to systems, assets, and networks that underlie the delivery of vital public services, whether they are in the private or public sector (Alkhaleel, 2024). They are fundamental to the

operation of cities, as they underpin essential services such as energy, transportation, and public safety. With increasing automation and digitalisation, infrastructure systems, processes, and resources are becoming more complex, forming highly interconnected networks (Brucherseifer et al., 2021). The proper functioning of a single CI system is crucial both by itself and for the systems it supports. A failure in one CI system can trigger cascading economic, social, environmental, and political impacts. For instance, the 2021 Texas blackout halted economic activities, disrupted communication, and compromised public safety (Busby et al., 2021). In particular, the crisis disproportionately affected low-income and minority communities, who endured longer power outages and faced greater challenges in accessing essential services (Lee et al., 2022). Similarly, in May 2021, a ransomware attack led to the shutdown of the Colonial Pipeline, disrupting the supply of gasoline, diesel, and jet fuel across the southeastern United States. This resulted in a surge in fuel prices, panic buying, and consumers struggling to secure enough fuel for daily operations (Beerman et al., 2023). Meanwhile, the intensifying climate change exacerbates the multifaceted risks to CI, such as flooding, sea-level rise, storms, and heatwaves (Argyroudis et al., 2022; Kantamaneni et al., 2023; Kumar et al., 2021). These climate-induced events strain the resilience of CI, highlighting the need for adaptive strategies to mitigate their impacts. It is therefore crucial to assess the impact of climate change on CI performance and to develop comprehensive adaptation strategies that also consider social, economic, and political factors (Jin & Zhu, 2024; Kingsborough et al., 2017).

Urban Digital Twins (UDTs) have gained significant traction in both research and practical applications in recent years, particularly in the study of CI within smart cities. By integrating real-time data from ubiquitous sensing devices, such as IoT, UDTs analyse and visualise infrastructure dynamics, enabling more informed decision-making (Boccardo et al., 2024). The concept of UDTs extends the Digital Twin (DT) paradigm, which was initially developed in the industrial sector to create virtual models of physical objects for monitoring and simulation. Applied to urban environments, UDTs construct dynamic, data-driven models of cities that integrate multiple urban systems and processes. They facilitate data-driven decision-making for urban operators, offering insights into predictive maintenance, proactive interventions, and efficient resource allocation (Kanigolla et al., 2024). Beyond merely mirroring physical infrastructure, UDTs capture the interconnections between individual entities, dismantling traditional silos to enhance stakeholder collaboration. This fosters innovation in addressing complex urban challenges, ranging from resilience planning to sustainable development (Ersan et al., 2024; Joshi & Badola, 2024). Cities such as Barcelona, Singapore, Helsinki, Copenhagen, Stuttgart, and Zurich have already implemented UDTs to support diverse applications, including infrastructure health monitoring, disaster response, environmental management, traffic control, and the optimisation of energy supply, lighting, parking, and waste management (Boorsma, 2016; Dembski et al., 2019; Euklidiadas, 2024; OPSI, 2024; Schrotter & Hürzeler, 2020).

UDTs development for CI has also garnered increasing recognition from governments and professional organisations, as evidenced by the publication of various roadmaps, manifestos, and reports. In 2018, the Centre for Digital Built Britain (CDBB) launched the National Digital Twin Programme, aiming to establish an interconnected ecosystem of DTs across the built environment. This initiative was designed to improve the management and resilience of national infrastructure (CDBB, 2020). Similarly, in 2020, the Defence Science and Technology Laboratory, an affiliate of the UK Ministry of Defence, published *Future Cities: Trends and Implications*, a report examining emerging urban trends and their impact on CI. The report highlighted how rapid urbanisation and the growing concentration of human activities in cities are pushing governments to address economic, political, social, and environmental challenges. It emphasised that UDTs could provide

cities with critical tools to navigate the complexities of future urban environments effectively (Bogan & Feeney, 2020). In addition, the World Economic Forum and Eurocities released comprehensive frameworks on UDTs in 2022 and 2024, respectively, outlining best practices and guiding principles for their infrastructure implementation. This framework underscored the transformative potential of UDTs in enhancing CI management (Euro Cities, 2024; World Economic Forum, 2022). Emphasising their transformative potential, both reports highlight how UDTs can enhance resilience, efficiency, and data-driven decision-making in urban planning and infrastructure development.

Recognising the growing interest in UDTs for CI, several review studies have explored their development, applications, and challenges. Jafari et al. (2023) and Vieira et al. (2022) examined the role of DTs in enhancing the efficiency and resilience of CI, particularly in energy grids and transportation networks. C. Liu et al. (2023) expanded the scope by categorising urban space as a distinct CI type, primarily focused on structural health monitoring. Other reviewers, such as Argyroudis et al. (2022) and Alibrandi (2022), have discussed DTs as part of broader digital solutions for CI resilience, with the latter introducing the concept of risk-informed DT for structural integrity assessment. Callcut et al. (2021) provided a unique perspective by integrating industry insights, revealing a strong demand for DT standardisation, governance, and decentralised administration, contrasting with the fragmented approaches in academic literature. Additional studies (Lehtola et al., 2022; Mazzetto, 2024; Riaz et al., 2023) have delved into data integration, decision-making frameworks, and the socio-technical challenges of UDTs implementation. However, despite valuable insights into specific CI sectors and technological progress, few reviews explicitly prioritise climate change adaptation. This indicates the research gap, as the potential of UDTs to address climate-induced risks and enhance long-term resilience remains underexplored.

More critically, the connectivity and the collective interdependencies and synergies of an SoS, which is critical in analysing the complexity of cities, have not been sufficiently investigated. Yu and He (2022) briefly discuss interdependencies in disaster management, noting that they add layers of complexity to disaster prediction. Their proposed DT framework incorporates multi-source data fusion, feature recognition, and semantic integration; however, it does not fully capture the cascading effects of interdependent infrastructure failures. Similarly, Fan (2022) highlights the role of human mobility data in enhancing resilience and equity within DT frameworks, yet without a comprehensive approach to modelling cross-sector interdependencies, the broader systemic vulnerabilities remain unaddressed.

Another critical gap is the limited consideration of citizen participation and engagement in UDTs development. While Ye et al. (2023) advocate for a human-centred approach to UDTs for CI resilience, stressing inclusivity in planning and the integration of socio-environmental data via social sensing, such efforts are largely confined to specific case studies, i.e., coastal communities, rather than being broadly applied to urban environments. Furthermore, despite growing calls for participatory UDTs, the implementation of mechanisms for public involvement remains fragmented. Mazzetto (2024) argues for adaptive governance structures and transparent communication channels to facilitate engagement, yet practical strategies for embedding citizen feedback into UDTs-driven decision-making processes are still lacking. These gaps highlight the need for a more holistic approach that not only models interdependent infrastructure networks but also fosters meaningful civic participation to enhance resilience and equity in urban planning.

This article aims to examine how UDTs support the operation and planning of CI for climate change adaptation. Specifically, by establishing the methods of selecting the review samples for comprehensive and systematic analysis, the article begins with an outline of the methodology used to identify and select the reviewed materials. Then, we reveal the impacts of climate change on CI, highlighting the resulting vulnerabilities and the necessity of adopting a UDTs approach. We analyse and categorise the CI studied, the risks addressed, and the applications provided in the reviewed samples; based on them, the genetic framework and the enabling technologies are synthesised. Finally, we identify future directions and challenges spanning technological, social, and policy-related barriers, and provide recommendations to address these gaps and strengthen the practical implementation of UDTs.

The article concludes by summarising key findings and their implications for advancing UDTs in climate-resilient CI planning and management. This cohesive structure contributes to the ongoing dialogue on leveraging digital innovation for sustainable and adaptive urban infrastructure.

2. Review Materials

The research follows the widely used PRISMA framework to guide its methodology. This involves searching for articles using keywords within established academic databases (commonly Web of Science, Scopus, and Google Scholar) and retrieving them. Irrelevant articles are then filtered out based on predefined criteria, such as language and duplication. Subsequently, the remaining articles are characterised, analysed, and systematically mapped. However, this approach has two significant limitations.

The first limitation is that, since being recognised as a top 10 strategic technology trend by Gartner in 2017, the concept of DT has gained prominence; however, its definition remains ambiguous, with no clear consensus in the scientific community (M. Liu et al., 2021; VanDerHorn & Mahadevan, 2021). The terminology associated with DT continues to evolve, as reflected in a regularly updated glossary published by the Digital Twin Consortium (DTC, 2025). Consequently, there is no universally accepted definition or formal guidance for referencing DT in scholarly literature. This ambiguity presents two key challenges: First, the term is often overapplied; some studies describe systems as DT despite them missing essential features such as real-time synchronisation, bidirectional data exchange, or predictive capabilities. Second, many studies that are highly relevant to the DT field do not explicitly use the terms “digital twin” or “urban digital twin” in their titles, abstracts, or keywords. As a result, excluding such studies risks overlooking important contributions and would limit the scope and comprehensiveness of this review.

The second significant limitation is that, outside academia, numerous UDTs initiatives have been led by governments, private enterprises, and civil society organisations. Given the significant financial, technical, and institutional resources required to implement UDTs in real-world settings, many of the most pioneering and innovative developments have emerged from these practice-based initiatives. Unlike academic studies, the outcomes and insights from these efforts are often disseminated through alternative formats such as policy reports, industry white papers, and project documentation. These sources offer valuable insights into the practical implementation of CI planning, management, and resilience. However, such materials are typically not indexed in standard academic databases, making them less visible to researchers and more difficult to systematically include in academic reviews.

Therefore, this article adopts a comprehensive approach that combines the results from academic search engines with knowledge from the authors' research experience in the field, collaborating with government bodies, private sectors, and social organisations. To align with the primary aims of this article, greater emphasis is placed on synthesising key theoretical and technological advancements, covering both the current state and future development in the main body of this article.

The detailed method of selecting the review samples is explained in Supplementary File 1 and the scientific mapping of the bibliometric data is displayed in Supplementary File 2: Supplementary File 1 outlines the step-by-step filtering procedure applied to the initial search results. As shown in Figure SF1, this includes removal of duplicates, screening based on relevance, and the addition of critical academic and industrial contributions identified through expert knowledge. Supplementary File 2 offered further descriptive insights. Table SF1 categorises the reviewed materials by document type, including research papers, review papers, conference papers, book chapters, and reports (primarily from non-academic sources). This typological breakdown demonstrates the diversity of sources included in the review and supports a balanced understanding of both scholarly and practice-based contributions. Figure SF2 highlights the temporal distribution of publications, showing a notable increase since 2019, which has remained consistently high. Tables SF2a, SF2b, and SF2c list the five most cited works in each category: research papers, review papers, and conference proceedings, respectively. Figure SF3 presents a keyword co-occurrence map generated from the initial dataset. This visualisation validates the breadth of covered topics, identifies key thematic clusters, and reveals dominant technical approaches and application domains. The mapping exercise supports the robustness of the methodology and underpins the final selection of review materials.

3. Climate Change and Its Impact on CI

Climate change presents a growing threat to CI by intensifying extreme weather events and exacerbating environmental stressors. Even with the implementation of the most ambitious decarbonisation programs, climate change will persist, bringing more extreme weather than previously experienced (Allard, 2021). Compared with general disaster risks, such as industrial accidents or incidental infrastructure failures, which often occur as discrete, short-term events, climate-induced risks are characterised by their chronicity, systemic impact, and growing uncertainty over time (Shortridge & Camp, 2019). Rising sea levels, projected to increase by 1.3 to 1.6 meters by 2100, will heighten flood risks and accelerate coastal erosion, endangering communities and infrastructure in low-lying areas (van de Wal et al., 2022). Additionally, the Intergovernmental Panel on Climate Change (IPCC) warns that rising global temperatures will lead to heavier rainfall and more frequent flooding, even in regions previously deemed low risk (O'Neill et al., 2017). These changes pose instant short-term disruptions to CI: Flooding can submerge transportation networks and energy systems, cutting off access and halting operations; heatwaves drive up energy demand while compromising infrastructure integrity, causing track buckling and runway degradation; and extreme winds, wildfires, and storms inflict structural damage, leading to power outages and transportation disruptions. As climate hazards intensify, the resilience of CI becomes increasingly critical to maintaining urban functionality and safety. In addition, long-term climate trends will continue to disrupt and reduce the capacity and efficiency of infrastructure (Dawson et al., 2018). The unpredictability of future weather events highlights the vulnerability of even robust systems to extreme conditions (Kim et al., 2017), affecting disadvantaged groups such as those with low socioeconomic status in particular (Yang & Ho, 2017); they demand holistic, anticipatory strategies rather than reactive ones.

Addressing these complex challenges requires a comprehensive approach that accounts for system interdependencies, prioritises sustainability, and anticipates cascading risks. This means not only integrating natural and human-made systems but also fostering innovation and applying a life cycle perspective to enhance infrastructure resilience. In this context, UDTs have emerged as a promising solution for the planning, monitoring, and adaptation of CI under climate pressures. They bridge the gap between reactive and anticipatory strategies by supporting both immediate operational adjustments and long-term planning. For example, the Gemini Principles, developed by the CDBB, distinguish between two main types of DTs: Type 1 DTs are focused on dynamic, real-time models for operational control, while Type 2 DTs are oriented towards strategic planning and investment based on long-term insights (Bolton et al., 2018). Both types provide actionable feedback loops, whether through automated controls or informed capital investments, that enhance the adaptive capacity of CI systems. Next, the implementation of these UDTs solutions in the reviewed works is revealed.

4. Implementation of UDTs for CI

To examine how UDTs are being implemented in the reviewed works, we first identified the types of CI addressed, the climate-induced risks considered, and the services or applications offered in each study. Table 1 presents representative case studies across four key sectors: transportation, water, energy, and the built environment. While some studies did not present concrete applications for generating actionable insights on climate-related risks, they were included due to their foundational conceptual contributions and the transferability of their methods to broader disaster risk management contexts. Most studies focus on acute hazards such as flooding, sea-level rise, strong winds, and extreme heat. In contrast, risks associated with water scarcity, such as prolonged droughts and large-scale wildfires, remain underexplored. While some studies consider shifts in water demand, few address the broader supply–demand dynamics under drought conditions. Where drought is considered, studies tend to focus on complex predictive modelling, with limited development of actionable decision-support tools (Henriksen et al., 2022; Wu et al., 2023). A similar pattern is evident in wildfire research, which emphasises detection and modelling through data fusion (Huang et al., 2024; Hyeong-su et al., 2019; Zhong et al., 2023); however, it offers little insight into the impacts or operational planning strategies of CI.

From a life cycle assessment (LCA) perspective, Michael Grieves, widely recognised as a leading advocate of DTs, proposed three distinct DT types. These include the Digital Twin Prototype (DTP), which represents conceptual designs; the Digital Twin Instance (DTI), corresponding to a specific system in operation; and the Digital Twin Aggregate (DTA), which integrates all existing DTIs to form a comprehensive system-level representation (Grieves, 2023). These paradigms, included in Table 1, though predominantly presented as DTIs, already exhibit characteristics of DTAs. They provide insights by correlating past state changes with subsequent behavioural outcomes while leveraging collective learning from user populations.

These insights emerge from complex interactions among a variety of adaptive agents, which include not only individual entities such as citizens, vehicles, and households, but also organisational stakeholders, such as investors, CI operators, and policymakers. These agents, whether cognitive or automated, continuously interact with their environment and each other, responding to constraints, making decisions, and adjusting behaviours. This creates dynamic feedback loops that shape system performance, inform policy interventions, and influence how reality is perceived and acted upon within the urban context.

Table 1. Paradigms of climate-induced risks addressed, and key stakeholder insights provided by UDTs of CI in existing studies.

CI sector	CI	Risks	Applications	Study
Transportation	Rail	Extreme temperature/ Flood	Providing stakeholders with accurate and up-to-date information for infrastructure investments and safety measures.	Kaewunruen et al. (2022)
	Road	Flood	Improving the coordination among different actors involved in disaster response.	Fan et al. (2021)
			Pinpointing vulnerable locations across the city under various flood scenarios.	Ghaith et al. (2022a)
			Adjusting traffic control measures in response to changing conditions, enhancing resilience to disruptions.	Xu et al. (2023)
	Port	Sea-level rise	Identifying vulnerabilities in port infrastructure, supporting investments and operational adjustments.	Karatvuuo et al. (2022)
Energy	Airport	Extreme temperature/ Strong wind	Fundamental data hub envisioning resilience planning.	Agapaki (2022)
	Grid	Storm	Identifying system vulnerabilities	Braik and Koliou (2023)
	Utility pole	Strong wind	Encouraging participatory sensing involves the community in monitoring and reporting infrastructure issues, fostering a collaborative approach to urban resilience.	Ham and Kim (2020)
Water	Gas pipe	Extreme temperature	Knowledge graph for integrating cross-domain data, enhancing collaboration among experts.	Savage et al. (2022)
	Reservoir	Storm	Utilising user-generated data from social media enables a more comprehensive understanding of local impacts during disasters.	Fan et al. (2020)
	Wetland	Flood	Supporting decision-making in pollution control and habitat preservation. Adjusting water flow and introducing filtration mechanisms.	Aheleroff et al. (2021)
	Drainage		Early warning systems enable mitigation implementation. Supporting land-use planning.	Ghaith et al. (2022b)
			Improving the accuracy of water level predictions, assessing the impact of different preventive measures.	Roudbari et al. (2024)
	Inland waterway	Generic	Forecasting responses to both anticipated and unforeseen events.	AlexandraMicu et al. (2025)

Table 1. (Cont.) Paradigms of climate-induced risks addressed, and key stakeholder insights provided by UDTs of CI in existing studies.

CI sector	CI	Risks	Applications	Study
Built environment	Buildings structure	Extreme temperature	Informed decisions on infrastructure design and maintenance.	Alibrandi (2022)
	Open space		Forecasting urban overhear exposure to reduce its impact.	Mavrokapnidis et al. (2021)
	Urban Morphology		Simulating cool air flows for UHI mitigation.	Schrotter and Hürzeler (2020)
		Extreme temperature/ Flood	Enabling collaboration among stakeholders, including citizens, for proactive planning.	Dembski et al. (2019)
	Heritage	Flood/ Sea-level rise	Protecting the natural and cultural heritage and the unique waterways and pedestrian roads.	Villani et al. (2025)

4.1. Synthesised UDTs Framework for CI Under Climate Change

Researchers have devoted substantial effort to developing a universal, adaptive, and replicable DT architecture, with a key characteristic being the widespread use of a layered approach to group similar components (Gürdür Broo et al., 2022). Despite variations in technical methods and naming conventions, certain core characteristics and essential components remain fundamental (Tao & Qi, 2019; Tao et al., 2018). These typically include: (a) a dynamic linkage between physical and virtual assets, (b) real-time bi-directional data exchange, (c) integration of heterogeneous data sources, (d) simulation and predictive modelling capabilities, and (e) an ability to support decision-making and stakeholder collaboration (Barresi, 2023; Bettencourt, 2024; Ferré-Bigorra et al., 2022; Gil et al., 2024; Poornima et al., 2024; Qanazi et al., 2025; Therias & Rafiee, 2023; Weil et al., 2023).

Across the literature, the layered UDTs framework structure reflects the need to integrate diverse technologies, data sources, and functionalities to provide a comprehensive and dynamic representation of urban environments. For example, Peldon et al. (2024) proposed a five-layer architecture, beginning with the physical reality and extending into digital domains encompassing data handling, modelling, integration, and service delivery. Aheleroff et al. (2021) conceptualised a three-layer structure comprising physical, digital, and cyber layers. These represent: (a) data actuation in real-world objects, (b) digital models such as computer aided design (CAD) for minimal viable representations of physical assets, and (c) a cloud-based layer for generating information, knowledge, and insights. Similarly, Ferré-Bigorra et al. (2022) outlined a four-layer UDTs architecture, including data acquisition, digital modelling, simulation, and service/actuation. While they position the physical environment prominently in their framework, they clarify that it is mirrored by the UDTs but not technically part of it. Deng et al. (2021) proposed a structure comprising three core layers: infrastructure construction, which includes sensing and transmission devices; an “urban brain” platform functioning as the intelligence hub; and application layers supporting service delivery and management. For this article, the adopted and proposed framework is based on the C2PS (Cloud-based cyber-physical systems) architecture by Alam and El Saddik (2017). It offers a reference architecture that integrates cloud computing with cyber-physical systems. It provides the capability of reconfiguration and scalability, enabling a complex SoS, making it particularly suitable for managing complex urban infrastructures.

As shown in Figure 1, a generic framework is proposed with a specific focus on contextualising UDTs for managing CI under climate-induced risks. While C2PS focuses predominantly on system-oriented cloud–cyber–physical interactions, this framework extends those principles by embedding socio-technical dynamics and governance considerations throughout the layers. Adaptive governance and citizen participation were explicitly introduced into the framework, as well as a five-layer structure—acquisition, processing, integration, intelligence, and interaction—reflecting the progression from raw data generation to actionable outcomes. We acknowledge that several existing studies define an extra forefront layer, usually named as the physical layer (Alva et al., 2022; Jiang et al., 2022; Lv et al., 2022), representing the actual physical counterpart that UDTs mirror. However, we argue that, while identifying these assets is a necessary step, it should not be considered part of the UDTs’ technical framework but rather as a prerequisite.

As the foundation, the acquisition layer collects data on CI operations and climate-induced environmental impacts. They are then transmitted to ensure synchronisation with their virtual representations. This layer is also referred to as the data layer in other studies (Aheleroff et al., 2021; Gürdür Broo et al., 2022; Kaewunruen et al., 2022; Peldon et al., 2024). Beyond these, we suggest that extra data sources are required, including participatory CI usage and status data via citizen science and community sensing, and relevant government policies and strategies addressing climate change mitigation.

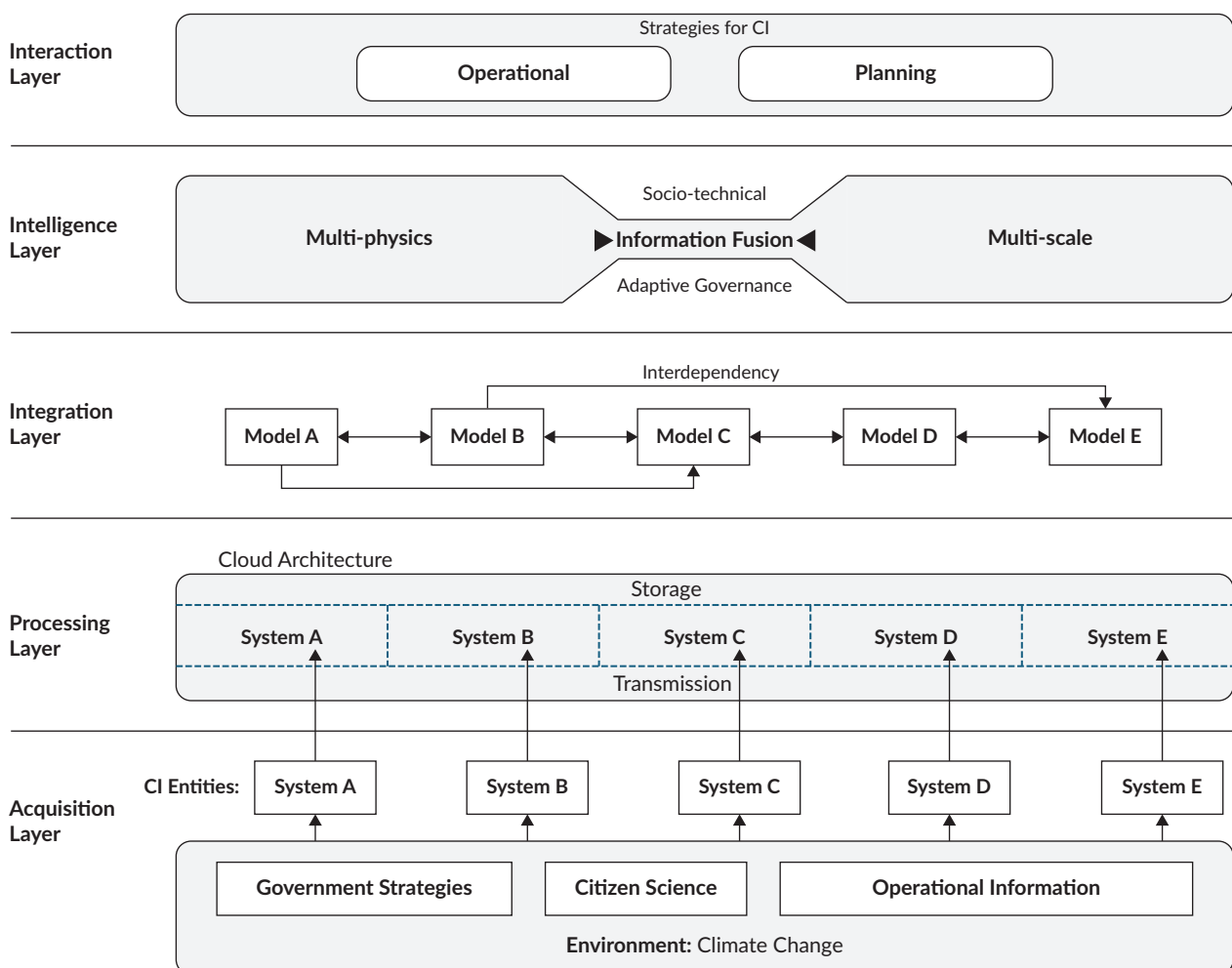


Figure 1. Generic framework of UDTs for managing climate-induced risks to CI.

Building on this, the processing layer handles the transmission, storage, and exchange of the collected data, facilitating the creation of the digital counterpart. High-speed, low-latency communication technologies, including 5G, Wi-Fi, Bluetooth, and LoRa, are vital for real-time data synchronisation (Durão et al., 2018; Liang et al., 2020; Mashaly, 2021). Additionally, scalable cloud-based storage solutions, such as data lakes, are increasingly adopted for advanced data mining and analysis (Neugebauer et al., 2024).

The integration layer incorporates knowledge-based and data-driven modelling approaches to simulate real-world behaviours at varying levels of abstraction (Jeong et al., 2022). Given the complexity of CI, a modular approach is frequently employed to ensure scalability and flexibility. System design tools such as SysML (systems modelling language) and AADL (architecture analysis and design language) are useful to define the structure and address interdependencies across components (Madni et al., 2019; Whyte et al., 2019). However, as UDTs are increasingly applied to SoS, identifying and managing hidden interdependencies remains a significant challenge. Effective detection and evaluation mechanisms are therefore essential for comprehensive integration.

Beyond integration, the intelligence layer enables the fusion of multi-physics and multi-scale simulation outputs, generating cross-domain intelligence by federating individual models. A common approach involves partitioning data into solution domains and implementing a hierarchical system that prioritises objectives accordingly (Jeong et al., 2022; Tuegel et al., 2011). In addition to technical analytics, this layer has been expanded in our framework to incorporate knowledge from socio-technical approaches and adaptive governance. These extensions aim to ensure that intelligence outputs are not only technically sound but also socially legitimate and contextually grounded.

At the top of the framework, the interaction layer serves as the interface between the UDTs and its end users. It supports a range of operational and planning applications, including scenario modelling, deliberative tools, and participatory planning, allowing users to explore system performance and co-develop informed strategies. Outputs generated in the digital space are fed back into the physical system, activating the twinning mechanism: Virtual simulations guide real-world interventions, while real-time changes in the physical environment continuously update and refine the digital counterpart.

Together, these layers constitute a structured yet flexible framework supporting UDTs applications for climate resilience in CI. This layered architecture enables end-to-end digital continuity from capturing real-time physical data to translating it into actionable insights, thereby supporting predictive and adaptive responses to climate-related stressors. Through this cohesive digital infrastructure, UDTs enhance the resilience of CI systems by making them more responsive, robust, and resource-efficient in the face of escalating environmental challenges.

4.2. Data Portfolios

The datasets underpinning UDTs contain data on CI entities, the change of surrounding environments due to climate change, and agents such as vehicles, cargo, and people, as categorised in Table 2. Remote sensing data and engineering models, including CAD, form the geometric foundation of UDTs data. The integration of GIS, BIM, and CityGML enriches these models by adding semantic information beyond spatial dimensions (Kasprzyk et al., 2024; Shi et al., 2023). As BIM data evolves towards multi-dimensional representations, it

serves as a crucial source for cost analysis, sustainability assessments, and life cycle management (Charef, 2022). Real-time environmental and agent-based data are primarily collected through sensing technologies such as IoT devices, CCTV, and GPS tracking. Additionally, crowd-sourced participatory data from social media, mobile applications, and public events is emerging as a key source, providing up-to-date information on disruptions while enhancing inclusivity (Argota Sánchez-Vaquerizo, 2025; Ham & Kim, 2020).

Table 2. Data structures and sources applied in the existing UDTs of CI for climate change.

Entity	Studies
Remote sensing (LiDAR point cloud, DEM, 3D Buildings, Satellite image)	Agapaki (2022); Alibrandi (2022); Dembski et al. (2019); Fan et al. (2021); Ghaith et al. (2022a, 2022b); Ham and Kim (2020); Mavrokapnidis et al. (2021); Roudbari et al. (2024); Schrotter and Hürzeler (2020)
Engineering model (CAD, CAE, BIM, CityGML)	Aheleroff et al. (2021); Ham and Kim (2020); Kaewunruen et al. (2022); Karatvuo et al. (2022); Mavrokapnidis et al. (2021)
Geospatial (Energy grid, Pipeline, Geo-tagged photo)	Agapaki (2022); Ghaith et al. (2022a); Ham and Kim (2020); Savage et al. (2022); Villani et al. (2025); Xu et al. (2023)
Sensor/IoT (Electric meters, Gas meters, Water meters, Sensors for structural health monitoring)	Alibrandi (2022); Ghaith et al. (2022b); Mavrokapnidis et al. (2021); Pesantez et al. (2022)
Stakeholder database	Braik and Koliou (2023); Roudbari et al. (2024); Villani et al. (2025)
Environment	
Sensor/IoT (temperature sensors, wind speed sensors, air quality monitor, flow gauge)	Agapaki (2022); Aheleroff et al. (2021); Ghaith et al. (2022a); Kaewunruen et al. (2022); Karatvuo et al. (2022); Mavrokapnidis et al. (2021); Villani et al. (2025); Xu et al. (2023)
Participatory (Disruption location, People perception, Newly built/proposed structure)	Dembski et al. (2019); Fan et al. (2020, 2021); Ham and Kim (2020); Schrotter and Hürzeler (2020)
Agents	
Sensor/IoT (flight data, traffic sensor)	Agapaki (2022); Xu et al. (2023)
CCTV (vehicle detection, pedestrian detection)	Mavrokapnidis et al. (2021); Xu et al. (2023)
GPS tracking (vessel location)	Villani et al. (2025)

4.3. Data Processing and Analytics

As shown in Table 3, to address the challenges posed by the heterogeneous and dynamic nature of urban data, UDTs commonly employ cloud-based architectures to facilitate data integration and interoperability. This approach enables seamless data sharing, enhances decision-making processes, and improves cross-sector collaboration. By harmonising diverse data standards from IoT, BIM, and GIS, UDTs ensures semantic-level interoperability across different industries, fostering a more cohesive digital ecosystem (Shi et al., 2023).

However, the seamless sharing and processing of data also raise critical concerns regarding data privacy, ownership, and security. Key issues such as consent management, data provenance, and the right to access and control data must be carefully considered, particularly when dealing with personally identifiable information or sensitive urban datasets. Legal and governance frameworks may impose restrictions on how

Table 3. Data processing and analytic methods in the existing UDTs of CI for climate change.

Modelling	Studies
Data mining/filtering	Fan et al. (2020); Ham and Kim (2020); Kaewunruen et al. (2022); Roudbari et al. (2024)
Multi-source fusion/integration	Aheleroff et al. (2021); Alibrandi (2022); Braik and Koliou (2023); Dembski et al. (2019); Fan et al. (2021); Ghaith et al. (2022a, 2022b); Ham and Kim (2020); Mavrokapnidis et al. (2021); Savage et al. (2022); Schrotter and Hürzeler (2020); Villani et al. (2025); Xu et al. (2023)
Cloud architecture	Aheleroff et al. (2021); Xu et al. (2023)
Ontology development	AlexandraMicu et al. (2025); Savage et al. (2022)
Analytic	
Knowledge graph	AlexandraMicu et al. (2025); Fan et al. (2020, 2021); Pesantez et al. (2022); Savage et al. (2022)
Simulation (hydraulic simulation, traffic simulation, energy simulation)	Alibrandi (2022); Dembski et al. (2019); Ghaith et al. (2022a, 2022b); Karatvuio et al. (2022); Schrotter and Hürzeler (2020); Xu et al. (2023)
ML (image ranking, neural network)	Aheleroff et al. (2021); Alibrandi (2022); Fan et al. (2020); Ghaith et al. (2022b); Mavrokapnidis et al. (2021); Roudbari et al. (2024)
Bayesian network	AlexandraMicu et al. (2025); Alibrandi (2022); Braik and Koliou (2023); Ham and Kim (2020)
Game theory	Alibrandi (2022); Fan et al. (2021)
Geospatial analytics (KDE, localisation)	Dembski et al. (2019); Fan et al. (2020); Ham and Kim (2020); Savage et al. (2022); Villani et al. (2025)
Statistical/Mathematical model)	Agapaki (2022); Braik and Koliou (2023); Kaewunruen et al. (2022); Villani et al. (2025)

data can be collected, stored, and shared, which may vary significantly across jurisdictions. Therefore, UDTs development can incorporate technologies such as blockchain for secure data provenance tracking and immutable audit trails, and employ privacy-preserving computation techniques (e.g., federated learning or differential privacy) to enable data analysis without exposing sensitive information. Automated consent management systems embedded in the UDTs architecture can also support users in maintaining control over their data. In parallel, robust data governance frameworks guided by principles of transparency, accountability, and regulatory compliance (e.g., GDPR) can be implemented to clearly define roles, responsibilities, and access protocols across stakeholders.

To assess the impact of climate change, UDTs leverage simulation techniques and machine learning models to predict system behaviour and evaluate potential risks (Ferré-Bigorra et al., 2022). These models integrate historical data and real-time inputs from urban sensors to produce high-resolution forecasts, enabling early-warning systems and scenario testing for extreme weather, flooding, or heat events. Advanced methods such as knowledge graphs and Bayesian networks further enhance predictive capabilities by providing structured knowledge representations, principled data assimilation, optimal control, and uncertainty quantification (Lei et al., 2023; Mandal & O'Connor, 2024). Additionally, for decision-making optimisation, game theory is applied to simulate competitive and cooperative interactions among stakeholders. By modelling strategic behaviours and trade-offs, this approach enables policymakers to test various intervention strategies and identify incentive structures that mitigate potential challenges and promote collaboration in urban planning and infrastructure management (Cai, 2024).

4.4. Services and Interfaces

As outlined in Table 4, current UDTs applications typically provide two main types of services: short-term operational services and long-term strategic services. Short-term services focus on real-time situational awareness, including monitoring dynamic demands, detecting emerging hazards, and assessing CI performance. These insights support immediate decision-making, enabling real-time control measures and adaptive resource allocation to mitigate the impact of unfolding events. In parallel, long-term services support broader strategic objectives. These include predictive maintenance of infrastructure systems, scenario-based urban planning, investment prioritisation, and enhanced public engagement in long-term policy processes. They are delivered through a variety of user interfaces, such as dashboards, APIs, and immersive visualisation tools, ensuring the accessibility of insights for diverse stakeholder groups, from technical operators to policymakers and the public. They align with the two types of DT categorised in the aforementioned Gemini Principle (see also Bolton et al., 2018).

Studies offer holistic approaches covering both types. For instance, Aheleroff et al. (2021) present a DT that features a live dashboard for real-time monitoring and control of pumps and valves in a wetland system to mitigate flooding. At the same time, it leverages historical data to support predictive maintenance. This architecture allows for immediate response to anomalies and, simultaneously, informed long-term decision-making.

Table 4. Actionable information provided and user interfaces in the existing UDTs of CI for climate change.

Service	Studies
Situation awareness	Aheleroff et al. (2021); Fan et al. (2020, 2021); Ghaith et al. (2022a, 2022b); Ham and Kim (2020); Mavrokapnidis et al. (2021); Pesantez et al. (2022); Roudbari et al. (2024); Villani et al. (2025); Xu et al. (2023)
Resource distribution	Agapaki (2022); Braik and Koliou (2023); Fan et al. (2021); Ghaith et al. (2022a, 2022b); Roudbari et al. (2024); Savage et al. (2022)
Predictive maintenance	Aheleroff et al. (2021); Alibrandi (2022); Ham and Kim (2020); Kaewunruen et al. (2022); Karatvuori et al. (2022)
Investment/Planning strategy	Dembski et al. (2019); Kaewunruen et al. (2022); Karatvuori et al. (2022); Schrotter and Hürzeler (2020); Villani et al. (2025)
Public engagement	Dembski et al. (2019); Ham and Kim (2020); Schrotter and Hürzeler (2020)
Real-time control	Aheleroff et al. (2021); Fan et al. (2020); Xu et al. (2023)
Interface	
Live dashboard	Aheleroff et al. (2021); Ghaith et al. (2022b); Karatvuori et al. (2022); Savage et al. (2022); Xu et al. (2023)
API	Aheleroff et al. (2021); Xu et al. (2023)
VR/AR	Aheleroff et al. (2021); Dembski et al. (2019); Ham and Kim (2020); Mavrokapnidis et al. (2021)
3D visual/interaction	Ghaith et al. (2022a); Roudbari et al. (2024); Schrotter and Hürzeler (2020)

5. Challenges and Future Directions

Despite growing commitment and attention to UDTs, their effective implementation in supporting CI under climate-induced risks faces multi-dimensional challenges. They are critical for improving the practicality of UDTs, ranging across technical, institutional, and social dimensions.

5.1. Technical Challenges

The primary technical challenges in implementing UDTs in CI, particularly in addressing climate change-induced risks, revolve around integrating multi-domain knowledge and identifying emergent properties within complex urban systems. Addressing these challenges requires a comprehensive approach that combines technological innovation, strategic planning, and cross-sector collaboration.

As previously discussed in Section 4.1, UDTs must integrate diverse data sources from multiple sectors, each with different levels of abstraction, as well as varying volumes, velocities, and formats of raw data (Iglesias et al., 2020). This often results in data heterogeneity and fragmentation, complicating the effective operation and maintenance of infrastructure systems. The fusion of various models and simulations requires interdisciplinary expertise and cooperation (Deng et al., 2021). Integrating segmented DTIs of existing infrastructure into DTAs is particularly challenging due to the lack of standardised frameworks and a shared understanding of DT architectures. Second, the implementation of UDTs is often hindered by high costs, driven by inefficient business models and the significant investment required for advanced technologies and infrastructure development (Wicaksono et al., 2023). Third, beyond technical complexity and cost barriers, ensuring data privacy and cybersecurity for CI is a critical challenge. As UDTs collect and process vast quantities of sensitive data, centralised architectures are particularly vulnerable to cyber threats and data breaches.

To address these challenges, the adoption of technical protocols and frameworks can facilitate smoother model integration and interoperability. Developing more efficient business models and leveraging cost-effective technologies, such as remote sensing, cloud computing, and AI-driven analytics, can help reduce financial constraints. Additionally, shifting towards decentralised architectures can enhance system resilience and security, mitigating risks associated with cyberattacks and data vulnerabilities.

5.2. Institutional Challenges

A major institutional challenge in UDTs implementation is the absence of widely accepted standards, which significantly impairs efforts to enhance infrastructure resilience. The lack of standardisation leads to inefficient data exchange, biased analyses, and inconsistencies in information interpretation. Consequently, this hampers deployment efforts, causes misalignment among stakeholders, and reduces willingness to participate in UDTs initiatives.

For solutions, developing robust regulatory frameworks and well-defined organisational structures is essential for guiding both the adoption and implementation. Regulatory frameworks will help to establish necessary guidelines and standards, ensuring consistency and interoperability, while organisational structures can further shape the strategic and operational integration of UDTs within institutions. Several

standardisation initiatives have emerged, like DIN SPEC 91357 “Reference Architecture Model Open Urban Platform” and the more recent DIN SPEC 91607 “Digital Twin for Cities and Municipalities,” provide nationally recognised specifications that align with existing standards. This type of standard ensures that the proposed specifications are compatible with existing standards and are officially published at the national level (Connected Urban Twins, 2025). Likewise, the GAIA-X initiative, organised in Brussels, promotes federated data infrastructure, emphasising transparency, interoperability, and sovereignty (Otto, 2022). These principles are crucial for UDTs ecosystems.

Platforms like Fiware, an open-source platform with growing adoption, offer modular components that support data standardisation and interoperability across domains (Bauer, 2022). Additionally, the DTC glossary plays a pivotal role in enhancing the interoperability of industrial systems by providing a standardised framework and common language for DT technologies. This glossary aids in creating a universal understanding and facilitates the integration of DT across various domains, thereby improving efficiency in industrial operations (DTC, 2025). These emerging standards and platforms present valuable foundations upon which UDTs development can build.

Moreover, valuable lessons can be drawn from sectors like manufacturing, healthcare, and maritime logistics. These fields have advanced in standardisation by focusing on key aspects such as interoperability, data exchange, safety, and reliability (Khan et al., 2023). Organisations like ISO, IEEE, and the Industrial Internet Consortium have introduced standards covering general frameworks, technical requirements, and best practices for manufacturing DT (Khan et al., 2023; Sun et al., 2022). UDTs development can build upon these examples to establish a more structured and coordinated approach to standardisation, facilitating broader adoption and impact.

5.3. Social Challenges

UDTs encounter significant social challenges, particularly in the uneven distribution of infrastructure data. Some areas experience excessive or redundant data collection, while others suffer from under-instrumentation and data poverty. For instance, newly developed or renovated communities may have access to high-resolution energy consumption data via smart meters, whereas older buildings still rely on manual data collection, which can compromise the accuracy and reliability of analytical outcomes.

This imbalance not only affects the quality of data but also exacerbates social divides, reinforces existing inequalities, and undermines public trust in governments and organisations. Data poverty is often correlated with broader technological and social deprivation (Serajuddin et al., 2015), and when a UDTs is built on incomplete or non-inclusive datasets, it risks producing less inclusive insights, potentially misleading decision-makers, and excluding vulnerable populations (Riaz et al., 2023). Most UDTs initiatives for CI are concentrated in economically developed cities with substantial funding. However, as climate change presents global challenges, many regions lack the necessary investment, limiting the widespread adoption and advancement of it.

In sectors like manufacturing, where DTs have advanced further, operations are typically governed by strict regulations, enabling structured implementation. In contrast, urban environments are more dynamic and less predictable, requiring UDTs to operate within both formal regulations and informal human behaviours. This

makes stakeholder engagement and public trust essential. Gaining public confidence requires transparent, evidence-based insights that reflect diverse perspectives. Once trust is established, UDTs can support meaningful participation by integrating community feedback into planning and decision-making tailored to local spatial and social contexts (Jin & Zhu, 2025).

Interactive platforms and user-friendly interfaces will allow citizens to co-create solutions, contribute local knowledge, and develop a sense of ownership over resilience strategies. This is especially valuable in the context of climate-induced disasters, where community insights can enhance understanding of how urban systems interact with environmental stressors and improve preparedness. UDTs also strengthen resilience by managing interdependencies across infrastructure systems. By simulating interactions among transport, energy, and water networks, they help identify critical failure points and support more effective planning and real-time response during extreme events (Jin & Zhu, 2024; Wang et al., 2024). A SoS approach allows decision-makers to anticipate cascading failures and vulnerabilities, strengthening urban resilience.

For future development, active collaboration with communities and stakeholders during the planning and implementation of UDTs is crucial. Clear communication of benefits and proactive efforts to address privacy and security concerns can enhance public confidence and encourage participation. Policymakers should also prioritise equitable access to UDTs technologies by supporting skills development and capacity building. Finally, establishing transparent governance frameworks for data management and ensuring ethical, responsible use of data will be vital for maintaining public trust and promoting widespread adoption.

6. Conclusion

The advancement of UDTs signifies a transformative shift from conceptual development to real-world implementation, offering unprecedented opportunities to enhance urban resilience, efficiency, and sustainability. This review examines how UDTs are emerging as a powerful tool for managing CI and mitigating climate-induced risks, enabled by progress in IoT, data modelling, simulation, and advanced analytics.

Our focus on CI as an interconnected SoS underscores the necessity of understanding and managing cross-domain interdependencies. Through the layered framework proposed in Figure 1, we illustrate how digital models can account for cross-sectoral data fusion, system-level simulation, and coordinated policy intervention. We also foreground the growing role of citizen participation in the UDTs lifecycle. The proposed framework incorporates participatory sensing, community-sourced data, and the use of deliberative tools and interaction platforms, facilitating two-way engagement between digital models and real-world users.

The review also highlights persistent technical, institutional, and social challenges in implementing UDTs. As its adoption grows, there is a pressing need for strengthened collaboration to manage interdependencies, ensure interoperability, and foster inclusiveness. Addressing these barriers demands coordinated action across disciplines, sectors, and governance levels. By integrating insights from both academic and practice-based sources, this study offers a holistic foundation for advancing UDTs approaches that are technically robust and socially responsive, bringing the field closer to resilient, inclusive, and anticipatory urban systems.

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Conflict of Interests

The authors declare no conflict of interests.

Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

References

- Agapaki, E. (2022). *Airport Digital twins for resilient disaster management response*. In D. E. Simos, V. A. Rasskazova, F. Archetti, I. S. Kotsireas, & P. M. Pardalos (Eds.), *Learning and intelligent optimization. LION 2022. Lecture Notes in Computer Science* (Vol. 13621) (pp. 467–486). Springer. https://doi.org/10.1007/978-3-031-24866-5_34
- Ahleroff, S., Xu, X., Zhong, R. Y., & Lu, Y. (2021). Digital twin as a service (DTaaS) in industry 4.0: An architecture reference model. *Advanced Engineering Informatics*, 47, Article 101225. <https://doi.org/10.1016/j.aei.2020.101225>
- Alam, K. M., & El Saddik, A. (2017). C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems. *IEEE Access*, 5, 2050–2062. <https://doi.org/10.1109/ACCESS.2017.2657006>
- AlexandraMicu, E., Asgari, F., Khouadjia, M., Connolly, L., & Zavitsas, K. (2025). A probabilistic digital twin model for inland waterway transportation systems using bayesian networks. In E. G. Nathanail, N. Gavanas, & E. Adamos (Eds.), *Climate crisis and resilient transportation systems. CSUM 2024. Lecture Notes in Intelligent Transportation and Infrastructure* (pp. 855–864). Springer. https://doi.org/10.1007/978-3-031-82818-8_64
- Alibrandi, U. (2022). Risk-informed digital twin of buildings and infrastructures for sustainable and resilient urban communities. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*, 8(3). <https://doi.org/10.1061/AJRUA6.0001238>
- Alkhaleel, B. A. (2024). Machine learning applications in the resilience of interdependent critical infrastructure systems—A systematic literature review. *International Journal of Critical Infrastructure Protection*, 44, Article 100646. <https://doi.org/10.1016/j.ijcip.2023.100646>
- Allard, R. F. (2021). Climate change adaptation: Infrastructure and extreme weather. In W. Leal Filho, A. M. Azul, L. Brandli, A. Lange Salvia, & T. Wall (Eds.), *Industry, innovation and infrastructure. Encyclopedia of the UN Sustainable Development Goals* (pp. 105–116). Springer. https://doi.org/10.1007/978-3-319-95873-6_53
- Alva, P., Biljecki, F., & Stouffs, R. (2022). Use cases for district-scale Urban digital twins. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-4/W4-2022, 5–12. <https://doi.org/10.5194/isprs-archives-XLVIII-4-W4-2022-5-2022>
- Argota Sánchez-Vaquerizo, J. (2025). Urban digital twins and metaverses towards city multiplicities: Uniting or dividing urban experiences? *Ethics and Information Technology*, 27(1), Article 4. <https://doi.org/10.1007/s10676-024-09812-3>
- Argyroudis, S. A., Mitoulis, S. A., Chatzi, E., Baker, J. W., Brilakis, I., Gkoumas, K., Vousdoukas, M., Hynes, W., Carluccio, S., Keou, O., Frangopol, D. M., & Linkov, I. (2022). Digital technologies can enhance climate resilience of critical infrastructure. *Climate Risk Management*, 35, Article 100387. <https://doi.org/10.1016/j.crm.2021.100387>

- Barresi, A. (2023). Urban digital twin and urban planning for sustainable cities. *TECHNE—Journal of Technology for Architecture and Environment*, 25, 78–83. <https://doi.org/10.36253/techne-13568>
- Bauer, M. (2022). FIWARE: Standard-based open source components for cross-domain IoT platforms. In 2022 IEEE 8th World Forum on Internet of Things (WF-IoT) (pp. 1–6). IEEE. <https://doi.org/10.1109/WF-IoT54382.2022.10152259>
- Beerman, J., Berent, D., Falter, Z., & Bhunia, S. (2023). A review of colonial pipeline ransomware attack. In 2023 IEEE/ACM 23rd International Symposium on Cluster, Cloud and Internet Computing Workshops (CCGridW) (pp. 8–15). IEEE. <https://doi.org/10.1109/CCGridW59191.2023.00017>
- Bettencourt, L. M. A. (2024). Recent achievements and conceptual challenges for urban digital twins. *Nature Computational Science*, 4(3), 150–153. <https://doi.org/10.1038/s43588-024-00604-9>
- Boccardo, P., La Riccia, L., & Yadav, Y. (2024). Urban echoes: Exploring the dynamic realities of cities through digital twins. *Land*, 13(5), Article 635. <https://doi.org/10.3390/land13050635>
- Bogan, J., & Feeney, A. (2020). *Future cities: Trends and implications*. Defence Science and Technology Laboratory. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/875528/Dstl_Future_Cities_Trends___Implications_OFFICIAL.pdf
- Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Fenemore, T., Harradence, F., Keaney, E., Kemp, A., Luck, A., Pawsey, N., Saville, S., Schooling, J., Sharp, M., Smith, T., Tennison, J., Whyte, J., Wilson, A., & Makri, C. (2018). *The Gemini principles*. Centre for Digital Built Britain. <https://doi.org/10.17863/CAM.32260>
- Boorsma, B. (2016, July 5). Twin City digitization deployments in Copenhagen. Cisco. <https://blogs.cisco.com/government/twin-city-digitization-deployments-in-copenhagen>
- Braik, A. M., & Koliou, M. (2023). A novel digital twin framework of electric power infrastructure systems subjected to hurricanes. *International Journal of Disaster Risk Reduction*, 97, Article 104020. <https://doi.org/10.1016/j.ijdr.2023.104020>
- Brucherseifer, E., Winter, H., Mentges, A., Mühlhäuser, M., & Hellmann, M. (2021). Digital twin conceptual framework for improving critical infrastructure resilience. *At—Automatisierungstechnik*, 69(12), 1062–1080. <https://doi.org/10.1515/auto-2021-0104>
- Busby, J. W., Baker, K., Bazilian, M. D., Gilbert, A. Q., Grubert, E., Rai, V., Rhodes, J. D., Shidore, S., Smith, C. A., & Webber, M. E. (2021). Cascading risks: Understanding the 2021 winter blackout in Texas. *Energy Research & Social Science*, 77, Article 102106. <https://doi.org/10.1016/j.erss.2021.102106>
- Cai, Z. (2024). Application and development of digital twins in smart cities. In 2024 4th International Conference on Big Data Engineering And Education (BDEE) (pp. 27–31). IEEE. <https://doi.org/10.1109/BDEE63226.2024.00012>
- Callcut, M., Cerceau Agliozzo, J.-P., Varga, L., & McMillan, L. (2021). Digital twins in civil infrastructure systems. *Sustainability*, 13(20), Article 11549. <https://doi.org/10.3390/su132011549>
- Centre for Digital Built Britain. (2020). *The approach to delivering a national digital twin for the United Kingdom*. https://www.cdbb.cam.ac.uk/files/approach_summaryreport_final.pdf
- Charef, R. (2022). The use of building information modelling in the circular economy context: Several models and a new dimension of BIM (8D). *Cleaner Engineering and Technology*, 7, Article 100414. <https://doi.org/10.1016/j.clet.2022.100414>
- Connected Urban Twins. (2025). *Urban digital twins: DIN standard “DIN SPEC 91607” as a guide for cities and municipalities*. <https://www.connectedurbantwins.de/en/loesungen/urban-digital-twins-din-standard-din-spec-91607-as-a-guide-for-cities-and-municipalities>
- Dawson, R. J., Thompson, D., Johns, D., Wood, R., Darch, G., Chapman, L., Hughes, P. N., Watson, G. V. R.,

- Paulson, K., Bell, S., Gosling, S. N., Powrie, W., & Hall, J. W. (2018). A systems framework for national assessment of climate risks to infrastructure. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 376(2121), Article 20170298. <https://doi.org/10.1098/rsta.2017.0298>
- Dembski, F., Wössner, U., & Letzgus, M. (2019). The Digital twin tackling urban challenges with models, spatial analysis and numerical simulations in immersive virtual environments. *Blucher Design Proceedings*, 1, 795–804. https://doi.org/10.5151/proceedings-ecaadesigradi2019_334
- Deng, T., Zhang, K., & Shen, Z.-J. (2021). A systematic review of a digital twin city: A new pattern of urban governance toward smart cities. *Journal of Management Science and Engineering*, 6(2), 125–134. <https://doi.org/10.1016/j.jmse.2021.03.003>
- Digital Twin Consortium. (2025). *The DTC glossary*. <https://www.digitaltwinconsortium.org/glossary/glossary>
- Durão, L. F. C. S., Haag, S., Anderl, R., Schützer, K., & Zancul, E. (2018). Digital twin requirements in the context of industry 4.0. In P. Chiabert, A. Bouras, F. Noël, & J. Ríos (Eds.), *Product Lifecycle Management to Support Industry 4.0. PLM 2018. IFIP Advances in Information and Communication Technology* (Vol. 540) (pp. 204–214). Springer. https://doi.org/10.1007/978-3-030-01614-2_19
- Ersan, M., Irmak, E., & Colak, A. M. (2024). Applications, insights and implications of digital twins in smart city management. In *2024 12th International Conference on Smart Grid (IcSmartGrid)* (pp. 378–383). IEEE. <https://doi.org/10.1109/icSmartGrid61824.2024.10578291>
- Euklidiadas, M. M. (2024, January 30). *Discover the alternative Barcelona, Europe's first digital twin*. Tomorrow City. <https://www.tomorrow.city/discover-the-alternative-barcelona-europes-first-digital-twin>
- Euro Cities. (2024). *Urban digital twins: Transforming city planning*. <https://eurocities.eu/latest/urban-digital-twins-transforming-city-planning-and-governance>
- Fan, C. (2022). Integrating human mobility and infrastructure design in digital twin to improve equity and resilience of cities. In *2022 IEEE 2nd International Conference on Digital Twins and Parallel Intelligence (DTPI)* (pp. 1–2). IEEE. <https://doi.org/10.1109/DTPI55838.2022.9998905>
- Fan, C., Jiang, Y., & Mostafavi, A. (2020). Social sensing in disaster city digital twin: Integrated textual visual geo framework for situational awareness during built environment disruptions. *Journal of Management in Engineering*, 36(3). [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000745](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000745)
- Fan, C., Zhang, C., Yahja, A., & Mostafavi, A. (2021). Disaster city digital twin: A vision for integrating artificial and human intelligence for disaster management. *International Journal of Information Management*, 56, Article 102049. <https://doi.org/10.1016/j.ijinfomgt.2019.102049>
- Ferré-Bigorra, J., Casals, M., & Gangoells, M. (2022). The adoption of urban digital twins. *Cities*, 131, Article 103905. <https://doi.org/10.1016/j.cities.2022.103905>
- Ghaith, M., Yosri, A., & El-Dakhakhni, W. (2022a). Digital twin: A city-scale flood imitation framework. In *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021. CSCE 2021. Lecture Notes in Civil Engineering* (Vol. 250) (pp. 577–588). Springer. https://doi.org/10.1007/978-981-19-1065-4_48
- Ghaith, M., Yosri, A., & El-Dakhakhni, W. (2022b). Synchronization-enhanced deep learning early flood risk predictions: The core of data-driven city digital twins for climate resilience planning. *Water*, 14(22), Article 3619. <https://doi.org/10.3390/w14223619>
- Gil, J., Petrova-Antonova, D., & Kemp, G. J. (2024). Redefining urban digital twins for the federated data spaces ecosystem: A perspective. *Environment and Planning B: Urban Analytics and City Science*. Advance online publication. <https://doi.org/10.1177/23998083241302578>
- Grieves, M. W. (2023). Digital twins: Past, present, and future. In N. Crespi, A. T. Drobot, & R. Minerva (Eds.), *The digital twin* (pp. 97–121). Springer. https://doi.org/10.1007/978-3-031-21343-4_4
- Gürdür Broo, D., Bravo-Haro, M., & Schooling, J. (2022). Design and implementation of a smart infrastructure

- digital twin. *Automation in Construction*, 136, Article 104171. <https://doi.org/10.1016/j.autcon.2022.104171>
- Ham, Y., & Kim, J. (2020). Participatory sensing and digital twin city: Updating virtual city models for enhanced risk-informed decision-making. *Journal of Management in Engineering*, 36(3), Article 04020005. [https://doi.org/10.1061/\(ASCE\)ME.1943-5479.0000748](https://doi.org/10.1061/(ASCE)ME.1943-5479.0000748)
- Henriksen, H., Schneider, R., Koch, J., Ondracek, M., Troldborg, L., Seidenfaden, I., Kragh, S., Bøgh, E., & Stisen, S. (2022). A new digital twin for climate change adaptation, water management, and disaster risk reduction (HIP digital twin). *Water*, 15(1), Article 25. <https://doi.org/10.3390/w15010025>
- Huang, Y., Li, J., & Zheng, H. (2024). Modeling of wildfire digital twin: Research progress in detection, simulation, and prediction techniques. *Fire*, 7(11), Article 412. <https://doi.org/10.3390/fire7110412>
- Hyeong-su, K., Jin-Woo, K., Yun, S., & Kim, W.-T. (2019). A novel wildfire digital-twin framework using interactive wildfire spread simulator. In *2019 Eleventh International Conference on Ubiquitous and Future Networks (ICUFN)* (pp. 636–638). IEEE. <https://doi.org/10.1109/ICUFN.2019.8806107>
- Iglesias, C. A., Favenza, A., & Carrera, Á. (2020). A Big Data reference architecture for emergency management. *Information*, 11(12), Article 569. <https://doi.org/10.3390/info11120569>
- Jafari, M., Kavousi-Fard, A., Chen, T., & Karimi, M. (2023). A review on digital twin technology in smart grid, transportation system and smart city: Challenges and future. *IEEE Access*, 11, 17471–17484. <https://doi.org/10.1109/ACCESS.2023.3241588>
- Jeong, D.-Y., Baek, M.-S., Lim, T.-B., Kim, Y.-W., Kim, S.-H., Lee, Y.-T., Jung, W.-S., & Lee, I.-B. (2022). Digital twin: Technology evolution stages and implementation layers with technology elements. *IEEE Access*, 10, 52609–52620. <https://doi.org/10.1109/ACCESS.2022.3174220>
- Jiang, F., Ma, L., Broyd, T., Chen, W., & Luo, H. (2022). Digital twin enabled sustainable urban road planning. *Sustainable Cities and Society*, 78, Article 103645. <https://doi.org/10.1016/j.scs.2021.103645>
- Jin, J., & Zhu, M. (2024). Towards adaptive and resilient strategies using digital twins: A study on the Port of Tyne, UK. In A. Cheshmehzangi, M. Batty, Z. Allam, & D. S. Jones (Eds.), *City information modelling. Urban sustainability* (pp. 165–184). Springer. https://doi.org/10.1007/978-981-99-9014-6_9
- Jin, J., & Zhu, M. (2025). Rendering the digital future: Understanding the social-spatial perception of a dynamic data intensive environment as an architect. In Y. Arayici, N. Thuraijah, & B. Kumar (Eds.), *Sustainable communities through digital transformation* (pp. 119–136). Routledge. <https://doi.org/10.1201/9781003380559-8>
- Joshi, R., & Badola, R. (2024). Digital twin: A transformative tool for smart cities. In S. Majumdar, V. Kandpal, & L. G. Anthopoulos (Eds.), *Smart Cities. S.M.A.R.T. Environments* (pp. 177–198). Springer. https://doi.org/10.1007/978-3-031-59846-3_8
- Kaewunruen, S., AbdelHadi, M., Kongpuang, M., Pansuk, W., & Remennikov, A. M. (2022). Digital twins for managing railway bridge maintenance, resilience, and climate change adaptation. *Sensors*, 23(1), Article 252. <https://doi.org/10.3390/s23010252>
- Kanigolla, L., Pal, G., Vaidhyanathan, K., Gangadharan, D., & Vатtem, A. (2024). Architecting digital twin for smart city systems: A case study. In *2024 IEEE 21st International Conference on Software Architecture Companion (ICSA-C)* (pp. 326–334). IEEE. <https://doi.org/10.1109/ICSA-C63560.2024.00061>
- Kantamaneni, K., Li, Q., Wu, H., Zhu, M., Apostolopoulou, A., Xu, W., Kenawy, I., Rajendran, L. P., Rice, L., Jimenez-Bescos, C., Panneer, S., & Pushparaj, R. R. B. (2023). Towards a combined physical and social evaluation of climate vulnerability in coastal urban megacities. *Water*, 15(4), Article 712. <https://doi.org/10.3390/w15040712>
- Karatvuo, H., Linde, M., Dolatshah, A., & Mortensen, S. (2022). Improved climate change adaptation in Port of

- Brisbane using a digital twin cloud-based modelling approach. In *ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering*. American Society of Mechanical Engineers. <https://doi.org/10.1115/OMAE2022-79613>
- Kasprzyk, J.-P., Nys, G.-A., & Billen, R. (2024). Towards a multi-database CityGML environment adapted to big geodata issues of urban digital twins. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLVIII-4/W10-2024, 101–106. <https://doi.org/10.5194/isprs-archives-XLVIII-4-W10-2024-101-2024>
- Khan, T. H., Noh, C., & Han, S. (2023). Correspondence measure: A review for the digital twin standardization. *The International Journal of Advanced Manufacturing Technology*, 128(5/6), 1907–1927. <https://doi.org/10.1007/s00170-023-12019-3>
- Kim, Y., Eisenberg, D. A., Bondank, E. N., Chester, M. V., Mascaro, G., & Underwood, B. S. (2017). Fail-safe and safe-to-fail adaptation: Decision-making for urban flooding under climate change. *Climatic Change*, 145(3/4), 397–412. <https://doi.org/10.1007/s10584-017-2090-1>
- Kingsborough, A., Jenkins, K., & Hall, J. W. (2017). Development and appraisal of long-term adaptation pathways for managing heat-risk in London. *Climate Risk Management*, 16, 73–92. <https://doi.org/10.1016/j.crm.2017.01.001>
- Kumar, N., Poonia, V., Gupta, B. B., & Goyal, M. K. (2021). A novel framework for risk assessment and resilience of critical infrastructure towards climate change. *Technological Forecasting and Social Change*, 165, Article 120532. <https://doi.org/10.1016/j.techfore.2020.120532>
- Lee, C.-C., Maron, M., & Mostafavi, A. (2022). Community-scale big data reveals disparate impacts of the Texas winter storm of 2021 and its managed power outage. *Humanities and Social Sciences Communications*, 9(1), Article 335. <https://doi.org/10.1057/s41599-022-01353-8>
- Lehtola, V. V., Koeva, M., Elberink, S. O., Raposo, P., Virtanen, J.-P., Vahdatikhaki, F., & Borsci, S. (2022). Digital twin of a city: Review of technology serving city needs. *International Journal of Applied Earth Observation and Geoinformation*, 114, Article 102915. <https://doi.org/10.1016/j.jag.2022.102915>
- Lei, B., Janssen, P., Stoter, J., & Biljecki, F. (2023). Challenges of urban digital twins: A systematic review and a Delphi expert survey. *Automation in Construction*, 147, Article 104716. <https://doi.org/10.1016/j.autcon.2022.104716>
- Liang, C.-J., McGee, W., Menassa, C., & Kamat, V. (2020). Bi-directional communication bridge for state synchronization between digital twin simulations and physical construction robots. In *Proceedings of the 37th International Symposium on Automation and Robotics in Construction* (pp. 1480–1487). IAARC. <https://doi.org/10.22260/ISARC2020/0205>
- Liu, C., Zhang, P., & Xu, X. (2023). Literature review of digital twin technologies for civil infrastructure. *Journal of Infrastructure Intelligence and Resilience*, 2(3), Article 100050. <https://doi.org/10.1016/j.iintel.2023.100050>
- Liu, M., Fang, S., Dong, H., & Xu, C. (2021). Review of digital twin about concepts, technologies, and industrial applications. *Journal of Manufacturing Systems*, 58, 346–361. <https://doi.org/10.1016/j.jmsy.2020.06.017>
- Lv, Z., Shang, W.-L., & Guizani, M. (2022). Impact of digital twins and metaverse on cities: History, current situation, and application perspectives. *Applied Sciences*, 12(24), Article 12820. <https://doi.org/10.3390/app122412820>
- Madni, A., Madni, C., & Lucero, S. (2019). Leveraging digital twin technology in model-based systems engineering. *Systems*, 7(1), Article 7. <https://doi.org/10.3390/systems7010007>
- Mandal, S., & O'Connor, N. E. (2024). LLMasMMKG: LLM assisted synthetic multi-modal knowledge graph creation for smart city cognitive digital twins. *Proceedings of the AAAI Symposium Series*, 4(1), 210–221. <https://doi.org/10.1609/aaais.v4i1.31795>

- Mashaly, M. (2021). Connecting the twins: A review on digital twin technology & its networking requirements. *Procedia Computer Science*, 184, 299–305. <https://doi.org/10.1016/j.procs.2021.03.039>
- Mavrokapnidis, D., Mohammadi, N., & Taylor, J. (2021). Community dynamics in smart city digital twins: A computer vision-based approach for monitoring and forecasting collective urban hazard exposure. In *Proceedings of the 54th Hawaii International Conference on System Sciences* (pp. 1810–1818). University of Hawaii at Manoa. <https://doi.org/10.24251/HICSS.2021.220>
- Mazzetto, S. (2024). A review of urban digital twins integration, challenges, and future directions in smart city development. *Sustainability*, 16(19), Article 8337. <https://doi.org/10.3390/su16198337>
- Neugebauer, J., Heilig, L., & Voß, S. (2024). Digital twins in the context of seaports and terminal facilities. *Flexible Services and Manufacturing Journal*, 36, 821–917. <https://doi.org/10.1007/s10696-023-09515-9>
- O'Neill, B. C., Oppenheimer, M., Warren, R., Hallegatte, S., Kopp, R. E., Pörtner, H. O., Scholes, R., Birkmann, J., Foden, W., Licker, R., Mach, K. J., Marbaix, P., Mastrandrea, M. D., Price, J., Takahashi, K., van Ypersele, J.-P., & Yohe, G. (2017). IPCC reasons for concern regarding climate change risks. *Nature Climate Change*, 7(1), 28–37. <https://doi.org/10.1038/nclimate3179>
- OPSI. (2024, November 5). *Virtual Singapore—Singapore's virtual twin*. <https://oecd-opsi.org/innovations/virtual-twin-singapore>
- Otto, B. (2022). A federated infrastructure for European data spaces. *Communications of the ACM*, 65(4), 44–45. <https://doi.org/10.1145/3512341>
- Peldon, D., Banihashemi, S., LeNguyen, K., & Derrible, S. (2024). Navigating urban complexity: The transformative role of digital twins in smart city development. *Sustainable Cities and Society*, 111, Article 105583. <https://doi.org/10.1016/j.scs.2024.105583>
- Pesantez, J. E., Alghamdi, F., Sabu, S., Mahinthakumar, G., & Berglund, E. Z. (2022). Using a digital twin to explore water infrastructure impacts during the COVID-19 pandemic. *Sustainable Cities and Society*, 77, Article 103520. <https://doi.org/10.1016/j.scs.2021.103520>
- Poornima, G., Y, S., & T N, M. (2024). A digital twin-enabled system for smart city. In *Futuristic trends in IOT—Volume 3, Book 2* (pp. 71–97). Iterative International Publishers. <https://doi.org/10.58532/V3BII02CH7>
- Qanazi, S., Leclerc, E., & Bosredon, P. (2025). Integrating social dimensions into urban digital twins: A review and proposed framework for social digital twins. *Smart Cities*, 8(1), Article 23. <https://doi.org/10.3390/smartcities8010023>
- Riaz, K., McAfee, M., & Gharbia, S. S. (2023). Management of climate resilience: Exploring the potential of digital twin technology, 3D city modelling, and early warning systems. *Sensors*, 23(5), Article 2659. <https://doi.org/10.3390/s23052659>
- Roudbari, N. S., Puneekar, S. R., Patterson, Z., Eicker, U., & Poullis, C. (2024). From data to action in flood forecasting leveraging graph neural networks and digital twin visualization. *Scientific Reports*, 14(1), Article 18571. <https://doi.org/10.1038/s41598-024-68857-y>
- Savage, T., Akroyd, J., Mosbach, S., Krdzavac, N., Hillman, M., & Kraft, M. (2022). Universal digital twin: Integration of national-scale energy systems and climate data. *Data-Centric Engineering*, 3, Article 23. <https://doi.org/10.1017/dce.2022.22>
- Schrotter, G., & Hürzeler, C. (2020). The digital twin of the City of Zurich for urban planning. *PFG—Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 88(1), 99–112. <https://doi.org/10.1007/s41064-020-00092-2>
- Serajuddin, U., Uematsu, H., Wieser, C., Yoshida, N., & Dabalen, A. (2015). *Data deprivation: Another deprivation to end* (Policy Research Working Paper No. 7252). World Bank Group. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2600334

- Shi, J., Pan, Z., Jiang, L., & Zhai, X. (2023). An ontology-based methodology to establish city information model of digital twin city by merging BIM, GIS and IoT. *Advanced Engineering Informatics*, 57, Article 102114. <https://doi.org/10.1016/j.aei.2023.102114>
- Shortridge, J., & Camp, J. S. (2019). Addressing climate change as an emerging risk to infrastructure systems. *Risk Analysis*, 39(5), 959–967. <https://doi.org/10.1111/risa.13234>
- Sun, W., Ma, W., Zhou, Y., & Zhang, Y. (2022). An introduction to digital twin standards. *GetMobile: Mobile Computing and Communications*, 26(3), 16–22. <https://doi.org/10.1145/3568113.3568119>
- Tao, F., & Qi, Q. (2019). Make more digital twins. *Nature*, 573(7775), 490–491. <https://doi.org/10.1038/d41586-019-02849-1>
- Tao, F., Zhang, M., Liu, Y., & Nee, A. Y. C. (2018). Digital twin driven prognostics and health management for complex equipment. *CIRP Annals*, 67(1), 169–172. <https://doi.org/10.1016/j.cirp.2018.04.055>
- Therias, A., & Rafiee, A. (2023). City digital twins for urban resilience. *International Journal of Digital Earth*, 16(2), 4164–4190. <https://doi.org/10.1080/17538947.2023.2264827>
- Tuegel, E. J., Ingrassia, A. R., Eason, T. G., & Spottswood, S. M. (2011). Reengineering aircraft structural life prediction using a digital twin. *International Journal of Aerospace Engineering*. Advance online publication. <https://doi.org/10.1155/2011/154798>
- van de Wal, R. S. W., Nicholls, R. J., Behar, D., McInnes, K., Stammer, D., Lowe, J. A., Church, J. A., DeConto, R., Fettweis, X., Goelzer, H., Haasnoot, M., Haigh, I. D., Hinkel, J., Horton, B. P., James, T. S., Jenkins, A., LeCozannet, G., Levermann, A., Lipscomb, W. H., . . . White, K. (2022). A high-end estimate of sea level rise for practitioners. *Earth's Future*, 10(11), Article 2022EF002751. <https://doi.org/10.1029/2022EF002751>
- VanDerHorn, E., & Mahadevan, S. (2021). Digital twin: Generalization, characterization and implementation. *Decision Support Systems*, 145, Article 113524. <https://doi.org/10.1016/j.dss.2021.113524>
- Vieira, J., Poças Martins, J., Marques de Almeida, N., Patrício, H., & Gomes Morgado, J. (2022). Towards resilient and sustainable rail and road networks: A systematic literature review on digital twins. *Sustainability*, 14(12), Article 7060. <https://doi.org/10.3390/su14127060>
- Villani, L., Gugliemetti, L., Barucco, M. A., & Cinquepalmi, F. (2025). A digital twin framework to improve urban sustainability and resiliency: The case study of Venice. *Land*, 14(1), Article 83. <https://doi.org/10.3390/land14010083>
- Wang, Y., Yue, Q., Lu, X., Gu, D., Xu, Z., Tian, Y., & Zhang, S. (2024). Digital twin approach for enhancing urban resilience: A cycle between virtual space and the real world. *Resilient Cities and Structures*, 3(2), 34–45. <https://doi.org/10.1016/j.rcns.2024.06.002>
- Weil, C., Bibri, S. E., Longchamp, R., Golay, F., & Alahi, A. (2023). Urban digital twin challenges: A systematic review and perspectives for sustainable smart cities. *Sustainable Cities and Society*, 99, Article 104862. <https://doi.org/10.1016/j.scs.2023.104862>
- Whyte, J., Chen, L., Gamble, C., Genes, C., Pierce, K., Fitzgerald, J., Coca, D., Mayfield, M., Babovic, F., Pedro, A., & Shah, N. (2019). *Analysing systems interdependencies using a digital twin*. CDBB. <https://www.cdbs.ac.uk/news/publication-final-report-analysing-systems-interdependencies-using-digital-twin>
- Wicaksono, H., Nisa, M. U., & Vijaya, A. (2023). Towards intelligent and trustable digital twin asset management platform for transportation infrastructure management using knowledge graph and explainable artificial intelligence (XAI). In *2023 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 528–532). IEEE. <https://doi.org/10.1109/IEEM58616.2023.10406401>
- World Economic Forum. (2022). *Digital twin cities: Framework and global practices*. <https://www.weforum.org/publications/digital-twin-cities-framework-and-global-practices>
- Wu, X., Lu, G., & Wu, Z. (2023). Remote sensing technology in the construction of digital twin basins: Applications and prospects. *Water*, 15(11), Article 2040. <https://doi.org/10.3390/w15112040>

- Xu, H., Berres, A., Yoginath, S. B., Sorensen, H., Nugent, P. J., Severino, J., Tennille, S. A., Moore, A., Jones, W., & Sanyal, J. (2023). Smart mobility in the cloud: Enabling real-time situational awareness and cyber-physical control through a digital twin for traffic. *IEEE Transactions on Intelligent Transportation Systems*, 24(3), 3145–3156. <https://doi.org/10.1109/TITS.2022.3226746>
- Yang, X., & Ho, S. S. (2017). Decreasing the knowledge gap among different socioeconomic status groups on the issue of climate change. *Environmental Hazards*, 16(3), 276–290. <https://doi.org/10.1080/17477891.2017.1279999>
- Ye, X., Du, J., Han, Y., Newman, G., Retchless, D., Zou, L., Ham, Y., & Cai, Z. (2023). Developing human-centered urban digital twins for community infrastructure resilience: A research agenda. *Journal of Planning Literature*, 38(2), 187–199. <https://doi.org/10.1177/08854122221137861>
- Yu, D., & He, Z. (2022). Digital twin-driven intelligence disaster prevention and mitigation for infrastructure: Advances, challenges, and opportunities. *Natural Hazards*, 112(1), 1–36. <https://doi.org/10.1007/s11069-021-05190-x>
- Zhong, C., Cheng, S., Kosoar, M., & Arcucci, R. (2023). Reduced-order digital twin and latent data assimilation for global wildfire prediction. *Natural Hazards and Earth System Sciences*, 23(5), 1755–1768. <https://doi.org/10.5194/nhess-23-1755-2023>

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Integrating Emerging Design-Build Technologies for Resilient Housing in the Navajo Nation

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Abstract

The Navajo Nation faces critical challenges in developing housing that is resilient to climate change while honoring cultural heritage. Socio-economic disparities, limited infrastructure, and extreme environmental conditions demand innovative solutions that integrate sustainable practices with traditional Navajo values. This study critically examines the potential of smart design-build technologies to create resilient, culturally appropriate housing tailored to the Navajo Nation’s unique needs, while interrogating the normative assumptions that often accompany Western frameworks of sustainability and innovation. This research combines a multidisciplinary literature review with a graduate-level design studio’s explorative and applied insight. The literature review synthesizes advancements in sustainable technologies—such as off-grid power systems, alternative materials, and participatory design methods—through a decolonial lens that challenges dominant planning paradigms. A conceptual framework was constructed to evaluate the intersection of cultural coherence, technological viability, material sustainability, socio-environmental adaptability, and governance. Off-grid solutions, including solar panels and wind turbines, offer clean energy alternatives, while locally sourced materials, like earth-based and carbon-environmentally informed additive manufacturing solutions, provide cost-effective, low-carbon options suitable for the arid climate. The study emphasizes participatory design, engaging local communities in developing housing solutions that align with cultural values and modern needs. By combining traditional Navajo architectural principles—such as circular forms and earthen materials—with smart technologies, the resulting designs are resilient, sustainable, and socially relevant. The design studio component enabled graduate students to explore speculative housing prototypes grounded in this framework, evaluated in dialogue with Navajo cultural liaisons and contextual constraints, thereby centering Indigenous perspectives in both process and output. The findings contribute to the broader discourse on smart, resilient infrastructure, offering insights for policymakers, designers, and funders to support localized, culturally and environmentally informed housing solutions in Indigenous communities.

Keywords

climate adaptation; Navajo Nation; off-grid systems; resilient housing; responsible design; smart building technologies; sustainable materials

1. Introduction

The Navajo Nation faces a multifaceted housing crisis rooted in historical, environmental, and socio-economic challenges. Overcrowding is prevalent, with homes being 6.5 times more crowded than the US average, often accommodating multi-generational families due to cultural practices and housing shortages. Infrastructure deficits are significant; approximately 32% of homes lack electricity, and many still do not have access to running water. Historical policies, such as the Bennett Freeze, imposed a 43-year development ban on 1.5 million acres of Navajo land, stalling infrastructure improvements and contributing to current housing inadequacies. These compounded issues necessitate a novel approach to housing development that is resilient, culturally appropriate, and sustainable. Resilience in housing, defined as the capacity of structures to withstand and adapt to environmental, social, and economic stresses, is particularly pertinent in Indigenous contexts where traditional knowledge and community cohesion play vital roles. However, dominant approaches to resilience and sustainability often reproduce Western design norms and governance frameworks that risk marginalizing Indigenous worldviews. The following literature review outlines the environmental, socio-economic, and policy-related challenges that necessitate a novel approach to housing development in Indigenous communities.

This research aims to explore the intersection of emerging design-build technologies and traditional Navajo architectural principles in the development of resilient housing. It seeks to identify key smart technologies applicable to off-grid and sustainable housing solutions. As many Navajo communities lack access to centralized utilities, this study evaluates advanced energy systems, such as solar panels and wind turbines, alongside water-harvesting techniques that promote self-sufficiency. The integration of these technologies is assessed for their viability in enhancing housing resilience while reducing dependence on external resources. This study therefore critically interrogates not only the applicability but also the assumptions embedded in emerging technologies, particularly their role in shaping housing governance, ownership, and autonomy within tribal contexts.

Another objective of this research is to examine the role of cultural heritage in shaping housing designs that align with Indigenous values. The traditional Navajo hogan, with its circular form and earthen materials, embodies principles of harmony with nature. Yet, these traditions also represent epistemologies that challenge Cartesian spatial logics and technocratic housing models. The research also acknowledges that resilience is not a neutral goal but a contested one, raising questions of who defines resilience, for whom, and through which institutional frameworks. By incorporating these elements into contemporary architectural strategies, the study aims to develop housing models that are both culturally relevant and environmentally sustainable. Understanding how cultural identity influences design choices ensures that new housing solutions reflect community needs and traditions. This study also assesses policy frameworks that support the implementation of resilient housing initiatives. Given the complex legal landscape of water and land rights in Indigenous territories, the research examines existing regulations, tribal governance structures, and funding mechanisms that shape housing development. By analyzing these frameworks, the

study identifies policy gaps and opportunities for creating more supportive and adaptive regulations that facilitate sustainable housing.

2. Methodology

To enhance transparency and rigor in our literature review, we adopted a structured approach inspired by the PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines. Our process involved identifying relevant literature across five thematic domains: smart design-build technologies, culturally coherent housing, environmental resilience strategies, participatory design practices, and governance and sovereignty frameworks. We conducted searches in databases such as JSTOR, Scopus, and Google Scholar using targeted keywords. After removing duplicates and screening abstracts, we assessed full-text articles for eligibility based on predefined inclusion and exclusion criteria. This process resulted in a curated selection of studies that informed our conceptual framework.

Our inclusion criteria focused on peer-reviewed articles, conference papers, and reputable grey literature published between 2000 and 2025, emphasizing Indigenous housing, resilience, and related technologies. We prioritized studies incorporating participatory design and governance frameworks relevant to the Navajo Nation. Exclusion criteria encompassed studies not pertaining to Indigenous communities, publications lacking empirical data or methodological transparency, and articles not available in English. This selection method ensured the relevance and quality of the literature reviewed.

The participatory component of this research primarily involved graduate students from Texas Tech University's Huckabee College of Architecture, who engaged through design studios, workshops, and collaborative mapping exercises. These activities facilitated the integration of academic insights with cultural perspectives, aligning with the project's objectives to explore resilient housing solutions within the Navajo Nation context. Additionally, future collaboration with faculty and students from Navajo Technical University is anticipated to provide valuable feedback on housing resilience, cultural relevance, and technological integration. Initial contact has been made with faculty members at NTU to explore this engagement as part of the continued development of the study. All participants were informed about the study's objectives, and ethical approval was obtained in accordance with institutional guidelines.

2.1. Multi-Disciplinary Literature Review

This research employs a multi-disciplinary literature review to explore the intersection of smart design-build technologies, environmental resiliency and traditional Navajo architectural principles. The review did not follow a systematic protocol; instead, we adopted a purposive sampling strategy focused on identifying literature that problematizes both technological optimism and development orthodoxy in Indigenous contexts. Our review was structured around five thematic domains: (a) smart design-build technologies, (b) culturally coherent housing, (c) environmental resilience strategies, (d) participatory design practices, and (e) governance and sovereignty frameworks. These categories informed the construction of a conceptual framework used to evaluate the housing prototypes. The review synthesizes insights from architecture, urban planning, environmental studies, Indigenous studies, and policy analysis to construct a comprehensive framework for resilient housing development. By examining various case studies from worldwide, the literature review identifies best practices and technological innovations relevant to the Navajo Nation.

Notably, we engaged with critiques from planning literature that expose the risks of applying Global North planning logics to Indigenous or subaltern settings (Star, 1999; Watson, 2009). This enabled us to interrogate the power-laden assumptions embedded in seemingly “neutral” technologies like GIS or modular prefabrication (Mehan, 2024a, 2024b, 2024c). Rather than treating the literature descriptively, we examined its internal tensions—such as the contradiction between portability in prefab design and the weight-dependence of thermal mass in earthen materials—and identified trade-offs that inform resilient housing strategy (Mehan & Mostafavi, 2024a, 2024b, 2024c).

Key sources include research on sustainable housing solutions that integrate off-grid energy systems, water conservation methods, and culturally informed design principles. Studies on indigenous rights and governance frameworks provide context on the regulatory challenges affecting housing development in Native American communities. Additionally, environmental science literature contributes knowledge on climate change impacts, resource scarcity, and ecological resilience strategies that inform housing adaptation measures. A critical component of the literature review is the examination of participatory design methodologies. Research on community-led housing initiatives highlights the significance of local engagement in the planning and implementation of sustainable housing solutions. Studies on spatial justice and equitable design emphasize the need for housing strategies that empower Indigenous communities and align with their cultural and social values (Mehan & Dominguez, 2024). By integrating insights from diverse academic fields, this literature review lays the foundation for understanding the complexities of housing resilience in the Navajo Nation. The findings from this review guide the research in identifying viable smart technologies, policy interventions, and design strategies that can be incorporated into the participatory design process.

2.2. Design Studio Component

This research advances the implementation of smart design-build technologies within the Navajo Nation through an applied design methodology structured around a graduate-level studio. The Augmented Adaptive Additive Manufacturing for Resilient Housing studio serves as a testing ground for computational workflows, advanced material systems, and participatory frameworks, allowing for a systematic evaluation of their applicability within the socio-environmental and cultural constraints of the Navajo context. To mitigate the risk of replicating top-down technological solutions, the studio adopted a participatory ethic that included structured engagements with Navajo community, cultural liaisons, and housing professionals. Their feedback informed material selection, spatial strategies, and site prioritization. The studio follows a structured three-phase process—research and mapping, design-build prototyping, and architectural system integration—each generating empirical data and design insights that contribute to the broader discourse on resilient and contextually adaptive housing solutions. Rather than serving solely as a pedagogical exercise, the studio was structured as a research-action platform where speculative design operated in tandem with grounded critiques of Western architectural paradigms. This integration of Indigenous consultation helped question assumptions of universality in modular design, additive manufacturing, and even data visualization through GIS (Mehan et al., 2023). The studio team documented instances where conventional approaches conflicted with cultural customs, such as building orientation, access hierarchy, or material meaning.

The first phase, research and mapping, establishes a quantitative and qualitative understanding of the Navajo Nation’s housing conditions, environmental risks, and infrastructure limitations. A key component of

this phase is the systematic analysis of traditional Navajo hogan dwellings, which demonstrate passive environmental strategies, circular spatial organization, and earthen material construction principles that remain relevant for contemporary applications. Figure 1 represents the typological variations of these dwellings alongside an assessment of existing housing conditions across the Navajo Nation, providing a baseline for evaluating deficiencies in resilience and opportunities for adaptation.

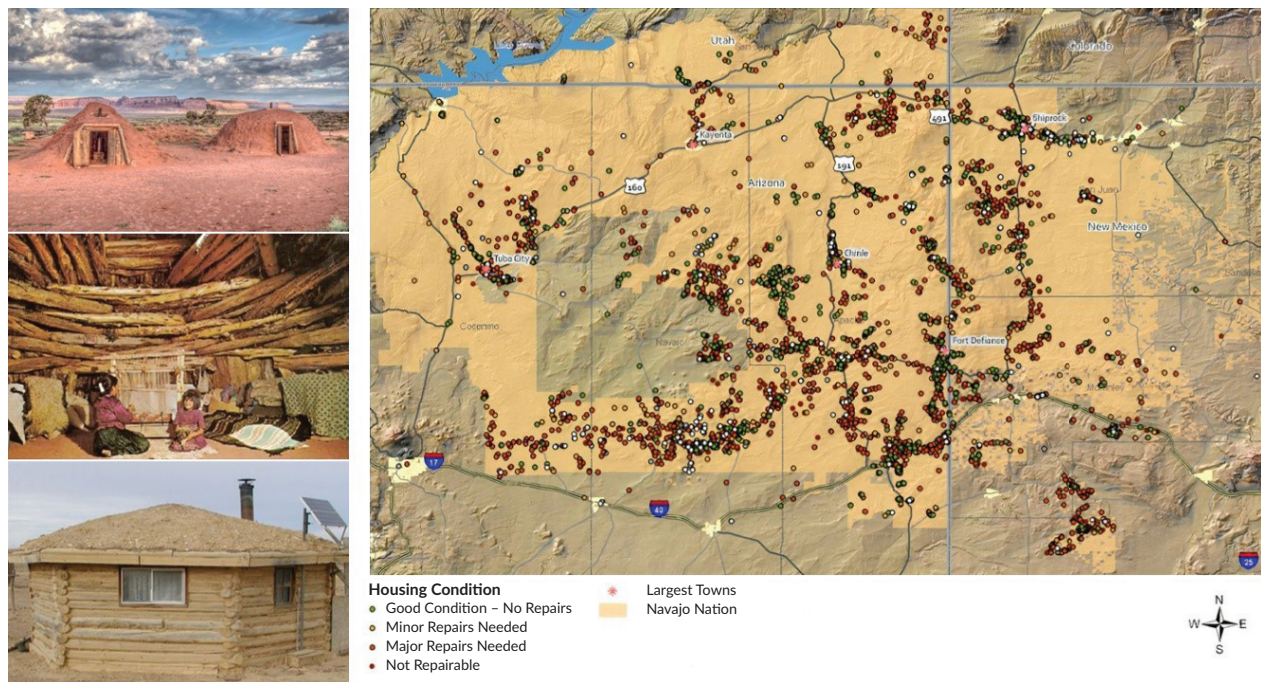


Figure 1. Traditional Navajo hogan dwellings and housing conditions across the Navajo Nation. Notes: The images on the left show variations in hogan construction, highlighting their cultural and architectural significance; the map on the right categorizes housing conditions, indicating units in good condition, those requiring repairs, and non-repairable structures; this analysis provides insight into housing resilience challenges in the region. Sources: Carey (2025, left); RPI Consulting prepared for Navajo Housing Authority (right).

This phase further employs spatial analysis and geospatial mapping exercises (Figure 2) to assess key resilience factors, including climate conditions, water accessibility, wildfire hazards, transportation networks, and material availability. These analyses integrate both macro-scale environmental data and micro-scale socio-economic indicators to identify vulnerabilities and opportunities for resilient housing interventions. Mapping efforts include site-specific studies of terrain conditions, water infrastructure, wind exposure, and the spatial distribution of existing housing units relative to essential services and resources. Additionally, comparative studies of traditional and contemporary building typologies within the Navajo Nation provide a deeper understanding of material flows, construction practices, and adaptation strategies. These multi-scalar assessments are synthesized into research booklets and mapping pinups, forming a data-driven foundation for subsequent design explorations. By embedding these mapping exercises within the broader framework of the studio, the research ensures that proposed housing solutions are informed by localized environmental parameters, resource availability, and culturally embedded spatial practices.

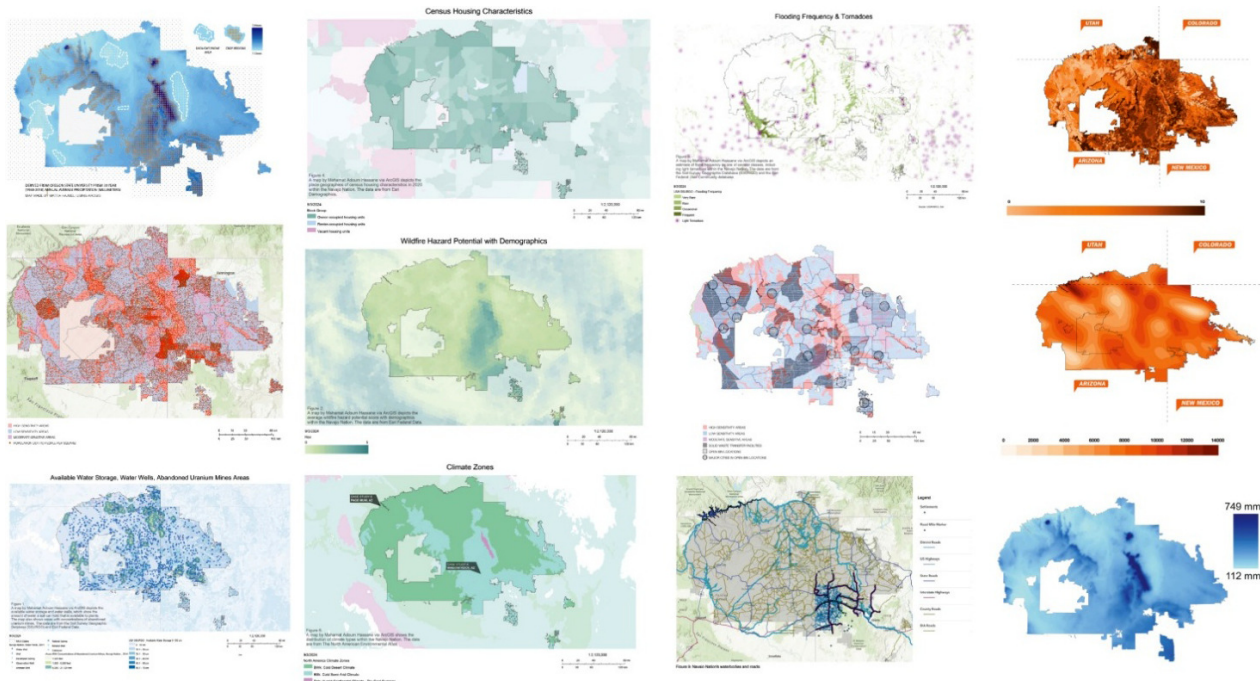


Figure 2. Samples of spatial analyses and geospatial mapping exercises of the Navajo Nation, spanning New Mexico, Arizona, Colorado, and Utah. Note: Each map examines specific socio-environmental parameters and resilience challenges, including housing conditions, climate zones, water accessibility, wildfire hazards, transportation networks, access to materials, and infrastructure systems. Source: Authors; mapping drawings part of Arch 5603 Spring 2024 studio, Augmented Adaptive Additive Manufacturing for Resilient Housing: Design-Build Systems Empowering the Navajo Nation, led by Sina Mostafavi at TTU HCOA.

Building on these findings, the second phase, design-build prototyping, develops and evaluates material and construction strategies for resilient housing components. This phase integrates augmented adaptive additive manufacturing, robotic fabrication, and hybrid digital construction methods to explore informed variation, wherein structural performance, material efficiency, and climatic adaptability drive design outcomes. Scaled sectional prototypes are produced using techniques such as earth-based 3D printing, robotic milling of modular components, and digitally mediated assembly systems tailored to site-specific constraints and cultural requirements. The iterative nature of this phase facilitates the refinement of adaptive construction strategies, ensuring that emerging technologies are critically integrated to enhance resilience rather than imposed as one-size-fits-all solutions. Findings from these engagements are reflected not only in final deliverables but also in the design criteria themselves, which were modified mid-process to better reflect cultural protocols and relational spatiality. By embedding these reflections in the workflow, the studio enacted a form of critical praxis that resisted treating Indigenous knowledge as “input” and instead foregrounded it as a co-constitutive design logic.

The final phase, architectural system integration, translates research and prototyping insights into complete housing models, contextualized within site locations identified through geospatial analysis and resilience assessments (Figure 3). The proposed single-family and multi-family housing typologies are evaluated for their structural performance, passive environmental strategies, and adaptability to shifting socio-economic conditions. The resulting designs incorporate locally sourced materials, decentralized energy systems, and computationally optimized spatial configurations, demonstrating a balance between technological advancement and cultural continuity. The final deliverables, including architectural documentation, scaled

physical models, and augmented visualizations, reinforce the argument that integrated digital design and fabrication workflows can support localized, culturally responsive housing innovation.

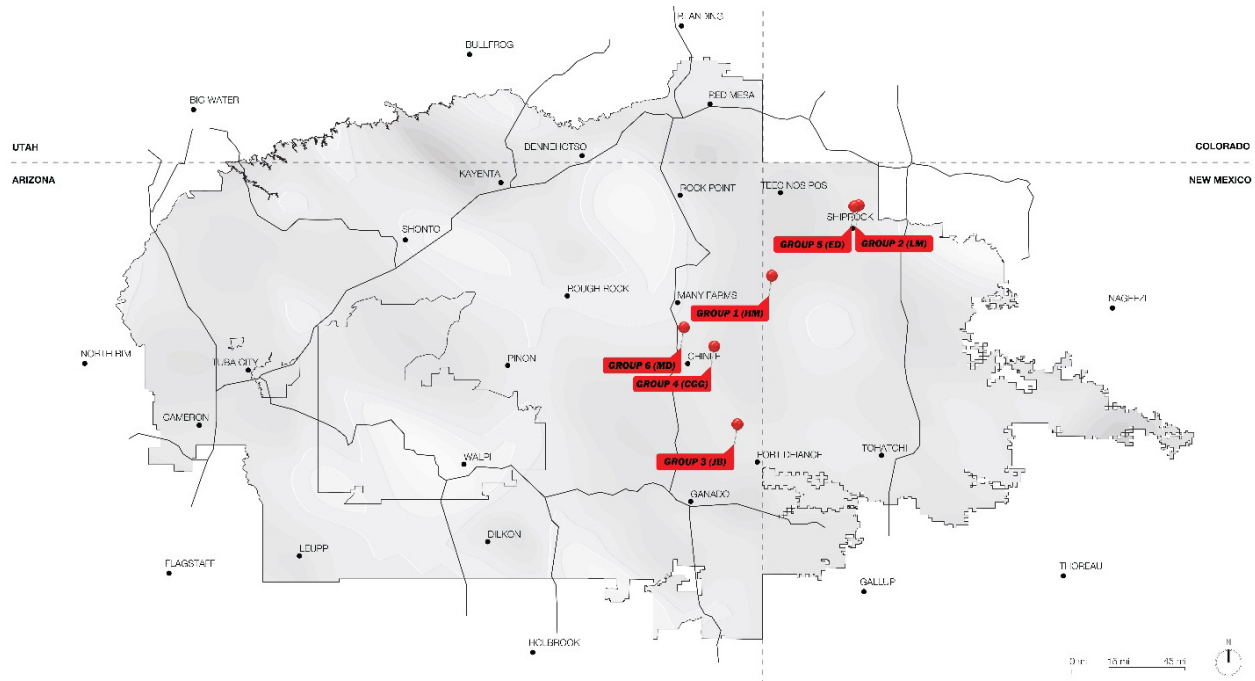


Figure 3. Selected site locations for the application of emerging design-build technologies based on initial mapping studies. Notes: These sites were identified through geospatial analysis of environmental resilience factors, material accessibility, infrastructure networks, and housing needs within the Navajo Nation; the selection process considers climate exposure, land conditions, and proximity to existing settlements to inform contextually responsive design-build explorations. Source: Authors; part of Arch 5603 Spring 2024 studio—Augmented Adaptive Additive Manufacturing for Resilient Housing: Design-Build Systems Empowering the Navajo Nation, led by Sina Mostafavi, diagram created by Caleb Scott.

This structured design research framework provides a methodological approach for evaluating the responsible application of smart design-build technologies in Indigenous contexts. By embedding multi-scalar investigations, from geospatial mapping to material prototyping and full-scale system integration, within a participatory studio setting, this study generates empirical data and replicable design strategies for resilient and culturally informed housing solutions. The iterative relationship between analytical mapping, experimental prototyping, and architectural synthesis positions this research as both a scientific and practice-based contribution to ongoing discussions on resilient housing, computational construction, and the integration of digital fabrication within Indigenous architectural traditions. The technological innovation section of this article further expands on this work, presenting selected projects from the six identified sites, where these methods are applied and analyzed in detail.

3. Literature Review

3.1. Smart Technologies and Responsible Design

Innovative approaches, such as smart design-build technologies, offer potential solutions to the housing challenges faced by the Navajo Nation. By integrating technological advancements with culturally sensitive

design principles, the Navajo Nation can benefit from resilient housing models that support sustainable living. While these technologies offer potential, they are not inherently neutral or universally applicable. Scholars such as Star (1999) and Watson (2009) warn of the risks of embedding Western-centric governance logics into “smart” systems that may overlook or overwrite local knowledge systems. For example, GIS-based planning and modular prefab typologies often assume standardized mobility and efficiency that may conflict with place-based values or local resource cycles. These tensions are especially evident when thermal mass materials, like adobe, are compared to transportable prefab units, revealing friction between cultural continuity and logistical scalability.

Recent studies have highlighted the importance of integrating traditional ecological knowledge into housing design to enhance resilience and sustainability in Indigenous communities (Alvarez & Montoya, 2022). This section outlines advancements in smart technologies that contribute to resilience, such as off-grid energy systems, water-efficient designs, and alternative materials. Key research has explored sustainable housing solutions that incorporate off-grid solar and wind power, rainwater harvesting systems, and energy-efficient design (Smith & Wouters, 2019). Off-grid energy technologies, such as photovoltaic solar panels and small-scale wind turbines, have been successfully implemented in remote Indigenous communities to reduce reliance on centralized grid systems (Gerlach et al., 2020). These solutions enhance energy independence and provide reliable power, particularly in areas where conventional grid infrastructure is limited or unreliable (Mehan, 2025; Mehan & Casey, 2025). Rather than treating these innovations as one-size-fits-all solutions, this study considers how they may be adapted or contested within Indigenous design tradition (Mehan & Mostafavi, 2023a, 2023b, 2023c). In doing so, it challenges the assumption that resilience can be achieved solely through technological optimization.

Advances in prefabrication and modular housing techniques also offer scalable solutions that can be customized to meet the specific needs of Indigenous communities (Alvarez & Montoya, 2022). Prefabricated housing units, developed using sustainable materials, have been implemented in First Nations communities in Canada, demonstrating their viability in addressing housing shortages while maintaining affordability and efficiency (Hodge, 2018). Additionally, modular housing allows for rapid deployment in disaster-prone areas, providing resilient shelter options that can be easily transported and assembled on-site (Murray & Bertram, 2020). Furthermore, emerging research on bioclimatic architecture and passive design strategies highlights how housing can be adapted to extreme climates, making them more suitable for regions like the Navajo Nation. Passive heating and cooling techniques, along with high thermal mass materials like adobe and rammed earth, improve indoor climate control and energy efficiency while respecting Indigenous construction traditions (Lopez & Dean, 2021). Studies on earth-based construction materials have emphasized their sustainability, affordability, and ability to regulate indoor temperatures in arid environments (Fathy, 1986; Minke, 2006).

Recent research on sustainable building materials has also explored the use of hempcrete, mycelium-based insulation, and straw bale construction as viable alternatives to conventional materials (Sutton & Black, 2021). These materials not only provide high thermal efficiency but also contribute to carbon sequestration, reducing the overall environmental impact of housing projects (Mostafavi et al., 2024; Pittau et al., 2018). In addition to material innovations, smart water management technologies are important for enhancing resilience in Navajo Nation housing. Water scarcity remains a major challenge in the region, making rainwater harvesting, greywater recycling, and efficient irrigation systems essential for sustainable living

(Gleick, 2014). Advanced filtration and desalination technologies have been tested in remote Indigenous communities, offering solutions to ensure access to clean drinking water while minimizing dependency on external water sources (Lalander et al., 2018). In summary, integrating smart design-build technologies with Indigenous knowledge and culturally appropriate materials presents a potential pathway for developing resilient housing in the Navajo Nation.

3.2. Cultural Sensitivity in Indigenous Housing

Housing in Indigenous communities requires a deep understanding of cultural traditions and environmental adaptation. The Navajo Nation has long embraced sustainable design using natural materials, passive solar strategies, and community-oriented spatial arrangements (Yazzie & Knapp, 2018). Incorporating modern technologies into these traditions ensures that housing solutions remain relevant and resilient in the face of climate change (Benally, 2020). Furthermore, the environmental impact of historical land use practices, such as uranium mining and large-scale infrastructure projects, necessitates design strategies that integrate water conservation and contamination remediation (Brugge et al., 2007). Exposure to hazardous materials has led to long-term health implications for the Navajo people, making sustainable housing solutions a critical component of public health (Charley et al., 2016). Addressing these environmental injustices through housing design can create safer living environments and contribute to the broader efforts of land restoration and community healing (Tso & McKinley, 2019). However, such characterizations risk reducing culture to aesthetic features rather than acknowledging Indigenous worldviews as ontological foundations for design. Cultural sensitivity, in this context, must move beyond symbolic gestures to confront the structural marginalization embedded in dominant planning regimes.

As Watson (2009) emphasizes, planning paradigms rooted in the Global North often carry implicit assumptions about rationality, order, and technical fixability, which can clash with Indigenous epistemologies grounded in relationality, sovereignty, and non-linear temporality. A key element of culturally sensitive design is the consideration of traditional spatial arrangements. The Navajo hogan, for example, follows a circular structure that reflects Indigenous cosmology and environmental harmony (Ferguson & Kniffen, 2015). Integrating such design principles into modern housing developments can strengthen cultural identity while enhancing resilience to climate-related challenges (Harris & Harper, 2021). This tension is especially evident in the practice of integrating passive solar design: While environmental performance may align with cultural precedent, the metrics used to evaluate success are often imported from Western standards of efficiency and comfort. Furthermore, the orientation of buildings based on solar and wind patterns—practices long embedded in Navajo architecture—can optimize energy efficiency and indoor comfort while reducing reliance on external power sources (Roaf et al., 2018).

Beyond spatial considerations, material selection is another major aspect of culturally responsive housing. Traditional adobe and rammed earth construction techniques not only align with Indigenous knowledge systems but also offer high thermal mass, making them well-suited for the region's temperature extremes (Smith & Wouters, 2019). Incorporating these materials into modern construction can reduce embodied carbon while maintaining structural integrity and aesthetic continuity with Navajo traditions (Lopez & Dean, 2021). Additionally, innovations such as hempcrete and straw bale insulation provide opportunities to merge Indigenous practices with contemporary sustainability advancements (Alvarez & Montoya, 2022). Furthermore, incorporating Navajo hogan typologies into digital design workflows demands not only

geometric translation but also ethical accountability, ensuring that sacred spatial orientations are not flattened into generic design tokens.

Participatory design in this context must not merely “consult” Indigenous communities, but validate Indigenous governance over space, materiality, and dwelling. Moreover, participatory design approaches have proven effective in ensuring Indigenous communities have agency in shaping their built environments. Collaborative efforts between architects, planners, and tribal members can help bridge the gap between traditional knowledge and contemporary sustainability practices, resulting in housing solutions that are both practical and culturally appropriate (Alvarez & Montoya, 2022). Engaging communities in co-design processes ensures that housing developments meet residents’ needs while fostering local skills and employment opportunities in construction and maintenance (Mason, 2020). This section explores the principles of culturally sensitive design and how they intersect with smart housing innovations, offering insights into best practices that honor Indigenous traditions while promoting environmental sustainability. By integrating these design principles, it is possible to create resilient housing that not only addresses climate change challenges but also strengthens cultural heritage and social cohesion within Indigenous communities.

3.3. Resilience and Policy Framework

Ensuring the resilience of housing in the Navajo Nation requires an integrated policy framework that addresses climate adaptation, sustainable resource management, and Indigenous self-determination. Policy interventions at federal, tribal, and local levels must support resilient housing solutions that align with the Navajo community’s unique environmental and cultural context (Tso & McKinley, 2019).

Resilience in Indigenous housing encompasses the ability of dwellings to adapt to environmental stresses, support cultural practices, and sustain community well-being. In the Navajo context, resilience is embodied in traditional structures like the hogan, which are designed to harmonize with the environment and cultural values. Modern interpretations of resilience also consider the integration of sustainable materials and technologies that align with traditional knowledge systems. However, calls for integrated policy frameworks must also confront the risk of reproducing Western governance models under the guise of “resilience.” Who defines integration? Whose governance structures are being privileged? These questions are especially pertinent in contexts like the Navajo Nation, where sovereignty is entangled with overlapping jurisdictions and historical injustices.

The literature on planning in the Global South (Watson, 2009) warns of the co-option of Indigenous governance into state-centric norms of “good planning,” a critique that applies here. Without mechanisms for Indigenous control over policy framing, even well-intentioned housing interventions can perpetuate epistemic violence. One major challenge in resilience planning is the legal complexity of Indigenous land and water rights. Historically, disputes over water allocation have hindered efforts to develop sustainable housing infrastructure (Brugge et al., 2007). Strengthening legal protections for water access is essential to ensuring long-term resilience, particularly due to climate change-induced droughts and groundwater depletion. The Winters Doctrine (1908) and subsequent Supreme Court rulings have affirmed Indigenous water rights, yet enforcement remains inconsistent. A formalized policy framework advocating for equitable water allocation and infrastructure investment would provide the foundation for housing resilience (Navajo Nation Water Resource Department, 2025).

Energy independence is another key component of resilience. Building codes, for instance, often default to Euro-American standards of health, safety, and efficiency, failing to account for traditional forms of resilience that are not easily quantifiable. Recognizing the legitimacy of Indigenous spatial reasoning, such as the symbolic orientation of hogans, is critical to avoiding cultural erasure. Tribal energy sovereignty initiatives, supported by the U.S. Department of Energy's Office of Indian Energy Policy and Programs, have successfully funded renewable energy projects in other Indigenous communities, providing a scalable model for the Navajo Nation (Smith & Wouters, 2019). Encouraging investment in microgrid systems and community-managed renewable energy infrastructure can further enhance housing sustainability. Energy sovereignty, while promising in concept, must also grapple with the colonial legacies of infrastructure development in tribal lands. Funding models and legal instruments should be designed to empower local ownership, not merely deploy renewable technologies as technical fixes.

Building codes and regulatory policies also play a significant role in ensuring housing resilience. Many existing building codes do not account for traditional Indigenous construction methods, which are often more environmentally and culturally appropriate than conventional Western designs. Recognizing and legitimizing traditional earth-based construction materials, such as adobe and rammed earth, within national and tribal housing regulations would promote sustainability and cultural preservation (Lopez & Dean, 2021). A policy framework that supports training programs for Navajo builders in both traditional and modern sustainable construction techniques would strengthen workforce capacity while ensuring long-term housing resilience (Alvarez & Montoya, 2022).

Community engagement is essential in the resilience policy framework. Policies must be designed to empower local governance structures, ensuring that housing initiatives are co-developed with the Navajo Nation rather than imposed externally. Participatory governance models that integrate Navajo leadership into state and federal housing policymaking would enhance the alignment of policies with local needs (Harris & Harper, 2021). In conclusion, a robust resilience policy framework for housing in the Navajo Nation must address legal protections for water rights, energy sovereignty, climate-adaptive building codes, and participatory governance structures. By prioritizing policies that integrate Indigenous knowledge with modern technological innovations, resilience planning can ensure sustainable, culturally informed housing solutions for future generations.

4. Findings

4.1. *Technological Innovation*

Building upon the findings of the mapping and research phase, six distinct housing prototypes were developed, each addressing specific socio-environmental challenges and opportunities within the Navajo Nation. These projects explore the integration of computational workflows, digital fabrication techniques, and material innovation, responding to the region's constraints and cultural context. The design strategies share a modular and adaptive framework, allowing for scalability, customization, and resilience in both off-site prefabrication and on-site assembly scenarios.

The studio-based work drew upon case studies such as the Navajo Hogan Project, which demonstrated the viability of constructing traditional hogans using locally sourced materials to address housing shortages.

These projects underscore the importance of culturally informed design in enhancing housing resilience. To evaluate the efficacy and cultural relevance of the proposed housing prototypes, feedback was solicited from members of the Navajo community through workshops and interviews. Participants emphasized the importance of designs that reflect traditional spatial arrangements, such as the circular form of the hogan, and the use of locally sourced materials. This community input informed iterative design modifications, ensuring that the final prototypes align with both cultural values and environmental considerations.

At the core of these proposals is the development of parametric housing systems that adapt to varying environmental conditions, material availability, and evolving household needs. This computational approach enables each project to generate design configurations that respond to local climate, passive energy strategies, and community-driven spatial requirements. Additionally, the projects implement kit-of-parts methodologies, ensuring flexibility in assembly and disassembly, and allowing for incremental expansion over time. By integrating modular construction techniques, the designs aim to improve constructability, optimize resource use, and enhance long-term adaptability. For instance, the Adaptive Hogan Kit was refined to incorporate community suggestions regarding interior layout and material choices, enhancing its acceptance and potential for adoption. This collaborative process underscores the value of integrating Indigenous perspectives into the design and implementation of housing solutions, fostering a sense of ownership and cultural continuity.

Each proposal also addresses specific resilience challenges, such as water scarcity, climate adaptation, and circular material use. Several projects integrate 3D-printed thermal mass walls to optimize passive heating and cooling strategies, while others explore elevated or porous foundations to mitigate risks associated with flood-prone areas. Some proposals focus on locally sourced and upcycled materials, such as recycled plastics, bio-waste composites, or earth-based construction, reducing environmental impact and strengthening material sovereignty. Additionally, multi-generational living models are embedded in the designs, ensuring that housing solutions remain culturally responsive and spatially flexible for extended families. The six resulting housing systems demonstrate scalable models for integrating smart design-build technologies into Indigenous housing frameworks:

- HexPrint Housing: Customizable, low-cost 3D-printed housing solutions;
- Tessellated Habitat: A modular approach integrating cultural patterns and circular material systems;
- Waterwise Dwelling: A flood-resilient housing strategy with passive design integration;
- Woven Walls: A hogan-inspired adaptive housing system;
- Adaptive Hogan Kit: A modular, digitally fabricated system for incremental expansion;
- Circular Dwelling Initiative: Earth-based 3D printing for sustainable homes.

HexPrint Housing leverages computational design tools and 3D concrete printing to enable rapid, low-cost, and customizable housing solutions. Through a parametric platform, users can adjust spatial configurations based on site conditions, family needs, and cultural preferences. The use of hexagonal structural logic allows for incremental expansion, while the automated fabrication process ensures efficiency and material optimization. By reducing reliance on conventional construction methods, this approach aims to increase housing accessibility and affordability.

Tessellated Habitat explores geometrically optimized modular housing inspired by Navajo cultural motifs. By employing recycled plastics and bio-based composites, it introduces a circular economy model where waste materials are repurposed into housing components. The project also incorporates woven façade elements that serve both structural.

Waterwise Dwelling is designed for flood-prone zones, integrating elevated housing structures that allow water to pass beneath the dwellings, mitigating flood risks without disrupting the natural flow of the land. The housing system incorporates 3D-printed structural elements, using adaptive material thicknesses to enhance thermal regulation.

By embracing water as part of the design strategy rather than resisting it, this approach ensures long-term resilience while maintaining alignment with Indigenous environmental knowledge. The first set of developed housing systems, integrating modular adaptability and digital fabrication strategies, is presented in Figure 4.

Woven Walls reinterprets the traditional Navajo hogan through a Fibonacci-based structural system, integrating 3D-printed earthen walls with timber frameworks. The continuous, spiraling wall provides structural integrity while allowing for flexible spatial arrangements that evolve with changing household needs. The use of digitally optimized, high-mass earthen materials enhances thermal efficiency, while the woven façade geometry echoes Navajo textile traditions, reinforcing cultural continuity within contemporary housing solutions.

Adaptive Hogan Kit employs a kit-of-parts approach, integrating 3D-printed concrete columns, earth-based walls, and a digitally fabricated interlocking wood roof. The assembly logic allows for incremental expansion, disassembly, and reconfiguration, supporting multi-generational family structures. By merging lightweight prefabricated roof elements with robust 3D-printed walls, the proposal achieves a balance between structural permanence and spatial flexibility, ensuring long-term adaptability and cultural relevance.

Circular Dwelling Initiative develops a polycentric housing system using locally sourced soil for 3D-printed construction. The design explores adaptive wall thicknesses to optimize thermal insulation, structural stability, and functional adaptability, integrating generative infill strategies that respond to environmental performance criteria. The circular form, rooted in traditional Navajo spatial configurations, allows for scalable, multi-family housing layouts while reducing the carbon footprint through localized material sourcing.

The second set of developed housing systems, emphasizing cultural continuity and structural adaptability, is presented in Figure 5. These six projects demonstrate diverse applications of computational design, digital fabrication, and emerging construction technologies in the development of climate-resilient and culturally adaptive housing. Each proposal highlights a distinct strategy, from material circularity and passive thermal adaptation to flood-resilient foundations and participatory parametric customization. While these prototypes are specific to the Navajo Nation, they offer scalable models for broader applications in Indigenous housing, remote settlements, and disaster-resilient architecture. The following section further evaluates material efficiencies, technological viability, and socio-cultural integration, analyzing their long-term applicability within smart design-build frameworks for Indigenous communities (see Figure 5).

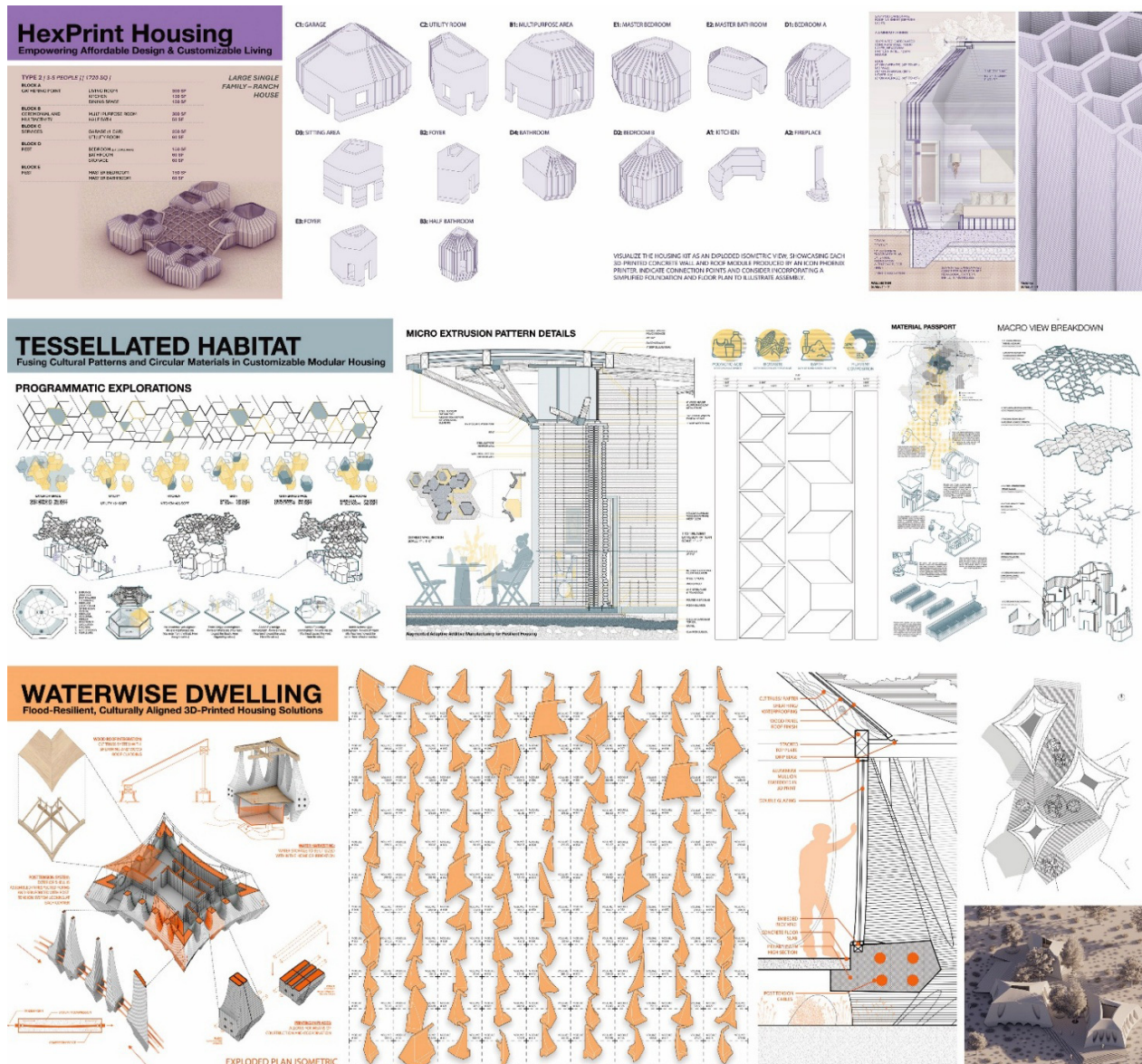


Figure 4. Sample housing systems of HexPrint Housing, Tessellated Habitat, and Waterwise Dwelling, demonstrating parametric design methodologies, material efficiency, and flood-resilient construction strategies. Note: The prototypes respond to environmental and cultural considerations, incorporating passive strategies, adaptive material systems, and customizable modular components. The image features projects developed during the studio: at the top, HexPrint Housing by Mahamatt Adoum Hasane and Luiz Trujillo; in the middle, Tessellated Habitat by Mattia Hajmeli and Harmony Smith; and at the bottom, Waterwise Dwelling by Caleb Scott, Gabe Herrera, and Garrett Whitehead. Source: Authors; part of Arch 5603 Spring 2024 studio—Augmented Adaptive Additive Manufacturing for Resilient Housing: Design-Build Systems Empowering the Navajo Nation, led by Sina Mostafavi.

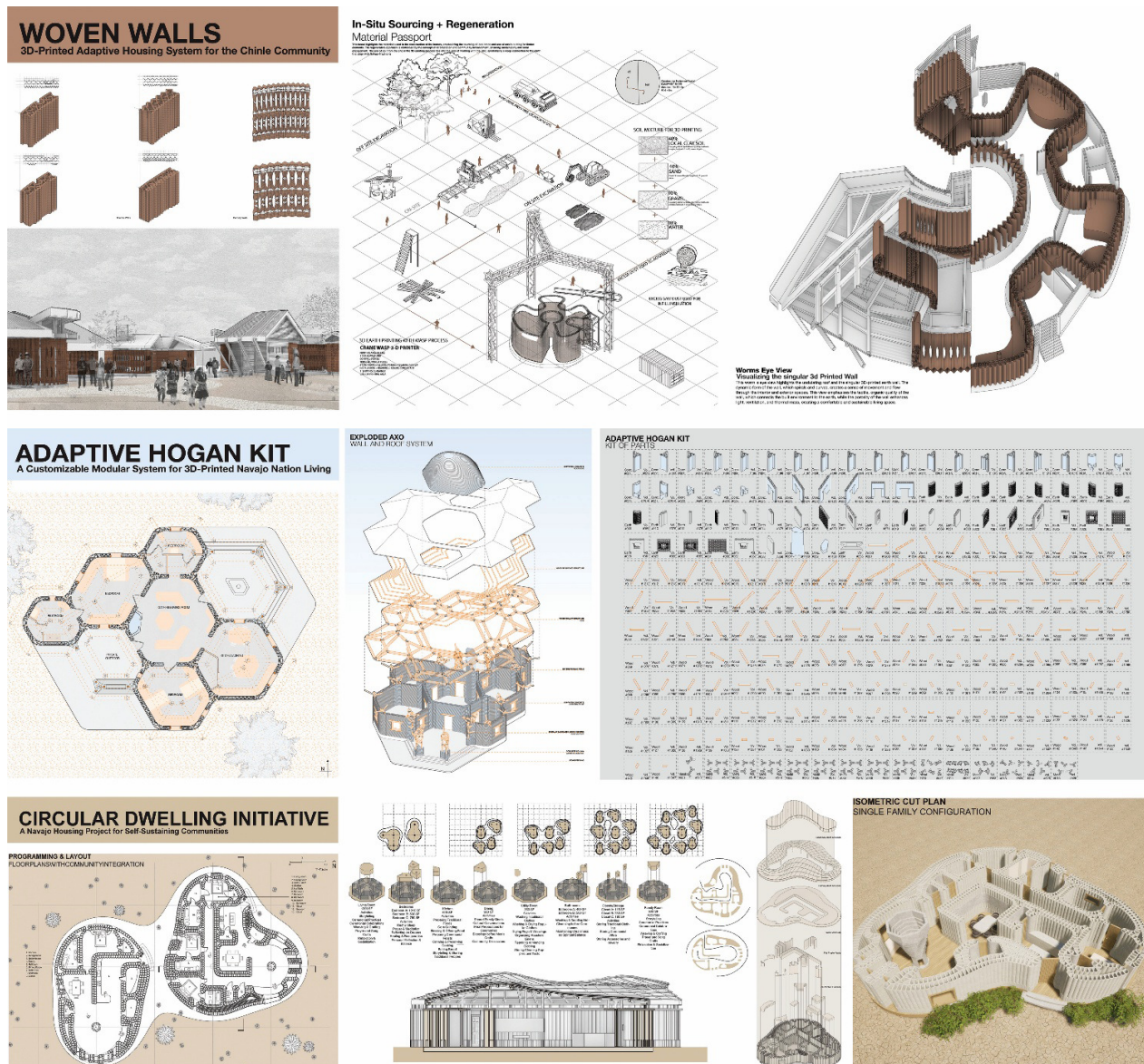


Figure 5. Sample housing systems of Woven Walls, Adaptive Hogan Kit, and Circular Dwelling Initiative, showcasing hybrid fabrication methods, modular spatial configurations, and context-responsive design. Notes: These prototypes reinterpret traditional Navajo architectural principles while integrating digital design and construction innovations. The image features projects developed during the studio: at the top, Woven Walls by Mark Segovia and Desiray Rodriguez; in the middle, Adaptive Hogan Kit by Enrique Espinoza and DeMarcus Clarke; and at the bottom, Circular Dwelling Initiative by Jylian Hanson and Brodey Myers. Source: Authors; part of Arch 5603 Spring 2024 studio—Augmented Adaptive Additive Manufacturing for Resilient Housing: Design-Build Systems Empowering the Navajo Nation, led by Sina Mostafavi.

4.2. Cultural Integration Outcomes

Integrating Indigenous cultural elements into housing design has demonstrated significant social and environmental benefits. However, cultural integration should not be reduced to symbolic incorporation of motifs or layouts. Rather, it must stem from a design logic grounded in Indigenous epistemologies where spatial practices, rituals, and environmental relationships constitute foundational principles, not secondary

features. The Navajo hogan, a traditional dwelling form, has inspired contemporary housing models that incorporate circular layouts and earthen materials, reflecting cultural heritage while improving passive solar heating and cooling efficiency (Ferguson & Kniffen, 2015). These adaptations not only enhance comfort but also reinforce community identity and continuity of traditions (Benally, 2020). Moreover, participatory design approaches have enabled local stakeholders to directly impact housing development. In recent projects, Navajo community members collaborated with architects and planners to ensure that new housing reflects traditional spatial orientations and social structures. For example, research on co-design workshops revealed that when Indigenous perspectives are incorporated into architectural plans, the acceptance and long-term sustainability of housing projects increase (Alvarez & Montoya, 2022).

Our co-design workshops revealed that even minor spatial decisions, such as door orientation or the sequencing of interior spaces, held ceremonial significance for participants, influencing their perception of the home's cultural legitimacy. Material choices have also been influenced by cultural and environmental factors. The preference for natural, locally available materials such as adobe and straw bale construction aligns with Navajo principles of sustainability and ecological harmony. Additionally, responses from community members highlighted skepticism toward “technological add-ons” that were not clearly grounded in traditional ecological knowledge. This feedback prompted revisions to minimize visible mechanical systems and prioritize natural ventilation and lighting strategies aligned with hogan teachings. The use of these materials reduces the carbon footprint of housing projects while providing thermal insulation suitable for desert climates (Mason, 2020). Additionally, indoor layouts that prioritize communal gathering spaces reflect the social fabric of Navajo life, reinforcing kinship ties and community cohesion (Tso & McKinley, 2019).

4.3. Resilience and Policy Recommendations

Policy recommendations should directly address identified challenges, such as infrastructure deficits and cultural dissonance in housing design. For instance, policies could support the incorporation of traditional architectural principles into modern housing programs and provide funding for community-led construction initiatives that prioritize resilience and cultural relevance. Federal and tribal policies must support the integration of smart technologies and culturally sensitive designs to address the unique environmental and social challenges faced by Indigenous communities (Tso & McKinley, 2019). As noted by Watson (2009), the imposition of “best practice” standards from dominant planning systems often results in cultural misalignment and institutional friction. A truly resilient policy framework must originate within the governance logics of the Navajo Nation and uphold its epistemic sovereignty. Existing policies such as the Indian Housing Block Grant program provide financial resources for housing development, but additional funding mechanisms and regulatory frameworks are needed to support resilient housing models (Navajo Nation Water Resource Department, 2025).

One critical policy recommendation is the expansion of water rights protections to ensure adequate access to clean drinking water. Legal disputes over water allocation have hindered infrastructure projects, making it essential for policymakers to prioritize Indigenous water rights in state and federal negotiations (Brugge et al., 2007). Additionally, incentivizing the adoption of sustainable building materials and renewable energy systems through tax credits and grant programs can accelerate the transition to climate-resilient housing (Harris & Harper, 2021). Furthermore, efforts to promote renewable energy should prioritize tribal ownership models and reinvestment in local workforce development—not merely infrastructure deployment

(Mostafavi & Mehan, 2024). Housing policy must move from transactional funding streams to regenerative governance partnerships.

5. Discussion: Resilient Housing Strategies for the Navajo Nation

Ensuring the resilience of housing in the Navajo Nation requires an integrated policy framework that addresses climate adaptation, sustainable resource management, and Indigenous self-determination. Policy interventions at federal, tribal, and local levels must support resilient housing solutions that align with the Navajo community's unique environmental and cultural context (Tso & McKinley, 2019). This discussion reframes the Navajo Nation not simply as a recipient of resilience policy, but as an epistemic site from which dominant narratives of smart housing and sustainability can be challenged. One major challenge in resilience planning is the legal complexity of Indigenous land and water rights. Historically, disputes over water allocation have hindered efforts to develop sustainable housing infrastructure (Brugge et al., 2007). Strengthening legal protections for water access is essential to ensuring long-term resilience, particularly due to climate change-induced droughts and groundwater depletion. The Winters Doctrine (1908) and subsequent Supreme Court rulings have affirmed Indigenous water rights, yet enforcement remains inconsistent. A formalized policy framework advocating for equitable water allocation and infrastructure investment would provide the foundation for housing resilience (Navajo Nation Water Resource Department, 2025).

While comparative frameworks with colonias help identify shared infrastructural and economic vulnerabilities, it is essential not to conflate the two. The Navajo Nation's unique governance structure, cultural systems, and legal history require not just tailored but co-produced policy interventions. Indigenous sovereignty, in this context, should be understood not only in legal or administrative terms but as a design principle (Mehan & Casey, 2024). This means resisting the normalization of Western spatial paradigms and instead privileging Indigenous logics of dwelling, stewardship, and kinship. The comparative analysis with colonias also underscores the risks of state-driven housing interventions that fail to embed local knowledge. Policy success in the Navajo Nation depends on redistributing decision-making authority, recognizing Indigenous expertise, and embedding design within relational land ethics rather than development efficiency.

Although the Navajo Nation benefits from a degree of tribal sovereignty that enables localized decision-making and policy development, both communities share challenges such as limited access to basic infrastructure, including potable water, sewage systems, and electricity (Esparza, 2010; Ward, 2018). This comparison highlights that while colonias struggle with fragmented service provision due to a lack of formal governance, the Navajo Nation's established self-governance can be leveraged to enact tailored resilience policies. By examining the vulnerabilities faced by colonias, such as inadequate drainage leading to severe flooding in Hidalgo County, Texas (Pezzoli et al., 2019), we gain insight into the critical importance of integrated infrastructure planning and community engagement for the Navajo Nation. These distinctions are summarized in Table 1, which provides a comparative analysis of housing resilience challenges between the Navajo Nation and colonies. Table 1 synthesizes these contrasts, emphasizing how governance, infrastructure access, environmental risks, and social capital inform divergent resilience strategies.

Table 1. Comparative analysis of housing resilience challenges between the Navajo Nation and colonias.

Category	Navajo Nation	Colonias
Governance structure	Tribal sovereignty with self-governance	Unincorporated communities with limited governance
Access to infrastructure	Limited potable water, electricity, and sewage systems	Poor infrastructure with fragmented service provision
Housing types	Traditional hogans and Western-style homes	Informal housing developments, often unregulated
Environmental challenges	Climate-induced drought, groundwater depletion	Flood risks, inadequate drainage systems
Energy solutions	Off-grid solar and wind initiatives	Potential for decentralized energy solutions
Social capital and resilience	Strong kinship networks, Indigenous governance	Informal economies, mutual aid networks

Historical case studies further illuminate these vulnerabilities. For instance, the legacy of uranium mining in the Navajo Nation has left many homes contaminated with radioactive materials, leading to severe health risks and compounding housing insecurity (Brugge & Goble, 2002). Acknowledging these challenges through comparative analysis underscores the necessity of adopting culturally appropriate, sustainable, and climate-resilient housing solutions.

In the Navajo Nation, traditional housing structures such as hogans, constructed with natural, locally sourced materials, offer inherent climate adaptability (Lopez & Dean, 2021). However, modern housing policies that favor Western-style construction may not suit the region's environmental or cultural context. Similarly, informal housing developments in colonias often lack regulatory oversight, resulting in substandard living conditions (Pezzoli et al., 2019). By comparing these situations, policymakers can identify the best practices, such as incorporating traditional earth-based construction techniques (Alvarez & Montoya, 2022) and supporting training programs for local builders, to enhance resilience in the Navajo Nation (See Table 1). Moreover, both communities underscore the vital role of social capital (Fathi et al., 2024). In the Navajo Nation, strong kinship networks and cultural traditions promote collective resource management and grassroots mobilization (Begay, 2017). While colonias build social capital through informal economies and mutual aid networks (Ward & Carew, 2020), the lack of institutional recognition for these systems limits their scalability (Varış Husar et al., 2023). Recognizing these dynamics reinforces the need for participatory governance models that empower Navajo leadership to co-develop resilient housing policies (Harris & Harper, 2021). Figure 6 presents a visual synthesis of the comparative housing resilience dynamics across the Navajo Nation and colonias, highlighting key factors like governance, infrastructure access, social capital, energy solutions, and environmental risks.

Energy independence also plays a key role in resilience. The Navajo Nation can leverage tribal energy sovereignty initiatives, such as off-grid solar and wind power installations supported by the U.S. Department of Energy's Office of Indian Energy Policy and Programs, to reduce reliance on an overstressed grid (Smith & Wouters, 2019). While colonias might similarly benefit from decentralized energy solutions (Pezzoli et al., 2019), the Navajo Nation's sovereignty provides a unique platform for implementing and scaling these innovations.

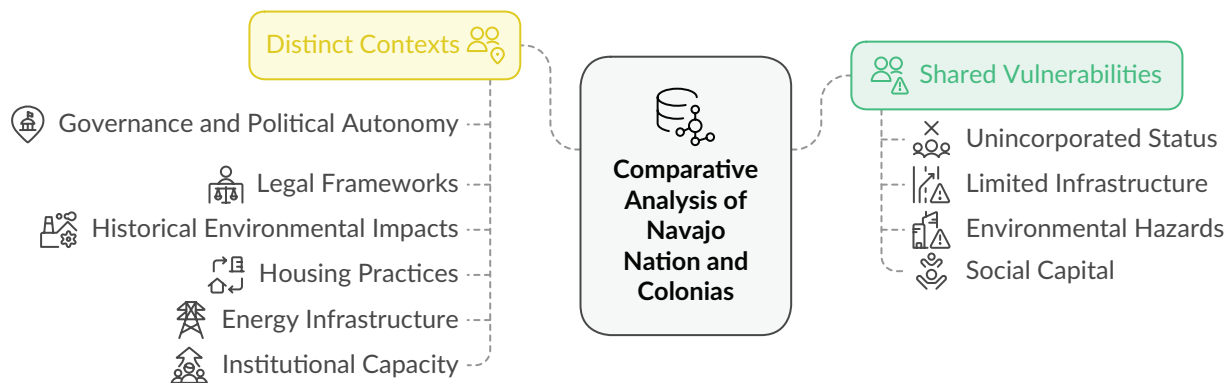


Figure 6. Comparative analysis of housing challenges in the Navajo Nation and colonias.

Recent legal developments have further complicated the landscape of housing resilience in the Navajo Nation. The 2023 U.S. Supreme Court decision in *Arizona v. Navajo Nation* (599 U.S. 555) determined that the federal government is not obligated to secure water for the tribe under the 1868 Treaty with the Navajo Tribe of Indians, despite the Treaty's provision establishing the reservation as a “permanent home” (Treaty with the Navajo Tribe of Indians, 1868). This ruling underscore the challenges the Navajo Nation faces in asserting their water rights—rights that are foundational to sustainable housing development. The decision has significant implications for infrastructure planning and resource allocation, as access to water is fundamental to both the construction and habitability of resilient housing. Addressing these legal and policy challenges is essential for advancing housing resilience strategies that are both culturally appropriate and environmentally sustainable.

Another contributing factor in housing resilience is the economic framework that supports construction and maintenance. In the Navajo Nation, limited access to financial capital and credit restricts the ability of residents to build and sustain resilient housing. Federal and tribal housing assistance programs, such as the Indian Housing Block Grant Program, have played a significant role in funding housing initiatives, but challenges persist in accessing these resources efficiently. Similarly, in colonias, economic marginalization and bureaucratic hurdles prevent residents from improving their housing conditions. Addressing these financial barriers requires the development of innovative lending programs tailored to Indigenous and underserved communities, incorporating microfinance solutions and cooperative housing models. Additionally, policy frameworks must integrate climate adaptation measures that are region-specific. The Navajo Nation's exposure to extreme temperatures, water scarcity, and land degradation necessitates adaptive housing strategies that focus on insulation, water-efficient designs, and sustainable land management practices. In colonias, addressing flood risks and improving drainage infrastructure must be prioritized to enhance housing resilience. Investing in green infrastructure, such as permeable pavements and rainwater harvesting systems, can provide long-term solutions to these challenges while fostering environmental sustainability (see Figure 6). In conclusion, while the primary focus remains on strengthening housing resilience in the Navajo Nation, a comparative analysis with colonias illuminates critical insights. This comparison helps us understand how integrated infrastructure investments, legal protections for water rights, culturally informed housing practices, and robust community engagement can be combined to formulate more holistic approaches to address existing vulnerabilities. By incorporating lessons from both contexts, policymakers can craft resilient housing solutions that not only preserve Indigenous cultural identity but also ensure long-term sustainability and self-sufficiency for the Navajo Nation. In contrast to dominant resilience frameworks that prioritize adaptability in material and performance metrics, we argue

that true resilience in Indigenous contexts is relational, ceremonial, and historically situated. This reframing opens space for a more critical and culturally grounded understanding of how design, governance, and infrastructure intersect in the pursuit of housing justice.

6. Conclusion

This study has explored the intersection of emerging design-build technologies and Indigenous architectural traditions to develop resilient, culturally informed housing solutions for the Navajo Nation. Rather than presenting conclusive solutions, this study offers a situated inquiry into how emerging technologies can be recontextualized within Indigenous design frameworks. While the housing prototypes explored demonstrate potential, they remain speculative and iterative intended as design provocations rather than finalized models. Their value lies in testing boundaries between technological advancement and cultural continuity. By integrating smart technologies, sustainable materials, and participatory design approaches, this research presents viable pathways to enhance housing resilience in remote Indigenous communities facing climate change, infrastructure limitations, and socio-economic challenges.

Key findings demonstrate that off-grid energy systems, alternative construction methods, and digital fabrication techniques, such as earth-based 3D printing and modular prefabrication, can provide cost-effective, low-carbon housing solutions while respecting cultural identity and environmental adaptation. The research underscores the importance of participatory design in ensuring that housing developments align with the lived experiences and traditions of the Navajo people, reinforcing community resilience and self-determination.

This research underscores that resilience, when defined through Indigenous worldviews, is not merely an outcome of material optimization but a process rooted in kinship, relational ecologies, and governance autonomy. The comparative analysis with colonias highlights shared vulnerabilities and underscores policy opportunities for strengthening housing governance, water rights, and infrastructure investment in marginalized communities. The integration of traditional spatial configurations, passive energy strategies, and sustainable materials presents a scalable model that can be adapted across other Indigenous and underserved regions.

The study's contribution is therefore conceptual and methodological: It presents a framework for aligning digital fabrication and sustainable innovation with Indigenous spatial practices, and it models participatory design processes that redistribute authorship to local communities. Moving forward, policy interventions must support the implementation of smart housing strategies by prioritizing Indigenous self-governance, sustainable development funding, and climate-adaptive building codes. Further research should focus on expanding digital fabrication capabilities, developing localized material supply chains, and testing full-scale housing prototypes in real-world conditions. Ultimately, this study contributes to the broader discourse on resilient housing design, equitable development, and Indigenous sovereignty by proposing a forward-thinking, contextually adaptive framework that merges technological innovation with cultural preservation. Future work must engage in longitudinal collaboration with Navajo partners to evaluate built outcomes, co-develop building codes that recognize traditional practices, and advocate for funding models that support sovereign-led housing development. By advancing collaborative design, environmental stewardship, and self-sufficiency, this research provides practical insights for architects, planners,

policymakers, and community stakeholders committed to building a sustainable future for the Navajo Nation and beyond.

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Conflict of Interests

The authors declare no conflict of interests.

References

- Alvarez, M., & Montoya, P. (2022). *Sustainable architecture and Indigenous housing: Best practices from North America*. University of Arizona Press.
- Begay, M. (2017). Community resilience in the Navajo Nation: Traditional practices and contemporary policies. *Indigenous Studies Review*, 45(1), 87–102.
- Benally, T. (2020). *Indigenous adaptation: Traditional knowledge and contemporary Housing in the Southwest*. Routledge.
- Brugge, D., & Goble, R. (2002). The history of uranium mining and the Navajo people. *American Journal of Public Health*, 92(9), 1410–1419.
- Brugge, D., Goble, R., & Lewis, J. (2007). The history of uranium contamination in the Navajo Nation. *Environmental Health Perspectives*, 115(4), 487–493.

- Carey, H. J., Jr. (2025). *Navajo creation story – The First World “Nihodilhil” (Black World)*. NavajoPeople. <https://www.navajopeople.org/blog/navajo-creation-story-the-first-world-nihodilhil-black-world>
- Charley, P. H., Lewis, J., Curley, T., & Torres, J. (2016). Environmental justice and housing in Native American communities. *Journal of Indigenous Studies*, 12(1), 45–67.
- Esparza, A. X. (2010). Colonias in the United States: Challenges and policy interventions. *Urban Affairs Review*, 46(5), 687–712.
- Fathi, M., Nasya, B., Mehan, A., Mariotti, J., & Astrouskaya, T. (2024). Homemaking or placemaking? Understanding home and place among vulnerable populations. In A. Delgado-Jiménez, T. Ruchinskaya, & C. Palmese (Eds.), *Placemaking in practice volume 3: The future of placemaking and digitization* (pp. 37–56). Brill.
- Fathy, H. (1986). *Natural energy and vernacular architecture: Principles and examples with reference to hot arid climates*. University of Chicago Press.
- Ferguson, T., & Kniffen, F. (2015). *Indigenous architecture of the American Southwest*. University of New Mexico Press.
- Gerlach, C., Ordóñez, A., & Cunningham, P. (2020). Renewable energy solutions for remote Indigenous communities. *Energy Policy Journal*, 35(2), 115–130.
- Gleick, P. H. (2014). *The world's water: The biennial report on freshwater resources*. Island Press.
- Harris, L., & Harper, B. (2021). Climate change and Indigenous housing resilience. *Environmental Research Journal*, 19(2), 78–93.
- Hodge, G. (2018). *Indigenous housing and policy in Canada: Lessons from First Nations communities*. Routledge.
- Lalander, C., Hill, G. B., & Vinnerås, B. (2018). Water reuse technologies for decentralized communities: Lessons from Indigenous settlements. *Water Research Journal*, 76(3), 221–238.
- Lopez, C., & Dean, P. (2021). *Earth-based construction: Lessons from Indigenous architecture*. Springer.
- Mason, R. (2020). *Indigenous housing and the built environment: A collaborative approach to sustainable design*. Oxford University Press.
- Mehan, A. (2024a). Decolonizing architectural pedagogy: Radical cities over time and through space. In D. R. Cole, M. M. Rafe, & G. Y. A. Yang-Heim (Eds.), *Educational research and the question(s) of time* (pp. 387–400). Springer. https://doi.org/10.1007/978-981-97-3418-4_21
- Mehan, A. (2024b). Digital feminist placemaking: The case of the “Woman, Life, Freedom” movement. *Urban Planning*, 9, Article 7093. <https://doi.org/10.17645/up.7093>
- Mehan, A. (2024c). Reimagining industrial legacy: Strategic urban adaptation for climate resilience in an era of radical environmental change. In F. Calabrò, L. Madureira, F. C. Morabito, & M. J. Piñeira Mantiñán (Eds.), *Networks, markets & people: Communities, institutions and enterprises towards post-humanism epistemologies and AI challenges* (Vol. 6, pp. 321–329). Springer. https://doi.org/10.1007/978-3-031-74716-8_32
- Mehan, A. (2025). Introduction: Navigating a post-oil future. In: A. Mehan (Ed.), *After oil: A comparative analysis of oil heritage, urban transformations, and resilience paradigms* (pp. 1–11). Springer. https://doi.org/10.1007/978-3-031-92188-9_1
- Mehan, A., & Casey, Z. S. (2024). The petrological imprint: A comprehensive study of Spindletop's role in the morphogenesis of the Golden Triangle of Texas. In F. Calabrò, L. Madureira, F. C. Morabito, & M. J. Piñeira Mantiñán (Eds.), *Networks, markets & people: Communities, institutions and enterprises towards post-humanism epistemologies and AI challenges* (Vol. 1, pp. 3–13). Springer. https://doi.org/10.1007/978-3-031-74501-0_1
- Mehan, A., & Casey, Z. S. (2025). Climate justice through design: A shift in paradigm within the Gulf of Mexico. In A. Mehan (Ed.), *After oil: A comparative analysis of oil heritage, urban transformations, and resilience paradigms* (pp. 139–155). Springer. https://doi.org/10.1007/978-3-031-92188-9_8

- Mehan, A., & Dominguez, N. (2024). Interdisciplinary urban interventions: Fostering social justice through collaborative research-led design in architectural education. *Architecture*, 4(4), 1136–1156. <https://doi.org/10.3390/architecture4040059>
- Mehan, A., & Mostafavi, S. (2023a). Immersive urban narratives: Public urban exhibit and mapping socio-environmental justice. *European Journal of Creative Practices in Cities and Landscapes*, 6(2), 117–138. <https://doi.org/10.6092/issn.2612-0496/17049>
- Mehan, A., & Mostafavi, S. (2023b). Navigating AI-enabled modalities of representation and materialization in architecture: Visual tropes, verbal biases, and geo-specificity. *Plan Journal*, 8(2). <https://www.doi.org/10.15274/tpj.2023.08.02.6>
- Mehan, A., & Mostafavi, S. (2023c). Portcityscapes as liminal spaces: Building resilient communities through parasitic architecture in port cities. In S. Haq, A. Sharag-Eldin, & S. Niknia (Eds.), *ARCC 2023 Conference Proceedings: The research design interface* (pp. 631–639). Architectural Research Centers Consortium.
- Mehan, A., & Mostafavi, S. (2024a). Emerging technologies in urban design pedagogy: Augmented reality applications. *Architectural Intelligence*, 3(1), Article 29. <https://doi.org/10.1007/s44223-024-00067-y>
- Mehan, A., & Mostafavi, S. (2024b). Immersive art and urban heritage: An interdisciplinary study of socio-environmental justice in Houston and Amsterdam. In F. Moral-Andrés, E. Merino-Gómez, & P. Reviriego (Eds.), *Decoding cultural heritage* (pp. 439–456). Springer. https://doi.org/10.1007/978-3-031-57675-1_19
- Mehan, A., & Mostafavi, S. (2024c). Spatial justice through immersive art: An interdisciplinary approach. In C. Gray, E. Ciliotta Chehade, P. Hekkert, L. Forlano, P. Ciuccarelli, & P. Lloyd (Eds.), *DRS2024: Research papers*. Design Research Society. <https://doi.org/10.21606/drs.2024.302>
- Mehan, A., Odour, N., & Mostafavi, S. (2023). Socio-spatial micro-networks: Building community resilience in Kenya. In A. Cheshmehzangi, M. Sedrez, H. Zhao, T. Li, T. Heath, & A. Dawodu (Eds.), *Resilience vs pandemics: Innovations in cities and neighbourhoods* (pp. 141–159). Springer. https://doi.org/10.1007/978-981-99-7996-7_9
- Minke, G. (2006). *Building with earth: Design and technology of a sustainable architecture*. Birkhäuser.
- Mostafavi, S., Bagheri, B., Bao, D. W., & Mehan, A. (2024). Smart prototyping: From data-driven mass-customization to community-enabled co-production. In M. Kannani (Ed.), *The Routledge companion to smart design thinking in architecture & urbanism* (pp. 633–642). Routledge.
- Mostafavi, S., & Mehan, A. (2024). De-coding visual clichés and verbal biases: Hybrid intelligence and data justice. In M. del Campo (Ed.), *Diffusions in architecture: Artificial intelligence and image generators* (pp. 150–159). Wiley.
- Murray, M., & Bertram, C. (2020). Modular housing and climate resilience: Innovations in Indigenous community housing. *Journal of Sustainable Architecture*, 22(4), 349–368.
- Navajo Nation Water Resource Department. (2025). *San Juan River Basin updates*. Navajo Nation. <https://nnwrc.navajo-nsn.gov/Basin-Updates/San-Juan-River-New-Mexico>
- Pezzoli, K., Hoon, R., Madero, C., & Munoz, D. (2019). Infrastructure vulnerability in colonias: Addressing environmental and housing challenges. *Journal of Borderlands Studies*, 34(2), 211–230.
- Pittau, F., Krause, F., Lumia, G., & Habert, G. (2018). Carbon sequestration potential of natural building materials. *Journal of Cleaner Production*, 172, 3884–3891.
- Roaf, S., Fuentes, M., & Thomas, S. (2018). *The eco-house design guide: Principles and practice for new-build and retrofit*. Routledge.
- Smith, R., & Wouters, C. (2019). *Participatory design in Indigenous communities*. The MIT Press.
- Star, S. L. (1999). The ethnography of infrastructure. *American Behavioral Scientist*, 43(3), 377–391.

- Sutton, S., & Black, A. (2021). Innovative and sustainable construction materials: Advances in hempcrete and mycelium-based insulation. *Journal of Green Building*, 16(1), 101–120.
- Tso, L., & McKinley, B. (2019). Environmental remediation and housing justice in the Navajo Nation. *Journal of Environmental Law*, 27(2), 112–130.
- Varış Husar, S. C., Mehan, A., Erkan, R., Gall, T., Allkja, L., Husar, M., & Hendawy, M. (2023). What's next? Some priorities for young planning scholars to tackle tomorrow's complex challenges. *European Planning Studies*, 31(11), 2368–2384. <https://doi.org/10.1080/09654313.2023.2218417>
- Ward, P. M. (2018). Colonias and housing conditions in the U.S.–Mexico borderlands. *Housing Policy Debate*, 28(1), 34–57.
- Ward, P. M., & Carew, J. (2020). Social capital in *colónias*: Informal economies and mutual aid. *Journal of Urban Affairs*, 42(5), 769–786.
- Watson, V. (2009). Seeing from the South: Refocusing urban planning on the globe's central urban issues. *Urban Studies*, 46(11), 2259–2275.
- Yazzie, T., & Knapp, G. (2018). Sustaining the hogan: Cultural preservation in Navajo architecture. *Journal of Native American Studies*, 10(3), 112–129.

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Baltic Spas in the Face of Climate Change: In Search of Resilience

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Abstract

In the context of urban centres exposed to climate change, spas represent a distinct and vulnerable cluster. Their sensitivity stems both from the health profile of spa visitors—often more susceptible to adverse weather—and from their reliance on local natural resources that justified their original therapeutic designation. These vulnerabilities are increasingly exacerbated by climate-related risks such as sea level rise (SLR), extreme weather, and environmental degradation. This article assesses the resilience of Polish Baltic spa towns to climate threats and proposes recommendations for future adaptation policies. Addressing a gap in the literature, the study integrates spatial, environmental, legal, and socio-economic dimensions into a local-scale assessment of small and medium-sized coastal spas. These towns vary in their spatial position within the settlement system, from metropolitan peripheries to isolated localities. A multi-criteria case study approach is applied, using indicators related to development prospects, spatial identity, and exposure to flooding and SLR. Spatial simulations (1-m and 5-m SLR scenarios) are used to identify risks to core spa infrastructure and supporting assets. Existing climate adaptation policies are also reviewed to assess institutional readiness and inform context-sensitive resilience strategies.

Keywords

Baltic Sea; climate adaptation; climate change; resilience; spa centres; spa towns

1. Introduction

Health resorts gained popularity in Europe during the Enlightenment era (Dargacz, 2020), initially developing inland around mineral springs, especially within the temperate climate zone (Kask & Raagmaa, 2010). Coastal spa tourism, based on the therapeutic benefits of sea bathing and maritime climate, emerged later, in 18th-century England, followed by Germany and the Prussian Baltic coast in the early 19th century (Dargacz, 2020).

This article assesses the resilience of Polish Baltic spa towns in the face of climate change and proposes recommendations for future adaptation policies. The analysis focuses on small and medium-sized coastal towns, each with distinct functional roles—ranging from metropolitan nodes to peripheral localities. The following research questions guide this study: To what extent are Polish coastal spas vulnerable to climate risks, particularly sea level rise (SLR) and extreme weather? And how might the spatial, functional, and institutional characteristics of these resorts support or hinder their resilience?

Spa zoning regulations and environmental quality criteria are typically more attainable in less urbanised settings. This creates opportunities to develop niche strategies in medical tourism, which is particularly relevant considering Europe's ageing population (GUS, 2024) and increasing health consciousness (Smith & Puczkó, 2015). However, small-town camaraderie brings structural limitations: constrained public finances and reduced flexibility in the face of economic shocks, compared to larger multifunctional centres.

In contrast to the collapse of British health resorts in the 1960s and 1970s (Kask & Raagmaa, 2010), Polish spas remained viable due to state-funded health access and restrictions on foreign travel during the socialist era. However, following the political transformation of the 1990s, outdated infrastructure and limited competitiveness became pressing challenges (Bachvarov, 2006; Dryglas & Smith, 2023). Efforts to modernise were undertaken through private investment, either via privatisation or public-private partnerships. In many cases, public protests halted full privatisation, preserving key spa functions. The offer was supplemented by private wellness facilities, yet serious gaps remain—particularly in upgrading ageing municipal infrastructures.

Present-day challenges include high costs of modernisation, excessive noise, air pollution (Gorczyca, 2024; Wirszyć-Sitkowska & Mędrzak, 2017), and inadequate healthcare service standards (Wirszyć-Sitkowska & Krawczyk, 2019). These factors collectively threaten the formal spa designation of many towns.

Climate change exacerbates these pressures. Beyond affecting people and infrastructure, it directly threatens the natural resources underpinning this spa's status. Coastal spas are particularly vulnerable to SLR and coastal erosion (IPCC, 2023; Meier et al., 2022). Spatial exposure to flooding and salinisation calls into question the long-term viability of some spa zones. In this context, evaluating the continued relevance of the spa function—and the implementation of effective preventive and corrective measures—becomes imperative.

2. Conceptual Framework

2.1. Socio-Ecological Resilience

In the context of the climate crisis, the concept of urban resilience has evolved significantly. Initially rooted in ecosystem theory (Holling, 1973), it now extends to the resilience of complex urban systems (Meerow et al., 2016). Unlike traditional risk management, resilience management addresses the uncertainties of large, integrated systems and future climate-related threats (Linkov et al., 2014). Communities form interconnected social-ecological systems, with resilience shaped by the ecosystems they inhabit (Adger, 2000; Chapin et al., 2006; Walker & Salt, 2012).

Anthropogenic pressures generate feedback loops that can either destabilise (positive feedback) or stabilise (negative feedback) such systems (Liu et al., 2007). These dynamics are particularly relevant in spa towns,

where natural resources, cultural identity, and health functions intersect. As Goldstein et al. (2015) argue, urban resilience research must also consider symbolic and social meanings attributed to places by local communities. Adaptive capacity—the ability to mobilise resources for transformation—bridges ecological resilience with social benefits (Nelson et al., 2007).

2.2. Spatial Identity and Location Context

Spa towns typically exist either as standalone health destinations or as part of larger recreational agglomerations. In the former, the spa defines the settlement's core function; in the latter, it contributes to a broader tourist or urban system (Pencakowska, 1978; Węclawowicz-Bilska, 2008). Due to the concentration of development and attractiveness of the Baltic coast, all analysed coastal spas fall into the agglomeration or conurbation category, making spatial identity relevant not only to the spa itself but to the entire urban belt.

Spas are characterised by distinct spatial structures, including public spaces that are rich in greenery—particularly the historic “cure parks” (Langer, 2020). Many spas retain protected monumental trees (Meller & Bernat, 2019) and other conservation areas near their central zones (CRFOP, 2024). In seaside towns, spatial form is further shaped by the presence of the sea, with promenades and piers reflecting the therapeutic appeal of marine air and bathing (Foley, 2016). Architectural elements and urban furnishings also express regional identity, although these are increasingly threatened by poor spatial planning (Bal, 2009; Bal & Czaczyńska-Podolska, 2020).

2.3. Trends

Understanding resilience in coastal resorts requires recognising evolving in-demand trends. In the 19th century, spas served the elite (Dargacz, 2020), but after World War II, social security and welfare policies made spa treatments broadly accessible (Diekmann et al., 2020). Today, there is increasing demand for wellness infrastructure that goes beyond resource-based therapies (Bočkus et al., 2024).

Spa and wellness tourism is expanding in Eastern Europe, with Poland already positioned in this niche (Yonov, 2024). Though the Covid-19 pandemic caused a temporary decline, by 2022, client numbers had rebounded to 2019 levels. Spa hospitals now serve both insured and commercial clients, with the latter group—particularly seniors—steadily growing (Urbas, 2023). A German study indicated a strong preference among seniors for seaside spas (Diller et al., 2023), suggesting Polish coastal resorts may attract similar interest. According to Dryglas and Różycki (2016), both commercial and public clients value natural resources, but non-commercial users especially appreciate contact with nature. Demand is increasingly driven by a desire to restore mental wellbeing (cf. De Vries et al., 2013; Dzhambov et al., 2021; Wang et al., 2019), a trend reinforced during the pandemic (Global Wellness Institute, 2021; Venter et al., 2021).

2.4. Impact of Climate Change

Climate change impacts on coastal regions can be assessed from two temporal perspectives: current phenomena and future projections. Along the Polish Baltic coast, the observed effects are already significant. Sea levels have been rising by 3–4 mm per year since 1995, with faster increases in the east (Tomczyk & Bednorz, 2022). Although the frequency of storms has not changed markedly, storm surges have intensified

due to higher sea levels, accelerating coastal retreat and threatening spa infrastructure (Soomere, 2024; Styszyńska et al., 2018).

Other hydrometeorological extremes affecting the region include high and low sea levels, windstorms, extreme waves, heavy rainfall, ice ridging, drought, and sea-effect snow (Rutgersson et al., 2021). Air and sea surface temperatures are also increasing, particularly in winter and spring. These trends contribute to harmful algal (cyanobacteria) blooms, which can release toxins and degrade bathing water quality, posing health risks and undermining spa attractiveness (Błaszczuk et al., 2021; Ibelings et al., 2016; Kownacka et al., 2021; Munkes et al., 2021).

Rising summer temperatures also increase heat stress, particularly for vulnerable groups such as the elderly and people with cardiac conditions (Błazejczyk & Kunert, 2011; Matthies & Menne, 2009). However, fluctuations in temperature, humidity, and wind limit the predictability of this risk (Kuchcik et al., 2021). The sea breeze and surrounding greenery in coastal resorts help mitigate heat stress effects (Dailidė et al., 2022; Wong et al., 2021).

Warming also affects snow cover duration and Baltic Sea ice extent (Styszyńska et al., 2018), contributing to hydrological drought and threatening ecosystems like peatlands and urban greenery (Choat et al., 2018; Minick et al., 2019). Although coastal medicinal water intakes are generally safe due to their depth (Davie, 2019; Polish Geological Institute – National Research Institute, 2024), long-term protection remains necessary.

Looking ahead, SLR is one of the most certain consequences of climate change. Even under low-emission scenarios, thermal inertia ensures a continued rise. In a high-emission SSP5–8.5 scenario, global sea levels could rise by 0.63–1.01 m by 2100, with 2 m possible under a 1.5 °C warming and over 5 m under 2 °C (IPCC, 2023). The regional SLR will likely reach about 87% of the global mean, though local factors—e.g., land subsidence, coastal morphology—create variation and uncertainty (Cazenave & Cozannet, 2014; Griggs & Trenhaile, 1994; Meier et al., 2022).

Additional projections include more frequent summer droughts in the southern Baltic basin and long-term ecosystem restructuring driven by rising sea temperatures (Meier et al., 2022; Neumann, 2010).

2.5. Formal Conditions for Spa Resilience

The resilience of Polish spa towns is shaped by formal conditions grounded in national legislation and spatial policy. According to the Act of 28 July 2005 on spa treatment, spa status requires the presence of natural resources with proven therapeutic value—specifically mineral waters and a climate with documented health benefits (Sejm of the Republic of Poland, 2005, Art. 34). While urban transformation is allowed, any changes compromising the spa's core functions or natural assets may lead to the loss of this official status.

A key spatial resilience tool is the system of spa protection zones, which integrates therapeutic, environmental, and planning standards (Art. 38). The law defines three zones:

- Zone A: $\geq 65\%$ green space, including treatment facilities;
- Zone B: $\geq 50\%$ green space, allowing limited services and housing;

- Zone C: $\geq 45\%$ biologically active space, focusing on landscape and climate protection.

These zones highlight areas of vulnerability while providing an institutional framework for adaptive capacity through mandated green space preservation.

This legal framework is supported by national and regional climate adaptation strategies, including the Strategic adaptation plan for sectors and areas vulnerable to climate change by 2020 with the prospects until 2030 (Ministry of Environment, 2013), flood risk management plans, drought management plans, retention and water management programmes, and the Maritime Spatial Plan (Council of Ministers, 2021). Under the Water Framework Directive (Commission of the European Communities, 2000), Poland delineates flood risk areas (ARFs) every six years, factoring in climate impacts (Sejm of the Republic of Poland, 2017).

Municipal responsibility for flood and climate risk management has evolved through the Crisis Management Act (Sejm of the Republic of Poland, 2007) and more directly via the Water Law (Sejm of the Republic of Poland, 2017). A major change came with the Act of 27 November 2024, which mandates climate adaptation plans (CAPs) for all towns over 20,000 residents by 2028 (Sejm of the Republic of Poland, 2024, Art. 96a), with updates every six years.

Among coastal spas, this requirement applies to Sopot, Świnoujście, and Koszalin, though several smaller towns have voluntarily begun developing a CAP with EU and national support.

Despite this framework, small and medium-sized coastal spas remain under-analysed in climate adaptation literature. Their dual vulnerability—social (patient demographics) and environmental (SLR, eutrophication, microclimate loss)—is rarely addressed through integrated, local-scale assessments that combine zoning, spatial structure, and risk modelling.

3. Methodology and Scope of the Study

The study used a multi-criteria analysis approach combining spatial, environmental, and socio-economic factors to assess the resilience of selected Baltic Sea resorts in the context of climate change. Following the literature review and analysis of the legal conditions described above, case studies were conducted. The research focuses on centres that currently have official spa status under Polish law: Świnoujście, Kamień Pomorski, Kołobrzeg, Dąbki, Ustka, and Sopot. The factors considered can be divided into three groups: development prospects, internal spatial specificity, and risk exposure.

Each case study is introduced with a description of its location within the region (based on scientific literature, strategic documents, and the authors' own research) and a presentation of the demographic situation showing the population of the town in 2023 and its change over the decade—the data comes from the Local Data Bank of the Central Statistical Office (GUS, 2024). The exception here is Dąbki, for which, due to its lack of municipality status, data were available for 2021, but the description was supplemented with a comparison for the municipality analogous to other cases.

Next, based primarily on a monographic publication by Węclawowicz-Bilska (2021), the historical context of the health resort is presented, supplemented with data on accommodation in tourist facilities and their

seasonality, as well as changes in these figures over a decade (GUS, 2024). Against this background, the number and change in the number of places in health resort facilities (GUS, 2024) are also shown.

The description is accompanied by information on the type of medicinal mineral and the ownership status of the health resort complex (Ministry of Health, 2024).

The above information is supplemented with data on current threats to the status of the health resorts, which come from health resort reports prepared for individual health resorts.

The case studies also include a spatial analysis showing the projected threats to the basic and key complementary elements of the spatial structure of health resorts coming from the sea.

The group of basic components includes the locations of medicinal mineral deposits and health resort protection zones (A, B, and C)—spatial data for both were obtained from the Polish Geological Institute – National Research Institute (2024). Key complementary elements are phenomena whose occurrence is not required by the status of a health resort, but other forms of protection confirm their special significance for the identity of the health resort. These include:

- Areas covered by forms of nature protection—spatial data obtained from the Central Register of Forms of Nature Protection maintained by the General Directorate for Environmental Protection (2024);
- Heritage conservation areas—spatial data obtained from the Zabytek.pl portal maintained by the National Heritage Institute (NID, 2024).

The spatial analysis covered three areas: (a) the extent of ARF; (b) a scenario of a 1-m SLR (SLR 1 m); and (c) a scenario of a 5-m SLR (SLR 5 m).

The ARF boundaries were derived from the National Defence Information System (ISOK) and were determined according to the following criteria: hydrography; topography; land use; description of historical floods; assessment of the potential negative effects of future floods; and forecast of long-term changes, in particular the impact of climate change on the occurrence of floods—based on the percentage change in Q90 flow intensity in the RCP 4.5 and RCP 8.5 scenarios for 2050 (Państwowe Gospodarstwo Wodne Wody Polskie, 2018).

Two further scenarios were based on the high-emission SSP5–8.5 scenario IPCC: SLR 1 until around 2100 and SLR 5 in the case of a 2 °C temperature increase.

Due to uncertainty about the progress of mitigation measures and the dynamics of the phenomenon, the authors did not specify a specific time horizon; the scenarios illustrate the direction of the phenomenon's development within the local area. The scope of the simulation covers a buffer zone of 500 m from the border of the health resort area (i.e., outside the health resort).

The study also examined the presence and scope of the CAPs in each municipality, assessing their compatibility with the resilience needs of the health resorts.

The results of the case studies, supplemented by the issues discussed horizontally in the introduction and conceptual framework, were used to formulate conclusions.

4. Case Studies

As mentioned, the following case studies cover all Polish coastal towns with spa status, which represent a wide range of development conditions. To begin with, a summary of the basic data is provided (Table 1), along with a presentation of their population size (Figure 1) and its changes (Figure 2) against the backdrop of the settlement structure.

Table 1. Basic information about the spas that were surveyed.

	Świnoujście	Kamień Pomorski	Kołobrzeg	Dąbki	Ustka	Sopot
Population (2023)	38,904	8,291	43,426	308 (2021)	13,722	31,903
Port	+	+	+	–	+	–
Number of places in spas (2023)	1,237	614	6,692	1,311 (Commune)	374	647
Number of peloid deposits	1	1	1	1	0	0
Number of medicinal (brine) water deposits	3	1	5	0	1	1
Number of spa faculties	10	11	5	6	7	6

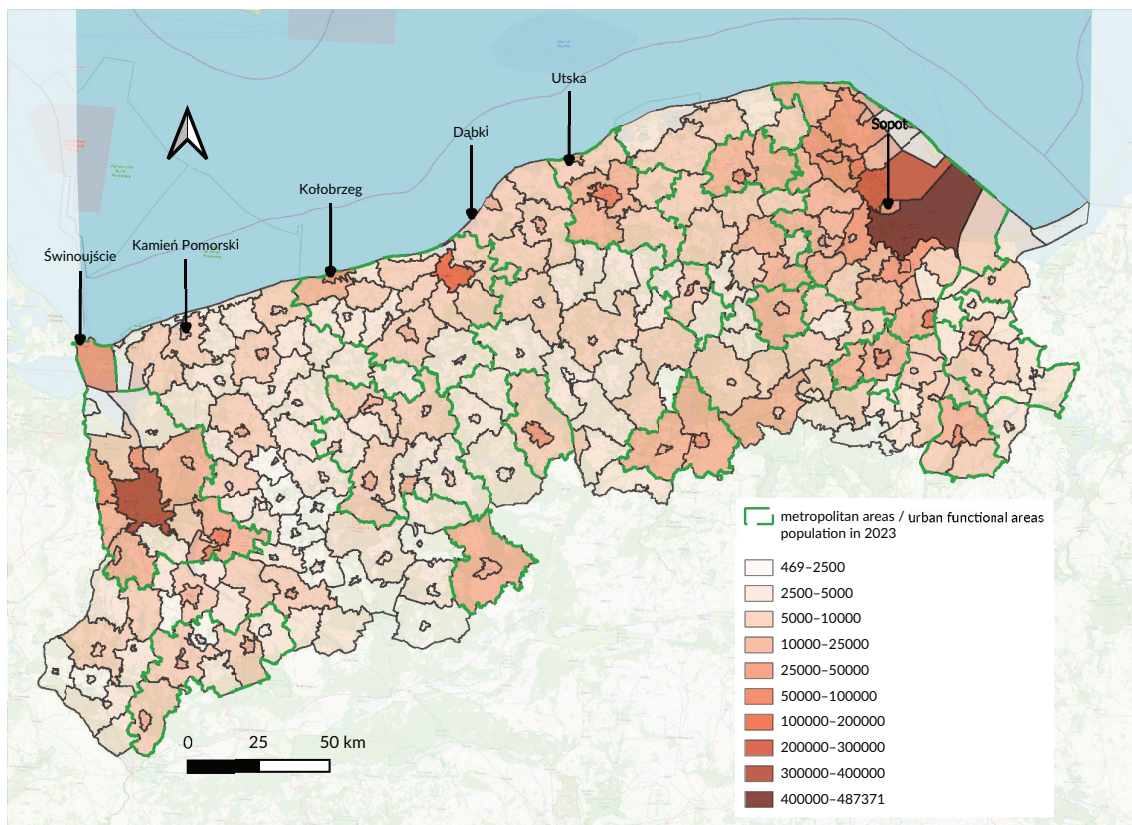


Figure 1. Seaside spa resorts against the backdrop of the settlement network of northern Poland (population as of 2023). Source: Based on data from GUS (2024); OpenStreetMap.

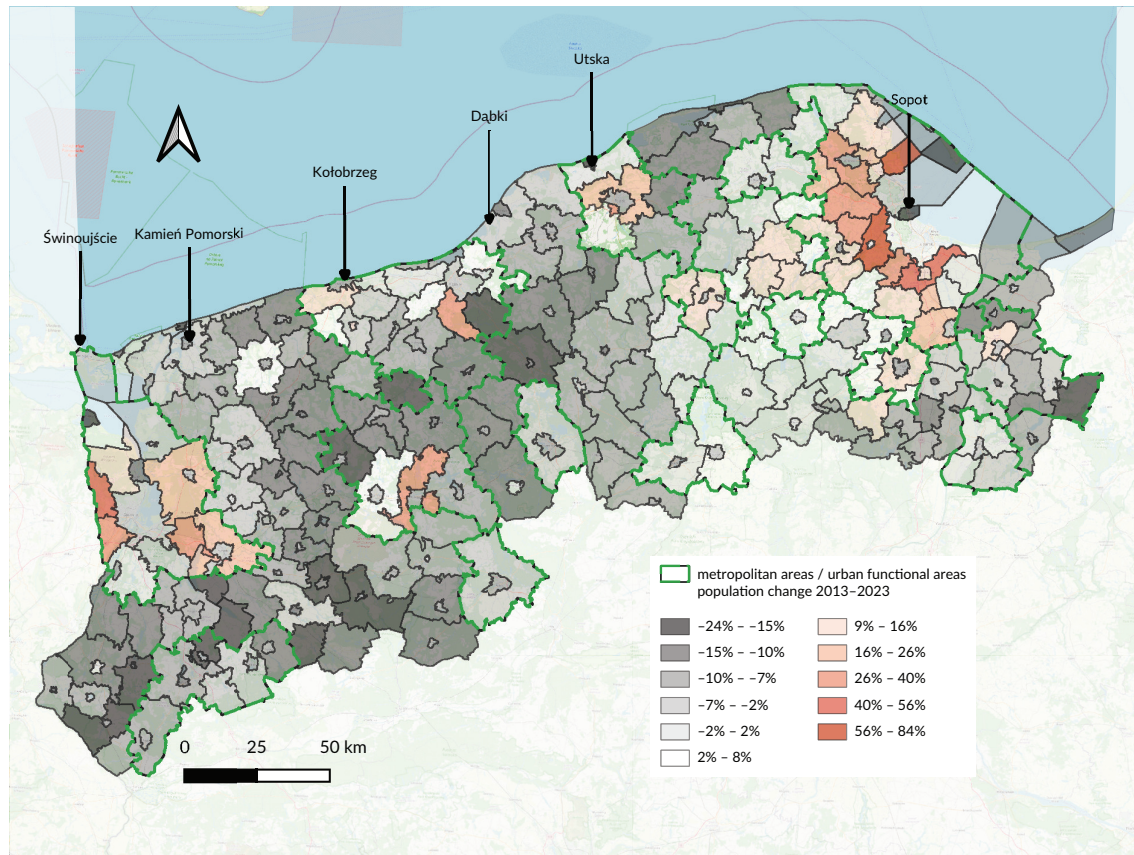


Figure 2. Seaside spas against the backdrop of the settlement network of northern Poland (population change between 2013 and 2023). Source: Based on data from GUS (2024); OpenStreetMap.

Świnoujście is a border city-archipelago on the Świna Strait and the Baltic Sea, encompassing 44 islands, with most urban functions concentrated on three. It is part of the Szczecin Metropolitan Area and forms a segment of a cross-border spa-resort conurbation including Kamień Pomorski, Dziwnów, Międzywodzie, Ahlbeck, and Heringsdorf (Węclawowicz-Bilska, 2021). The city had 38,904 residents in 2023—a decline of 5.96% over the past decade (GUS, 2024). Its economy is driven by the Szczecin–Świnoujście Port Complex, Poland’s third-largest seaport (GUS, 2024).

Established as a resort in 1824 and a spa in 1895 following the discovery of brine and peloid resources, Świnoujście retains traces of its historical spa identity through the spatial layout and large historic parks, despite extensive wartime destruction (Węclawowicz-Bilska, 2021).

Świnoujście stands out among Polish coastal destinations for its year-round readiness. In 2023, 84.5% of accommodation places were operational year-round—8,965 year-round spots (+30.8% since 2013) versus 2,589 seasonal (+8.1%). Spa infrastructure includes 1,237 spa beds (+41.7% over the decade). The city holds three deposits of medicinal water and peloids. Zone A lies adjacent to the seashore. A 2010 privatisation attempt of the spa hospital was blocked by union and government resistance, resulting in a regional takeover.

A 2023 spa report identifies several threats to spa status. Non-climate-related risks include traffic noise (not in Zone A) and air pollution—e.g., benzo(a)pyrene from outdated heating systems and elevated ozone levels

linked to weather, transport, and regional pollution influx. Water quality also poses a risk: The Szczecin Lagoon is eutrophic, worsened by nutrient flows from the Oder River and local pollution sources (Municipality of Świnoujście, 2023).

Climate-related hazards include forest fires (due to extensive forest cover) and flooding, which affects parts of the city—minimally in Zone A. The 1-m SLR scenario would not endanger Zone A aside from beach loss, but parts of the harbour and southern Zone C (allotment gardens) would be inundated. A 5-m SLR would devastate the city (Figure 3).

ARFs overlap with recreational areas along the coast (including Natura 2000 sites), parts of all spa zones, and areas near medicinal water intakes (Figure 3). A CAP, adopted in 2023, focuses on thermal risk reduction through urban greening but omits SLR scenarios.

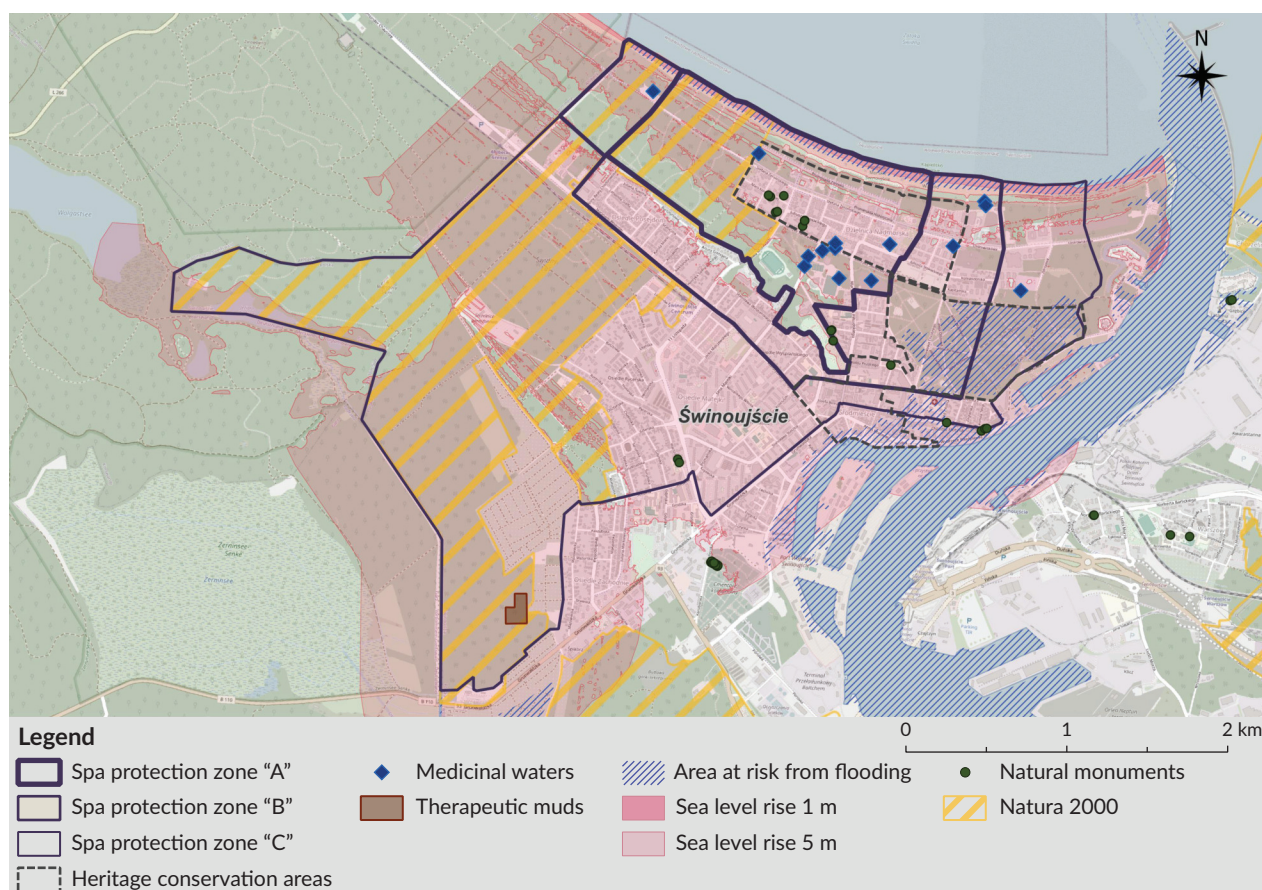


Figure 3. Simulation for Świnoujście.

Kamień Pomorski lies in the floodplain of the Dziwna Strait, which forms the Kamieński Lagoon. It is part of a cross-border spa-resort corridor extending towards the German Basin (Węclawowicz-Bilska, 2021), but is less connected to major urban centres than Świnoujście. In 2023, the town had 8,291 residents—a decline of 8.59% over the decade. The surrounding rural area (population 5,140) also saw a decline of 5.41% (GUS, 2024).

Although the town dates to the 12th century (Stępiński, 1975), its spa function emerged in the late 19th century. Following a 60% wartime destruction (Kwilecki, 1979), it retains average cultural value

(Węclawowicz-Bilska, 2021), with the Old Town—coinciding with Zone A—being its most historically significant area.

Kamień Pomorski's tourism offer is oriented towards year-round visitors. In 2023, 91.2% of accommodations were available year-round (685 places, +11.9% over the decade), while seasonal places reached 66 (+66.7%). The town had 614 spa beds in 2023—a 41% increase since 2013 (GUS, 2024).

Within the town limits are an exploited mud deposit and a medicinal water deposit, now mostly under private ownership since 2021.

Key threats to spa continuity include dispersed urban development and anthropopressure on ecologically sensitive areas. Fragmentation of ecological corridors and unchecked tourism in protected zones contribute to environmental degradation. Intensive agriculture also threatens groundwater quality through nutrient runoff. Much of Zone A lies in a flood risk area, where reduced river catchment capacity—due to urbanisation—exacerbates flooding (Municipality of Kamień Pomorski, 2018).

The spatial analysis confirms that both Zone A and large portions of the town fall within the ARF, including peatlands in Zone C. A January 2025 storm surge cut off Chrzążczewska Island in Zone C (Kraśnicki, 2025). A 1-m SLR closely matches current ARFs, while a 5-m SLR would likely destroy the town (Figure 4).

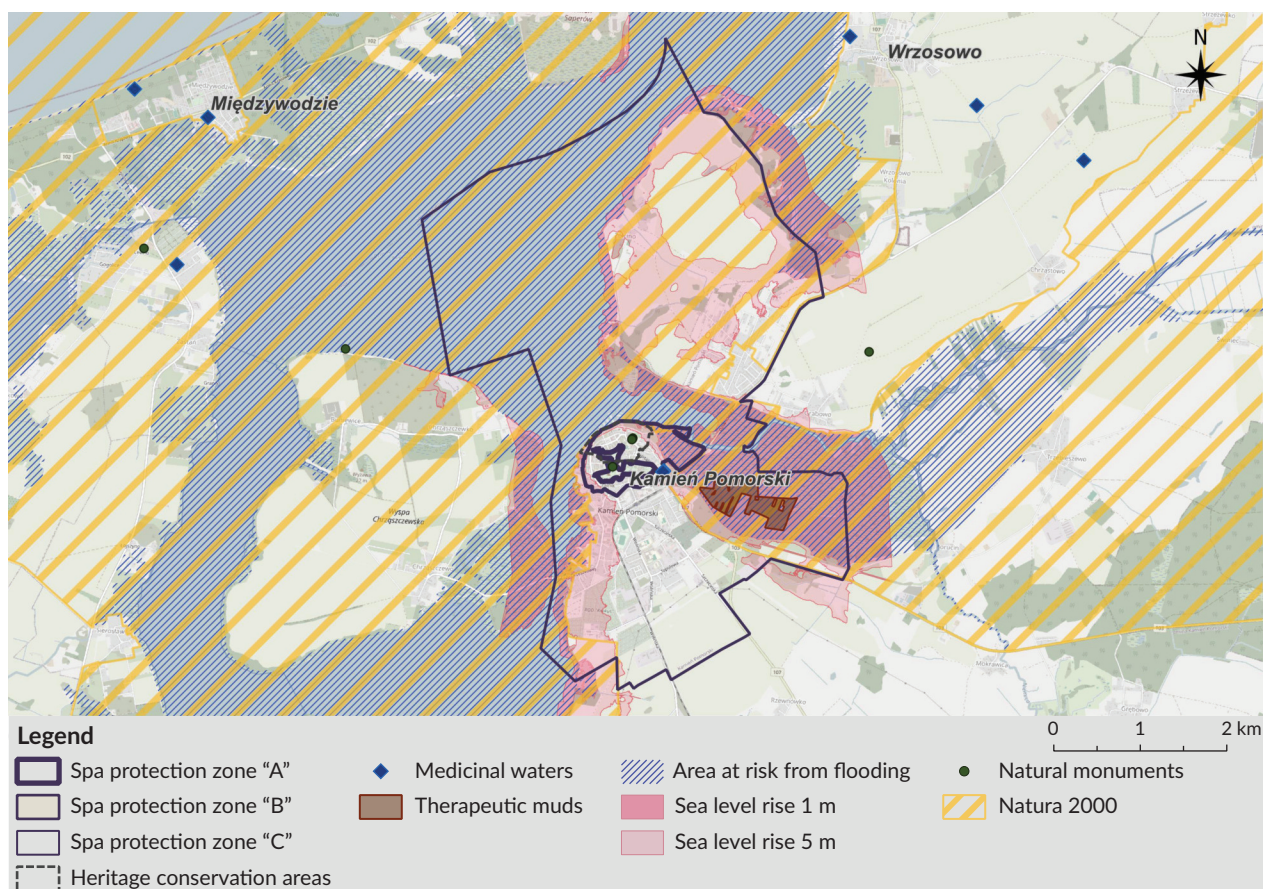


Figure 4. Simulation for Kamień Pomorski.

Kamień Pomorski lacks a citywide climate adaptation plan but began a pilot project in 2024—the Adaptation of the Urbanised Areas of the Municipality of Kamień Pomorski to Climate Change project—focussed on improving microclimates in key public spaces via blue-green infrastructure.

Kołobrzeg is part of the central southern Baltic spa and resort agglomeration and is functionally linked to nearby Koszalin. In 2023, it had 38,904 residents, a decline of 5.96% over the past decade (GUS, 2024).

While Kołobrzeg dates back to the Middle Ages, spa development began in the early 19th century. Due to wartime destruction, it is considered to have medium cultural value (Węclawowicz-Bilska, 2021). The city includes Natura 2000 sites, a protected landscape area, and monumental trees.

Kołobrzeg's tourism offer is strong year-round. In 2023, 84.5% of its accommodation was year-round (8,965 places, +30.8% over the decade), while its seasonal beds fell by 40.5% to 2,589. Spa capacity reached 6,692 beds in 2023—a 13% increase since 2013. The spa includes one peloid intake and five medicinal water deposits. Attempts to privatise the health resort were blocked, and it remains publicly managed (GUS, 2024).

Challenges to spa continuity include urbanisation pressure, air pollution during the heating season, and traffic noise in Zone A. Additionally, nutrient loads from the Parsęta River contribute to eutrophication (Municipality of Kołobrzeg, 2023).

The ARFs are concentrated near the Parsęta River and touch the eastern edge of Zone A, which includes valuable peatlands and marshes. These areas are relatively undeveloped and distant from key public spaces. A 1-m SLR would result in substantial flooding, particularly in eastern Zone A and along the river. A 5-m SLR scenario would nearly destroy the city, sparing only a small enclave in the historic centre (Figure 5).

Although Kołobrzeg lacks a CAP, the Smart City strategy adopted in 2021 includes plans for such a document and a retention scheme, though neither has yet been implemented (Municipality of Kołobrzeg, 2021).

Dąbki is a village in the Darłowo commune, with a population of 308 in 2021. The wider municipality had 7,596 residents in 2023, down 5.4% over the decade (GUS, 2024). Located far from major cities, Dąbki is part of a string of coastal spa and resort towns.

It is the youngest of the Polish seaside spas, having developed only in the late 20th and early 21st centuries (Węclawowicz-Bilska, 2021). Traces of local history remain in four preserved fishing huts. The town's defining feature is the narrow strip of land between the Baltic Sea and Lake Bukowo, where most of Zone C lies. The area includes Natura 2000 sites, a protected landscape area (covering Zones A and B), and a group of natural monuments near the spa.

Tourism in the Darłowo commune remains highly seasonal. In 2023, seasonal accommodation reached 4,532 beds (a 30.2% decrease over a decade), while year-round beds increased by 81.2% to 1,066. Spa capacity grew by 145%, reaching 1,311 beds (GUS, 2024).

The resort is publicly owned, with confirmed peloid therapeutic properties and recent investments from local and state budgets.

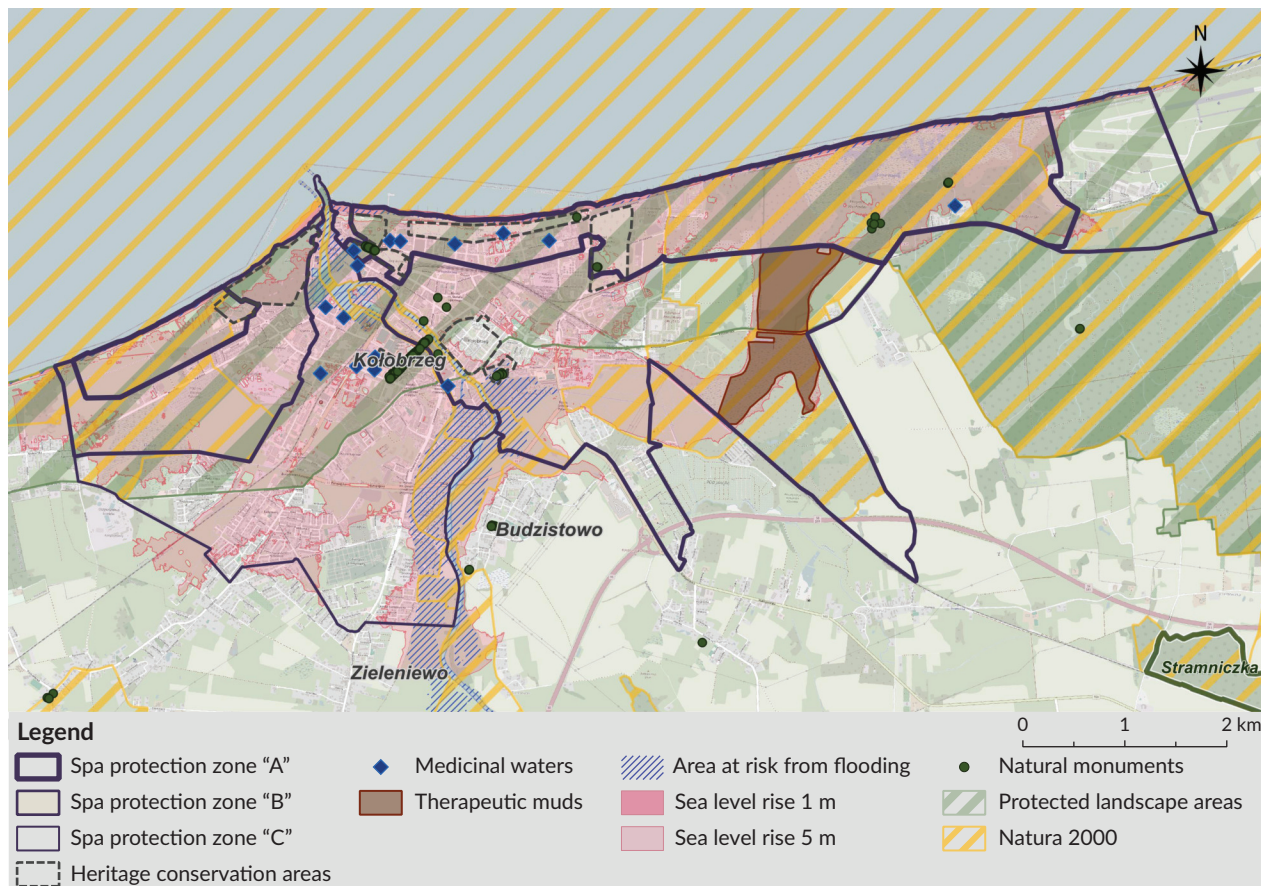


Figure 5. Simulation for Kołobrzeg.

The 2017 spa report highlights traffic noise in Zone A and air quality concerns. Dąbki is also highly vulnerable to flooding (Commune of Darłowo, 2017). Due to its low elevation between the sea and the lake, the ARF includes all of Zone A, most of Zone B, and large parts of Zone C—encompassing public spaces, spa facilities, and the mud deposit. Even with a 1-m SLR, much of the area would be submerged (Figure 6).

As of 2025, the Darłowo commune lacks a CAP.

In 2023, Ustka had 13,722 residents, a 15.6% decline over the decade. The surrounding rural municipality recorded a population of 8,026, with minimal growth (+0.12%; GUS, 2024). Ustka is part of the Słupsk Urban Functional Area, which had 160,588 residents in 2020, reflecting a 1.3% population decline since 2011 (Strategy 2022–2030). In addition to its spa, Ustka's economy is supported by a seaport and associated industries.

Spa development began in the early 20th century and accelerated post-1950s. The town is considered to have average cultural value (Węćławowicz-Bilska, 2021). Tourism remains highly seasonal: in 2023, seasonal places reached 5,327 (+8% over a decade), while year-round places rose by 34% to 2,933. In 2023, Ustka offered 374 spa beds—a 45% decline from 2013, with a 55% drop between 2019 and 2021.

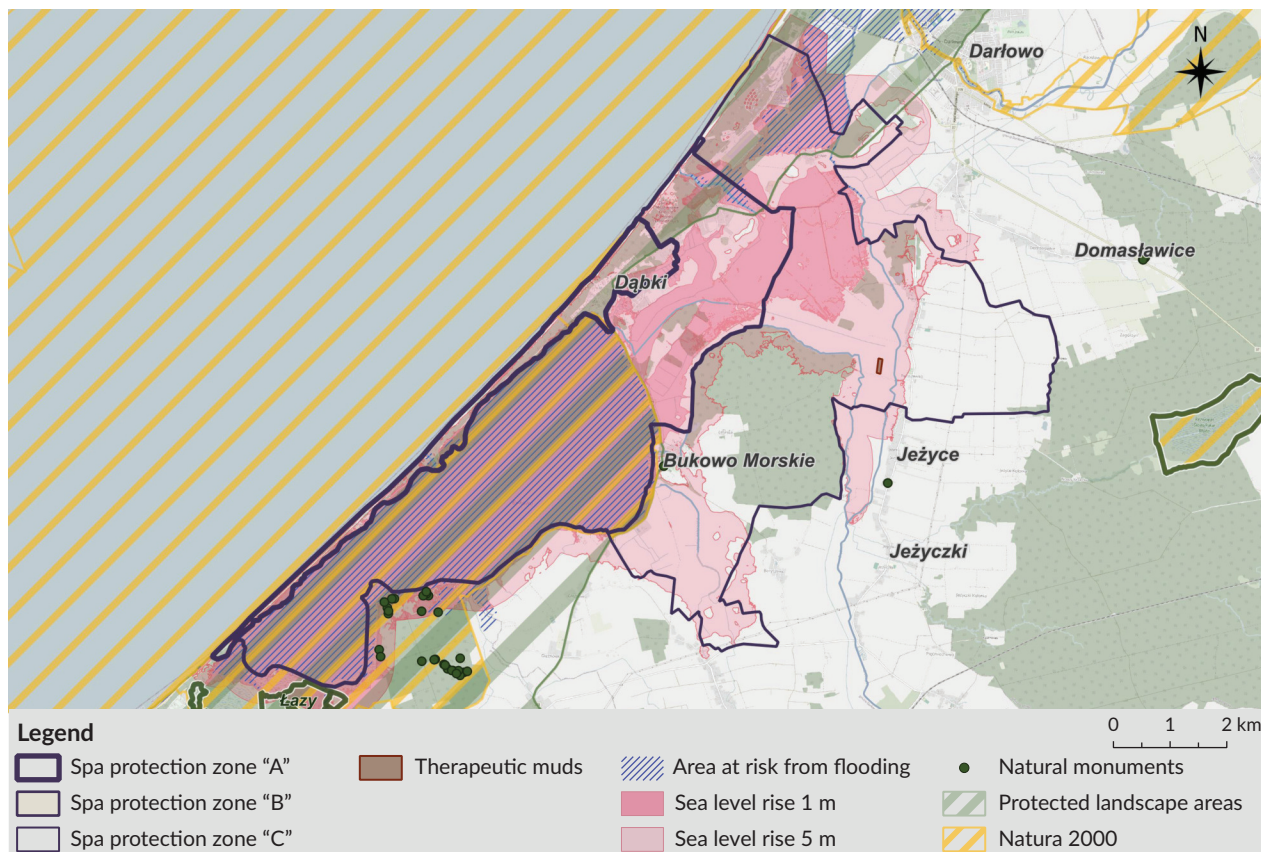


Figure 6. Simulation for Dąbki.

The primary spa resource is medicinal water. After partial privatisation in 2010, the spa has operated as a private entity with ongoing infrastructure investment.

Key threats include investment pressure and traffic noise, both affecting Zone A (Municipality of Ustka, 2008). ARF is concentrated along the coast, covering parts of all zones, including the promenade (Zone A) and harbour quays (Zone C). While a 1-m SLR affects only a narrow coastal strip (largely overlapping with ARF), widening the Słupia River estuary could flood ecologically valuable areas in Zone C. A 5-m SLR would inundate much of Zone C, reaching areas near the spa's water intake at the Zone A boundary (Figure 7).

Ustka adopted a CAP in 2020 (horizon: 2030), aimed at increasing the resilience to heavy rainfall, flooding, and drought. Measures include a monitoring system, emergency service planning, reconstruction of the harbour entrance, and the construction of open reservoirs.

Sopot lies within a major spa and resort corridor (Węćławowicz-Bilska, 2021) and, despite its small size, plays an outsized role due to its position in the Tri-City metropolitan area (Lorens & Gołędzinowska, 2022). The spa established in the early 19th century was the catalyst for the city's development (Stankiewicz & Szermer, 1959) and holds high cultural value (NID, 2024; Węćławowicz-Bilska, 2021). Almost all of Zone A is protected as an area monument. Natural assets are extensive, including monumental trees (all zones), a nature reserve (Zone C), and part of the Tri-City Landscape Park (Zones A2 and C).

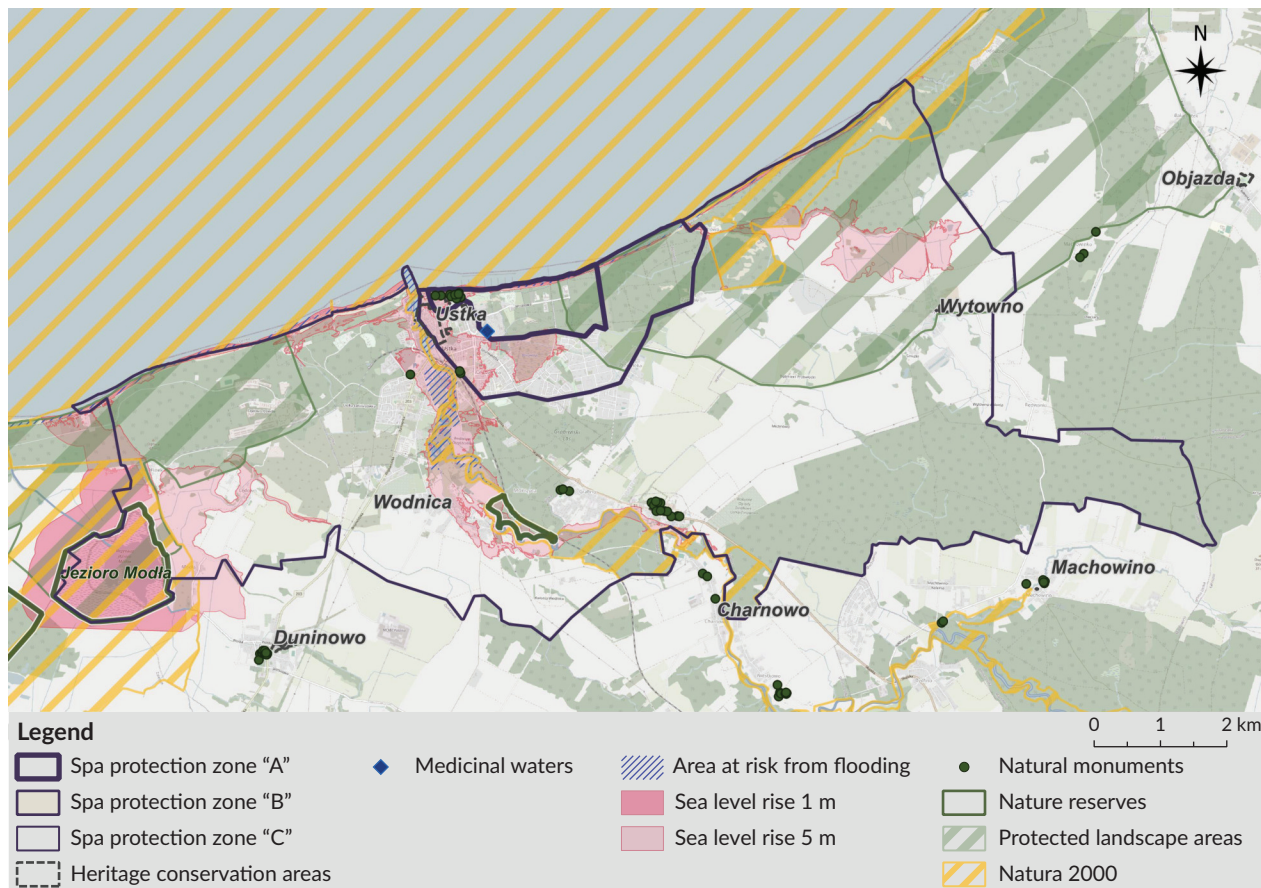


Figure 7. Simulation for Ustka.

In 2023, Sopot had 31,903 residents—a 15.8% population decline over the decade (GUS, 2024). In contrast, the broader metropolitan area, including Gdańsk (pop. >1.6 million), is growing (Obszar Metropolitalny Gdańsk-Gdynia-Sopot, 2024).

The city's tourism figures are difficult to assess directly due to the proximity of Gdańsk and Gdynia. In 2023, 75% of tourist beds were available year-round (4,837, +47.4% since 2013), while seasonal beds rose dramatically to 1,657 (a 1,690% increase from zero). The number of spa beds rose slightly to 647 (+2%; GUS, 2024).

The city has one medicinal water intake, located in Zone A1 by the coast, while Zone A2 lies in forested uplands. The health resort remains city-owned. Between 1997 and 2009, major upgrades were completed via a public–private partnership.

Key risks include traffic noise in Zone A1 (LEMITOR Ochrona Środowiska, 2022) and cyanobacterial blooms, exacerbated by summer warming and nutrient inflows (Błaszczuk et al., 2021; Municipality of Sopot, 2020). Although the storm risk is low, Sopot faces future SLR. A 1-m SLR would impact only the beach area, but a 5-m SLR would submerge Zone A1 and much of Zone B, including historic areas. Zone A2 would remain unaffected due to its elevation (Figure 8).

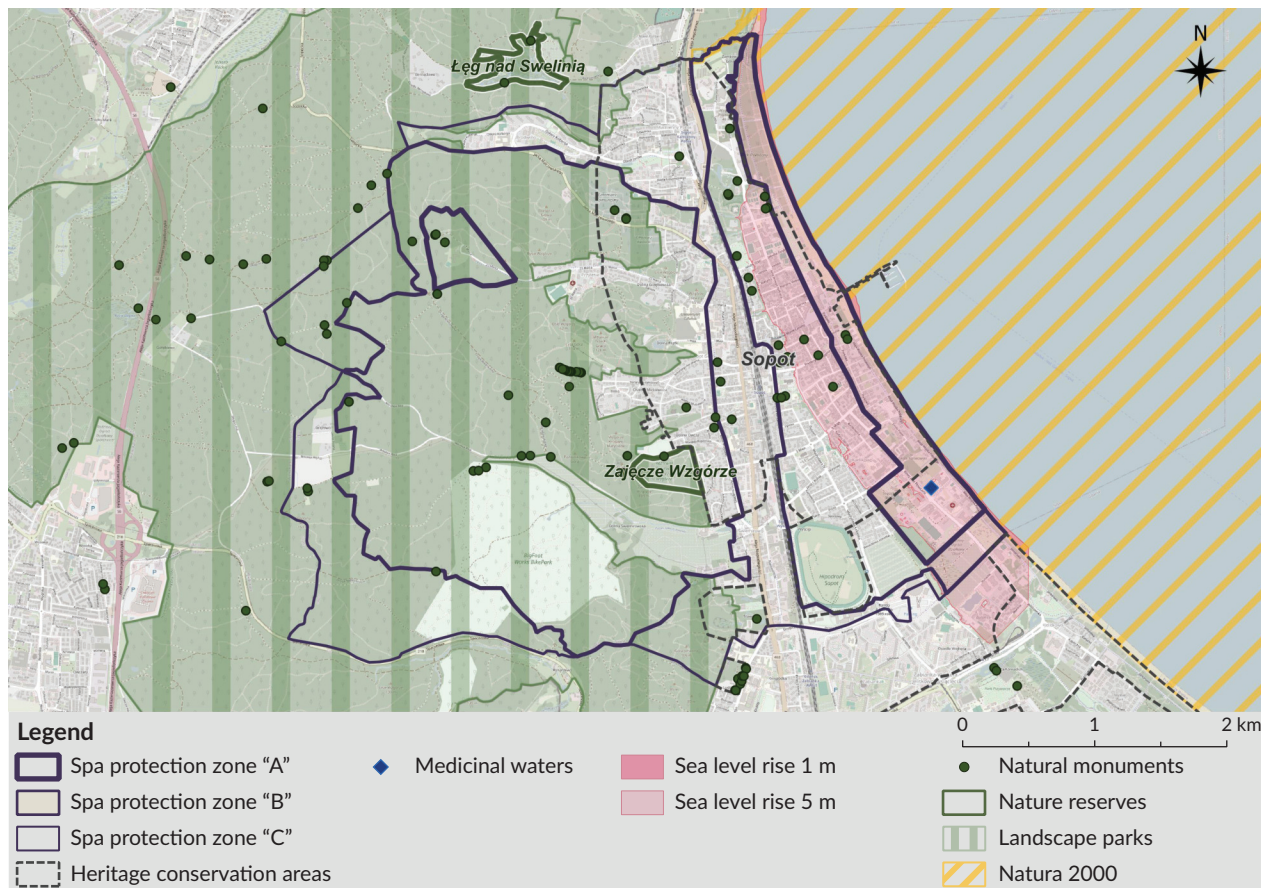


Figure 8. Simulation for Sopot.

Sopot's CAP (horizon: 2030) includes both organisational and infrastructural measures: dune reinforcement, climate monitoring, service coordination, and planning document updates. Notably, it is the only spa to consider decommissioning infrastructure in future risk zones.

In summary, certain characteristics, such as population loss, are horizontal for all the studied centres, even though there is significant variation in several other factors, including development prospects, internal specificity, and identified threat areas. The following table lists the most important features for each centre (Table 2).

Table 2. Summary of the case studies.

Spa locality	Key conditions		Exposure risk (ARF/SLR)	CAP
	Development prospects	Internal spatial specificity		
Świnoujście	strong port economy metropolitan area	historic spa parks, multiple brine/mud deposits poor air quality moderate cultural and natural values	moderate ARF risk minor flooding in Zone A (SLR 1m) catastrophic SLR 5m scenario	adopted (2023), lacks SLR response
Kamień Pomorski	small town; some private investment moderate tourism growth	Old Town overlaps with Zone A moderate cultural and natural values	extensive ARF and SLR 1m exposure (esp. Zones A & C) high risk of ecosystem fragmentation catastrophic SLR 5m scenario	partial, via blue-green infrastructure project
Kołobrzeg	high year-round tourism functional urban area	extensive spa infrastructure poor air quality moderate cultural and high natural values	ARF risk near the Parsęta River mud deposit at risk with SLR 1m catastrophic SLR 5m scenario	Smart City strategy (2022), no CAP yet
Dąbki	peripheral; high seasonal fluctuation significant increase in spa beds	unique spit-land setting between sea and lake poor air quality low cultural but high natural values	Zone A almost fully within ARF heavy flood risk even with SLR 1m catastrophic SLR 5m scenario	no CAP; high priority for protection
Ustka	moderate development of tourist and spa function functional urban area	spa facility under private ownership noise moderate cultural and natural values	ARF overlaps key spa zones SLR 1m threatens coastal facilities severe SLR 5m scenario	adopted (2020) with a long-term focus
Sopot	highly valued spa and wellness tourism metropolitan area	dual Zone A structure includes resilient forested areas (Zone A2) noise high cultural and natural values	ARF minimal SLR 1m minor effect on beach severe SLR 5m scenario (A2 stays intact)	comprehensive CAP to 2030 includes SLR and decommissioning scenarios

5. Discussion

The results of the analyses contribute to a broader body of research on the resilience of local communities and urban systems under pressure from climate change and other anthropogenic factors. In this context, coastal spas demonstrate a degree of infrastructural and functional resilience, particularly in their ability to maintain both core and ancillary spa services (Konecka-Szydłowska, 2018). This discussion critically reflects on these findings, especially regarding the specific climate-related challenges faced by spas and their potential adaptation strategies.

Although the scientific consensus on climate change is strong, projections regarding localised long-term impacts remain uncertain due to the complexity of climatic interactions (Meier et al., 2022; Styszyńska et al., 2018; Zscheischler et al., 2018). Some studies suggest that certain regions of Europe may experience fewer adverse weather days, potentially enhancing tourism and lengthening the spa season (Djordjevic et al., 2016; Rosselló-Nadal, 2014). However, given the vulnerability of natural spa assets and infrastructure, this scenario requires cautious interpretation.

Importantly, the study confirms that environmental quality issues—independent of climate change—already threaten the status of health resorts. This underscores the importance of proactive adaptation, which can be framed through the lens of a triple dividend of resilience approach (Heubaum et al., 2022). This model highlights:

- First dividend: avoided climate-related losses;
- Second dividend: induced economic and development benefits;
- Third dividend: social and environmental gains from resilience-building—including the resolution of existing structural or environmental issues.

Notably, the second and third dividends occur regardless of whether projected climate impacts materialise, reinforcing the value of investing in adaptation.

To guide implementation, adaptation measures can be structured across three planning horizons (see Supplementary File):

- Up to 2034 (short-term);
- Up to 2050 (mid-term);
- Up to 2150 (long-term), with flexibility to extend the timeline as new information emerges.

Despite negative demographic trends—most pronounced in Sopot—the spa towns analysed retain a strong, well-established resort image that continues to attract both visitors and investors. In some cases, economic resilience is bolstered by structural advantages, such as large-scale port operations (e.g., Świnoujście) or proximity to metropolitan cores (Świnoujście, Sopot), which help buffer fluctuations in the tourism sector (Szymańska & Wiśniewska, 2022).

Importantly, local and regional actors have, in several instances, successfully resisted the privatisation of spa infrastructure. As a result, four of the six spas remain publicly owned, reinforcing community influence over

strategic assets. In all cases, the local tourism economy continues to benefit from cultural and natural values linked to spa specialisation. Strengthening resilience, therefore, requires not only protecting these assets but also empowering local authorities to lead coordinated adaptation efforts that include private stakeholders.

The CAPs currently in place prioritise issues such as flood control, stormwater retention, monitoring, and microclimate regulation, which is consistent with national guidelines and their shared 2030 time horizon (Ministry of Environment, 2017). Among them, Sopot's CAP stands out for adopting long-term, strategic goals: protecting and restoring coastal dunes, revising spatial plans, and prohibiting development in high-risk flood zones. Research suggests that coastal protection strategies aimed solely at land preservation often prove ineffective in the long term (Łabuz, 2013).

Despite their limitations, the current CAPs place appropriate emphasis on blue-green infrastructure, which is critical in spa towns where high proportions of green space contribute to microclimatic stability. However, many spa zones also contain extensive sealed surfaces (e.g., roads, harbour areas), reducing adaptive capacity. Increased urbanisation and rising temperatures may undermine the natural heat balance mechanism provided by sea breezes—once a major locational advantage (Xie et al., 2023).

Although the current 1-m SLR scenarios do not critically affect the core spa functions in most towns, they do pose risks to essential public infrastructure—promenades, waterfronts, and harbour basins. In contrast, a 5-m SLR would result in the wholesale transformation of water systems and ecosystems (IPCC, 2023; Meier et al., 2022), moving the issue beyond resilience and into the realm of transformability—the capacity to build a new system when the existing one becomes unsustainable (Walker et al., 2004).

6. Conclusions

When analysing the socio-economic determinants of spa resilience, it is important to emphasise that spa accommodation constitutes only a portion of the overall tourism base, with its significance varying by location. In four of the six cases studied, strong local and regional opposition successfully halted privatisation, ensuring continued public ownership of key spa assets. These centres benefit not only from cultural and natural heritage but also from their distinct spa specialisation. Local authorities thus have a dual responsibility: implementing adaptation strategies and coordinating broader resilience-building processes in collaboration with private actors.

This study confirms that all Polish Baltic spa towns are already experiencing environmental quality issues and face a range of climate-related risks. However, the scale and nature of these threats vary based on the location, degree of urbanisation, and local governance structures. While demand for spa services is rising, delays in infrastructure modernisation and environmental pressures necessitate corrective actions, many of which can double as climate adaptation measures.

The spa protection zone framework (Zones A, B, and C) offers a spatial basis for adaptation. Yet, enforcement and flexible management remain inconsistent or outdated. Future CAPs should prioritise preserving and enhancing spa and health-promoting functions—assets closely tied to local identity and less dependent on seasonal tourism. These also enable more efficient infrastructure use throughout the year.

The immediate planning priority is to ensure that local spatial development plans comprehensively cover spa areas and (a) prohibit development in flood-prone areas, (b) control chaotic urbanisation that erodes cultural identity and adaptive capacity, and (c) reserve land for alternative public uses and spa infrastructure.

This is particularly urgent for Dąbki; in the long term, all centres should establish spatial reserves—except for Sopot, which already benefits from the elevated and resilient A2 zone surrounded by protected forest.

In terms of organisational measures, efforts must target the reduction of eutrophication, both regionally and locally, to mitigate annual cyanobacteria blooms, while improving air quality and noise reduction should also be prioritised in Świnoujście, Kołobrzeg, Dąbki, Ustka, and Sopot.

This study provides an outline of the problem. Further research is needed at different scales. The first is the in-depth modelling of local phenomena for the development of specific centre policies. This group includes issues such as changes in the healing properties of the climate, changes in the microclimate, the vulnerability of green areas to hydrological drought, and the projected impact of storm surges on specific parts of a locality after SLR. Another scale involves analysing and forecasting phenomena at a regional level, e.g., the potential development of spa and health tourism over time, and analysing climate change trends. Finally, a further research issue is how to build the resilience of Baltic spas within the framework of national policies or the European Union cohesion policy, and to what extent.

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Conflict of Interests

The authors declare no conflict of interests.

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Supplementary Material

Supplementary material for this article is available online in the format provided by the authors (unedited).

References

- Adger, W. N. (2000). Social and ecological resilience: are they related? *Progress in Human Geography*, 24(3), 347–364.
- Bachvarov, M. (2006). Spas in Central-Eastern Europe between decline and revitalisation. In M. Smith & L. Onderwater (Eds.), *The transformation of tourism spaces ATLAS Reflections 2006* (pp. 43–51). ATLAS.
- Bal, W. (2009). Tożsamość kulturowa kurortów nadmorskich. Przestrzeń inspirująca, wymagające dziedzictwo. *Przestrzeń i Forma*, 12, 135–152.

- Bal, W., & Czałczyńska-Podolska, M. (2020). The stages of the cultural landscape transformation of seaside resorts in Poland against the background of the evolving nature of tourism. *Land*, 9(2), Article 55. <https://doi.org/10.3390/land9020055>
- Błaszczuk, A., Kobos, J., & Mazur-Marzec, H. (2021). *Letnie zakwity cyjanobakterii w Zatoce Gdańskiej-zagrożenia i nadzieje*. Division of Marine Biotechnology, University of Gdańsk.
- Błażejczyk, K., & Kunert, A. (2011). *Bioklimatyczne uwarunkowania rekreacji i turystyki w Polsce*. Instytut Geografii i Przestrzennego Zagospodarowania Im. Stanisława Leszczyckiego PAN. https://rcin.org.pl/igipz/Content/19801/PDF/WA51_39725_r2011-nr13_Monografie.pdf
- Boćkus, D., Vento, E., & Komppula, R. (2024). Cross-national analysis of wellness tourism concepts, tourists motivations, and service preferences. In H. Konu & M. K. Smith (Eds.), *A research agenda for tourism and wellbeing* (pp. 157–176). Edward Elgar Publishing. <https://doi.org/10.4337/9781803924342.00018>
- Cazenave, A., & Cozannet, G. L. (2014). Sea level rise and its coastal impacts. *Earth's Future*, 2(2), 15–34. <https://doi.org/10.1002/2013EF000188>
- Chapin, F. S., III, Robards, M. D., Huntington, H. P., Johnstone, J. F., Trainor, S. F., Kofinas, G. P., Ruess, R. W., Fresco, N., Natcher D. C., & Naylor, R. L. (2006). Directional changes in ecological communities and social-ecological systems: A framework for prediction based on Alaskan examples. *The American Naturalist*, 168(S6), S36–S49.
- Choat, B., Brodribb, T. J., Brodersen, C. R., Duursma, R. A., López, R., & Medlyn, B. E. (2018). Triggers of tree mortality under drought. *Nature*, 558(7711), 531–539. <https://doi.org/10.1038/s41586-018-0240-x>
- Commission of the European Communities. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Union*, L 327. <https://eur-lex.europa.eu/eli/dir/2000/60/oj>
- Commune of Darłowo. (2017). *Operat uzdrowiska Dąbki*. Unpublished manuscript.
- Council of Ministers. (2021). *Rozporządzenie Rady Ministrów z dnia 14 kwietnia 2021 r. w sprawie przyjęcia planu zagospodarowania przestrzennego polskich obszarów morskich* (Dz.U. 2021 poz. 935). <https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20210000935>
- CRFOP. (2024). *Centralny rejestr form ochrony przyrody*. <https://crfop.gdos.gov.pl/CRFOP>
- Dailidė, R., Dailidė, G., Razbadauskaitė-Venskė, I., Povilanskas, R., & Dailidienė, I. (2022). Sea-breeze front research based on remote sensing methods in coastal Baltic Sea climate: Case of Lithuania. *Journal of Marine Science and Engineering*, 10(11), Article 1779. <https://doi.org/10.3390/jmse10111779>
- Dargacz, J. (2020). *Od Sopotu po Stogi: Początki kąpielisk morskich w okolicach Gdańska (1800–1870)*. Muzeum Gdańska.
- Davie, T. (2019). *Fundamentals of hydrology*. Routledge. <https://doi.org/10.4324/9780203798942>
- De Vries, S., Van Dillen, S. M., Groenewegen, P. P., & Spreeuwenberg, P. (2013). Streetscape greenery and health: Stress, social cohesion and physical activity as mediators. *Social Science & Medicine*, 94, 26–33.
- Diekmann, A., Smith, M. K., & Ceron, J. P. (2020). From welfare to wellness: European spas at the crossroads. In *Handbook of social tourism* (pp. 108–122). Edward Elgar Publishing. <https://doi.org/10.4337/9781788112437.00020>
- Diller, C., Litmeyer, M. L., & Göbel, J. (2023). Spa towns in Germany. *Erdkunde*, 77(2), 113–126. <https://doi.org/10.3112/erdkunde.2023.02.02>
- Djordjevic, D. S., Secerov, V., Filipovic, D., Lukic, B., & Jeftic, M. R. (2016). The impact of climate change on the planning of mountain tourism development in Serbia: Case studies of Kopaonik and Zlatibor. *Fresenius Environmental Bulletin*, 25(11), 5027–5034.
- Dryglas, D., & Różycki, P. (2016). European spa resorts in the perception of non-commercial and commercial

- patients and tourists: The case study of Poland. *e-Review of Tourism Research*, 13(1/2). <https://scispace.com/pdf/european-spa-resorts-in-the-perception-of-non-commercial-and-2sv9dhrup9.pdf>
- Dryglas, D., & Smith, M. K. (2023). A critical analysis of how Central European spas create health tourism experiencescapes. *Tourism Planning & Development*, 21(5), 570–593. <https://doi.org/10.1080/21568316.2023.2259357>
- Dzhambov, A. M., Lercher, P., Browning, M. H., Stoyanov, D., Petrova, N., Novakov, S., & Dimitrova, D. D. (2021). Does greenery experienced indoors and outdoors provide an escape and support mental health during the Covid-19 quarantine? *Environmental Research*, 196, Article 110420. <https://doi.org/10.1016/j.envres.2020.110420>
- Foley, R. (2016). *Healing waters: Therapeutic landscapes in historic and contemporary Ireland*. Routledge.
- Global Wellness Institute. (2021). *The Global Wellness economy: Looking beyond COVID*. https://globalwellnessinstitute.org/wp-content/uploads/2021/11/GWI-WE-Monitor-2021_final-digital.pdf
- Goldstein, B. E., Wessells, A. T., Lejano, R., & Butler, W. (2015). Narrating resilience: Transforming urban systems through collaborative storytelling. *Urban Studies*, 52(7), 1285–1303.
- Gorczyca, M. (2024). Jakość powietrza w uzdrowiskach-stałe przekraczanie norm zanieczyszczeń. *Kontrola Państwowa*, 69(5), 67–81. <https://doi.org/10.53122/ISSN.0452-5027/2024.1.32>
- Griggs, G. B., & Trenhaile, A. S. (1994). Coastal cliffs and platforms. In C. Woodroffe & R. W. G. Carter (Eds.), *Coastal evolution: Late quaternary shoreline morphodynamics* (pp. 425–450). Cambridge University Press.
- GUS. (2024). *Local data bank*. <https://bdl.stat.gov.pl/bdl/metadane/cechy/szukaj?slovo=tourism>
- Heubaum, H., Brandon, C., Tanner, T., Surminski, S., & Roezer, V. (2022). *The triple dividend of building climate resilience: Taking stock, moving forward*. World Resources Institute. <https://doi.org/10.46830/wriwp.21.00154>
- Holling, C. S. (1973). Resilience and stability of ecological systems. *Annual Review of Ecology and Systematics*, 4, 1–23.
- Ibelings, B. W., Fastner, J., Bormans, M., & Visser, P. M. (2016). Cyanobacterial blooms. Ecology, prevention, mitigation and control: Editorial to a CYANOCOST Special Issue. *Aquatic Ecology*, 50, 327–331. <https://doi.org/10.1007/s10452-016-9595-y>
- IPCC. (2023). Summary for policymakers. In Core Writing Team, H. Lee, & J. Romero (Eds.), *AR6 Synthesis Report: Climate change 2023* (pp. 3–32). Cambridge University Press. <https://doi.org/10.59327/IPCC/AR6-9789291691647.001>
- Kask, T., & Raagmaa, G. (2010). The spirit of place of West Estonian resorts. *Norsk Geografisk Tidsskrift/ Norwegian Journal of Geography*, 64(3), 162–171.
- Konecka-Szydłowska, B. (2018). Rozwój małych miast powiatowych województwa wielkopolskiego w ujęciu koncepcji. *Space–Society–Economy*, 2018(24), 27–44. <http://doi.org/10.18778/1733-3180.24.02>
- Kownacka, J., Busch, S., Göbel, J., Gromisz, S., Hällfors, H., Högländer, H., Huseby, S., Jaanus, A., Jakobsen, H. H., Johansen, M., Johansson, M., Jurgensone, I., Liebeke, N., Kobos, J., Kraśniewski, W., Kremp, A., Lehtinen, S., Olenina, I., v. Weber, M., . . . Wasmund, N. (2021). *Cyanobacteria biomass 1990–2020*. HELCOM. <https://helcom.fi/wp-content/uploads/2022/04/BSEFS-Cyanobacteria-biomass-1990-2020.pdf>
- Kraśnicki, A., Jr. (2025, January 12). Cofka w Zachodniopomorskim uwięziła na wyspie ponad 200 osób. Takiej wody w regionie dawno nie widziano. *Gazeta Wyborcza*. <https://szczecin.wyborcza.pl/szczecin/7,34939,31607632,cofka-w-zachodniopomorskim-uwiezila-na-wyspie-ponad-200-osob.html>
- Kuchcik, M., Błażejczyk, K., & Halaś, A. (2021). Long-term changes in hazardous heat and cold stress in humans: multi-city study in Poland. *International Journal of Biometeorology*, 65(9), 1567–1578. <https://doi.org/10.1007/s00484-020-02069-7>

- Kwilecki, S. (1979). Odbudowa zabytków Pomorza Zachodniego po drugiej wojnie światowej. *Ochrona Zabytków*, 1979(4), 281–287.
- Łabuz, T. (2013). *Sposoby ochrony brzegów morskich i ich wpływ na środowisko przyrodnicze polskiego wybrzeża Bałtyku: Raport*. Fundacja WWF Polska.
- Langer, P. (2020). Groundwater mining in contemporary urban development for European spa towns. *Journal of Human, Earth, and Future*, 1(1), 1–9. <https://doi.org/10.28991/HEF-2020-01-01-01>
- LEMITOR Ochrona Środowiska. (2022). *Strategiczna mapa hałasu miasta Sopotu dla dróg, po których przejeżdża ponad 3 000 000 pojazdów rocznie*. <https://bip.sopot.pl/api/files/49034>
- Linkov, I., Bridges, T., Creutzig, F., Decker, J., Fox-Lent, C., Kröger, W., Lambert, J. H., Levermann, A., Montreuil, B., Nathwani, J., Nyer, R., Renn, O., Scharte, B., Scheffler, A., Schreurs, M., & Thiel-Clemen, T. (2014). Changing the resilience paradigm. *Nature Climate Change*, 4(6), 407–409. <https://doi.org/10.1038/nclimate2227>
- Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., Pell, A. N., Deadman, P., Kratz, T., Lubchenco, J., Ostrom, E., Ouyang, Z., Provencher, W., Redman, C. L., Schneider, S. H., & Taylor, W. W. (2007). Complexity of coupled human and natural systems. *Science*, 317(5844), 1513–1516. <https://doi.org/10.1126/science.1144004>
- Lorens, P., & Gołędzinowska, A. (2022). Developing polycentricity to shape resilient metropolitan structures: The case of the Gdansk–Gdynia–Sopot Metropolitan Area. *Urban Planning*, 7(3), 159–171. <https://doi.org/10.17645/up.v7i3.5502>
- Matthies, F., & Menne, B. (2009). Prevention and management of health hazards related to heatwaves. *International Journal of Circumpolar Health*, 68(1), 8–12.
- Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, 147, 38–49. <https://doi.org/10.1016/j.landurbplan.2015.11.011>
- Meier, H. M., Kniebusch, M., Dieterich, C., Gröger, M., Zorita, E., Elmgren, R., Myrberg, K., Ahola, M. P., Bartosova, A., Bonsdorff, E., Börgel, F., Capell, R., Carlén, I., Carlén, T., Christensen, O. B., Dierschke, V., Frauen, C., Frederiksen, M., Gaget, E., . . . Zhang, W. (2022). Climate change in the Baltic Sea region: A summary. *Earth System Dynamics*, 13(1), 457–593. <https://doi.org/10.5194/esd-13-457-2022>
- Meller, M., & Bernat, S. (2019). Drzewa pomnikowe na terenie uzdrowisk w Polsce. *Sylvan*, 163(03), 258–264. <https://doi.org/10.26202/sylvan.2018104>
- Minick, K. J., Mitra, B., Noormets, A., & King, J. S. (2019). Saltwater reduces potential CO₂ and CH₄ production in peat soils from a coastal freshwater forested wetland. *Biogeosciences*, 16(23), 4671–4686. <https://doi.org/10.5194/bg-16-4671-2019>
- Ministry of Environment. (2013). *Strategiczny plan adaptacji dla sektorów i obszarów wrażliwych na zmiany klimatu do roku 2020 z perspektywą do roku 2030 (SPA 2020)*. <https://bip.mos.gov.pl/strategie-plan-programy/strategiczny-plan-adaptacji-2020>
- Ministry of Environment. (2017). *Podręcznik adaptacji dla miast. Wytyczne do przygotowania miejskiego planu adaptacji do zmian klimatu*. http://projektymiejskie.pl/wpcontent/uploads/2021/09/podrecznik_adaptacji_dla_miast_20191126.pdf
- Ministry of Health. (2024). *Rejestr uzdrowisk*. <https://www.gov.pl/web/zdrowie/rejestr-uzdrowisk-i-obszarow-ochrony-uzdrowiskowej-wraz-z-kierunkami-leczniczymi>
- Municipality of Kamień Pomorski. (2018). *Operat uzdrowiska Kamień Pomorski*. Unpublished manuscript.
- Municipality of Kołobrzeg. (2021). *Strategia Smart City miasta Kołobrzeg*. <https://bip.um.kolobrzeg.pl/api/files/117528>
- Municipality of Kołobrzeg. (2023). *Operat uzdrowiska Kołobrzeg*. Unpublished manuscript.

- Municipality of Sopot. (2020). *Operat uzdrawiska Sopot*. Unpublished manuscript.
- Municipality of Świnoujście. (2023). *Operat uzdrawiska Świnoujście*. https://www.swinoujscie.pl/uploads/files/1/Operat_Uzdrawiskowy_Swinoujscie_listopad_2023_do_druku.pdf
- Municipality of Ustka. (2008). *Operat uzdrawiska Ustka*. https://www.ustka.pl/uploads/files/RIE/1_O_Operat.pdf
- Munkes, B., Löptien, U., & Dietze, H. (2021). Cyanobacteria blooms in the Baltic Sea: A review of models and facts. *Biogeosciences*, 18(7), 2347–2378. <https://doi.org/10.5194/bg-18-2347-2021>
- National Heritage Institute. (2024). *Map*. <https://zabytek.pl/en/mapa?setlang=1>
- Nelson, D. R., Adger, W. N., & Brown, K. (2007). Adaptation to environmental change: Contributions of a resilience framework. *Annual Review of Environment and Resources*, 32(1), 395–419. <https://doi.org/10.1146/annurev.energy.32.051807.090348>
- Neumann, T. (2010). Climate-change effects on the Baltic Sea ecosystem: A model study. *Journal of Marine Systems*, 81(3), 213–224.
- Obszar Metropolitalny Gdańsk-Gdynia-Sopot. (2024, July 27). *Więcej mieszkańców w OMGGs*. <https://www.metropoliagdansk.pl/metropolitalne-wiadomosci/wiecej-mieszkancow-w-omggs>
- Państwowe Gospodarstwo Wodne Wody Polskie. (2018). *Raport z przeglądu i aktualizacji wstępnej oceny ryzyka powodziowego*. https://powodz.gov.pl/powodz/aWORP/ostateczna%20wersja/RAPORT_WORP.pdf
- Pencakowska, W. (1978). *Zdrowska: Kształtowanie struktury przestrzennej w koncepcji zespołów rekreacyjnych*. Politechnika Krakowska.
- Polish Geological Institute – National Research Institute. (2024). *The HYDRO Bank*. <https://spd.pgi.gov.pl/PSH/Psh.html?locale=en>
- Rosselló-Nadal, J. (2014). How to evaluate the effects of climate change on tourism. *Tourism Management*, 42, 334–340. <https://doi.org/10.1016/j.tourman.2013.11.006>
- Rutgersson, A., Kjellström, E., Haapala, J., Stendel, M., Danilovich, I., Drews, M., Jylhä, K., Kujala, P., Larsén, X. G., Halsnæs, K., Lehtonen, I., Luomaranta, A., Nilsson, E., Olsson, T., Särkkä, J., Tuomi, L., . . . Wasmund, N. (2021). Natural hazards and extreme events in the Baltic Sea region. *Earth System Dynamics Discussions*, 2021, 1–80. <https://doi.org/10.5194/esd-13-251-2022>
- Sejm of the Republic of Poland. (2005). *Ustawa z dnia 28 lipca 2005 r. o lecznictwie uzdrowiskowym, uzdrowiskach i obszarach ochrony uzdrowiskowej oraz gminach uzdrowiskowych* (Dz. U. z 2024 r. poz. 1420, 1572). <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20051671399/U/D20051399Lj.pdf>
- Sejm of the Republic of Poland. (2007). *Ustawa z dnia 26 kwietnia 2007 r. o zarządzaniu kryzysowym* (Dz. U. 2007 nr 89 poz. 590). <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20070890590/U/D20070590Lj.pdf>
- Sejm of the Republic of Poland. (2017). *Ustawa z dnia 20 lipca 2017 r. Prawo wodne* (Dz. U. 2017 poz. 1566). <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20170001566/U/D20171566Lj.pdf>
- Sejm of the Republic of Poland. (2024). *Ustawa z dnia 27 listopada 2024 r. o zmianie ustawy–Prawo ochrony środowiska oraz niektórych innych ustaw* (Dz. U. 2024 poz. 1940). <https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20240001940/T/D20241940L.pdf>
- Smith, M., & Puczkó, L. (2015). More than a special interest: Defining and determining the demand for health tourism. *Tourism Recreation Research*, 40(2), 205–219. <https://doi.org/10.1080/02508281.2015.1045364>
- Soomere, T. (2024). *Climate change and coastal processes in the Baltic Sea*. Oxford Research Encyclopedias. <https://doi.org/10.1093/acrefore/9780190228620.013.897>
- Stankiewicz, J., & Szermer, B. (1959). *Gdańsk: Rozwój urbanistyczny i architektoniczny oraz powstanie zespołu; Gdańsk, Sopot, Gdynia*. Arkady.

- Stępiński, W. (1975). *Kamień Pomorski w XII i XIII wieku* (Vol. 26). Państwowe Wydawnictwo Naukowe.
- Styszyńska, A., Krośnicka, K., & Marsz, A. A. (2018). Contemporary climate changes and their impact on functioning of urban systems (on the example of Polish coastal zone). *Studia KPZK*, 187, 51–80. http://psjd.icm.edu.pl/psjd/element/bwmeta1.element.oai-journals-pan-pl-110309/c/oai-journals-pan-pl-110309_full-text_06_20Styczy_C5_84ska__20Kro_C5_9Bnicka_20-_20Studia_20187.pdf-1
- Szymańska, W., & Wiśniewska, A. (2022). Socio-economic development of coastal health resort communes in Poland. *Journal of Geography, Politics and Society*, 12(2), 51–72. <https://doi.org/10.26881/jpgs.2022.2.06>
- Tomczyk, A. M., & Bednorz, E. (2022). *Atlas klimatu Polski (1991–2020)*. Bogucki Wydawnictwo Naukowe.
- Urbas, M. (2023, July 3–5). *Badanie zakładów lecznictwa uzdrowiskowego—Aktualny stan w kontekście zmian demograficzno-ekonomicznych* [Paper presentation]. MET2023, Warszawa, Poland.
- Venter, Z. S., Barton, D. N., Gundersen, V., Figari, H., & Nowell, M. S. (2021). Back to nature: Norwegians sustain increased recreational use of urban green space months after the Covid-19 outbreak. *Landscape and Urban Planning*, 214, Article 104175. <https://doi.org/10.1016/j.landurbplan.2021.104175>
- Walker, B., Holling, C. S., Carpenter, S. R., & Kinzig, A. (2004). Resilience, adaptability and transformability in social–ecological systems. *Ecology and Society*, 9(2), Article 5. <http://www.ecologyandsociety.org/vol9/iss2/art5>
- Walker, B., & Salt, D. (2012). *Resilience thinking: Sustaining ecosystems and people in a changing world*. Island Press.
- Wang, R., Helbich, M., Yao, Y., Zhang, J., Liu, P., Yuan, Y., & Liu, Y. (2019). Urban greenery and mental wellbeing in adults: Cross-sectional mediation analyses on multiple pathways across different greenery measures. *Environmental Research*, 176, Article 108535. <https://doi.org/10.1016/j.envres.2019.108535>
- Węclawowicz-Bilska, E. (2008). *Uzdrowiska polskie: Zagadnienia programowo-przestrzenne*. Politechnika Krakowska im. Tadeusza Kościuszki.
- Węclawowicz-Bilska, E. (2021). *Uzdrowiska, kąpieliska termalne i ośrodki spa*. Politechnika Krakowska im. Tadeusza Kościuszki.
- Wirszyc-Sitkowska, K., & Krawczyk, S. (2019). Surowce w leczeniu uzdrowiskowym—Nadzór nad ich wykorzystywaniem i wykonywaniem zabiegów. *Kontrola Państwowa*, 64(4), 99–109.
- Wirszyc-Sitkowska, K., & Mędrzak, B. (2017). Uzdrowiska muszą bronić statusu—konieczne zmiany w systemie lecznictwa. *Kontrola Państwowa*, 62(6), 68–81.
- Wong, N. H., Tan, C. L., Kolokotsa, D. D., & Takebayashi, H. (2021). Greenery as a mitigation and adaptation strategy to urban heat. *Nature Reviews Earth & Environment*, 2(3), 166–181. <https://doi.org/10.1038/s43017-020-00129-5>
- Xie, Y., Ishida, Y., Watanabe, H., & Mochida, A. (2023). Impacts of urban development between 2002 and 2022 on the effects of sea breezes in Sendai, Japan—Analyzing heat balance mechanism in urban space. *Atmosphere*, 14(4), Article 677. <https://doi.org/10.3390/atmos14040677>
- Yonov, I. (2024). Observations about tourism trends in Europe—From West to East. *KNOWLEDGE—International Journal*, 63(1), 47–50.
- Zscheischler, J., Westra, S., Van Den Hurk, B. J., Seneviratne, S. I., Ward, P. J., Pitman, A., AghaKouchak, A., Bresch, D. N., Leonard, M., Wahl, T., & Zhang, X. (2018). Future climate risk from compound events. *Nature Climate Change*, 8(6), 469–477. <https://doi.org/10.1038/s41558-018-0156-3>

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