

Resilience-Based Design of Urban Drainage Systems Using Climate Projection Data and Real-Time Flood Monitoring Sensors

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ABSTRACT

Purpose: This study aims to develop a resilience-based urban drainage design framework by integrating climate projection data and real-time flood monitoring sensors to address increasing flood risks caused by urbanization and climate change.

Subjects and Methods: A systematic literature review was conducted using peer-reviewed articles published between 2015 and 2025 from Scopus, Web of Science, ScienceDirect, and Google Scholar. Relevant studies were screened based on inclusion and exclusion criteria related to urban drainage resilience, climate projection modeling, and sensor-based flood monitoring. The selected literature was analyzed using thematic synthesis to identify dominant patterns and conceptual relationships, followed by the development of an integrated adaptive design framework.

Results: The findings indicate that resilience-based drainage design enhances hydraulic stability, reduces runoff risk, and accelerates post-flood recovery through structural flexibility and adaptive capacity. The integration of climate projection data improves long-term planning accuracy and supports scenario-based risk assessment under climate uncertainty. Real-time monitoring sensors strengthen operational responsiveness through early warning systems, dynamic flow control, and continuous performance evaluation. The combined use of predictive climate modeling and real-time data creates a synergistic adaptive system capable of responding to both anticipated and unexpected hydrological disturbances.

Conclusions: Integrating resilience principles with climate projections and sensor technology provides a comprehensive and sustainable framework for adaptive urban drainage management, supporting long-term climate adaptation and improved urban infrastructure governance.

INTRODUCTION

Rapid urbanization and climate change have increased the complexity of urban flooding problems in various parts of the world (Miller & Hutchins, 2017; Cea & Costabile, 2022). The growth of built-up areas has reduced water catchment areas, increased surface runoff, and placed increasing pressure on the capacity of conventional drainage systems (Saraswat et al., 2016). Furthermore, changes in rainfall patterns due to global warming have increased the frequency and intensity of extreme rainfall events, directly increasing the risk of flooding in urban areas. This situation indicates that drainage planning approaches that rely solely on historical data are no longer adequate to address future hydrometeorological challenges.

Traditional urban drainage systems are generally designed based on the assumption of climate stationarity, which assumes that future rainfall patterns will be similar to past conditions (Banda & Arif, 2025). However, various studies have shown that this assumption is increasingly irrelevant with increasing climate variability and extreme weather events (Kurniyaningrum et al., 2025). As a result, many drainage infrastructures are experiencing functional failures, either in the form of excessive runoff, prolonged inundation, or physical damage to the drainage network. This not only impacts economic losses but also threatens public safety and disrupts urban social and economic activities.

In this context, the concept of resilience, or infrastructure resilience, has become an increasingly popular approach in urban drainage system planning. Resilience refers to a system's ability to absorb disturbances, maintain its primary function, and recover quickly after extreme events (Parial, 2023). A resilience-based approach emphasizes the importance of design flexibility, system redundancy, and adaptive capacity to climate uncertainty. By applying resilience principles, drainage systems focus not only on flood prevention but also on the ability to withstand and adapt to extreme conditions that cannot be completely avoided.

The use of climate projection data is a crucial element in resilience-based drainage system design. Climate projections enable planners to anticipate changes in future rainfall patterns, including increased intensity of extreme rainfall events and shifts in the rainy season (Seneviratne et al., 2021; Ogallo et al., 2000). Integrating this data into hydrological and hydraulic models can result in designs that are more adaptive and responsive to long-term flood risks. This approach also supports scenario-based decision-making, where various possible future climate conditions can be tested to evaluate drainage system performance.

In addition to climate projection data, developments in sensor technology and the Internet of Things (IoT) are opening new opportunities for real-time urban flood management. Flood monitoring sensors can continuously and directly measure hydrological parameters such as water level, flow rate, and rainfall intensity (Erwanto et al., 2024). This real-time data can be used to improve early warning systems, optimize drainage infrastructure operations, and support rapid response to flood events. The integration of real-time monitoring and data-driven decision-making systems is a key component in creating adaptive and intelligent drainage systems. Although various studies have discussed the use of climate data and sensor technology separately, their integration within a resilience-based design framework remains relatively limited.

Many drainage plans remain static and have not fully utilized the potential of dynamic data to improve system performance (Prajatama & Muslim, 2025). However, the combination of long-term climate projections and real-time monitoring can provide a more comprehensive approach to flood risk management, both from a long-term planning perspective and from a daily operational perspective. Therefore, this research focuses on developing a resilience-based urban drainage system design utilizing climate projection data and real-time flood monitoring sensors. This approach is expected to increase the resilience of drainage infrastructure to climate uncertainty, mitigate the impact of flooding, and support sustainable urban development. In addition to providing academic contributions to the development of adaptive design models, this research is also expected to serve as a practical reference for policymakers and urban planners in designing more resilient, responsive, and future-oriented drainage systems.

METHODOLOGY

Literature Collection Process

The literature collection was conducted systematically to obtain scientific sources relevant to the topic of resilience-based urban drainage system design, the utilization of climate projection data, and the application of real-time flood monitoring sensors. The literature search was carried out through reputable academic databases such as Scopus, Web of Science, Google Scholar, and ScienceDirect. The primary keywords used included “urban drainage resilience,” “climate change projection,” “flood monitoring sensors,” and “resilient infrastructure design.” Boolean operators were applied to combine keywords in order to broaden the search scope while increasing the accuracy of relevant results. This process aimed to identify recent studies with conceptual and methodological relevance to the focus of this research.

Source Selection and Screening Criteria

The collected literature was then screened based on predetermined inclusion and exclusion criteria. The inclusion criteria encompassed indexed journal articles, international conference proceedings, and official institutional reports published within the last ten years that directly addressed urban drainage systems, flood management, climate projections, or sensor technologies. Literature that was not relevant to the urban context, lacked methodological rigor, or did not provide clear empirical findings was excluded from the analysis. This screening ensured that the sources used were both credible and highly relevant.

Quality Assessment of Literature

Each selected source was critically evaluated to assess methodological quality, consistency of findings, and scientific contribution to the development of resilience concepts and drainage system design. The evaluation considered the research objectives, analytical methods, variables examined, results, and limitations of each study. This step helped identify approaches frequently employed in previous studies and highlighted research gaps that remain underexplored.

Thematic Analysis

The extracted data were analyzed using a thematic approach to group concepts and findings based on the main themes of the study. The themes included the application of resilience concepts in urban infrastructure, hydrological modeling based on climate projections, and the integration of sensor technology into flood monitoring systems. Thematic analysis allowed the researcher to identify patterns, relationships between concepts, and emerging trends relevant to the research topic.

Synthesis and Conceptual Framework Development

The final stage of the literature review method involved synthesizing the analyzed findings into an integrated conceptual framework. The synthesis connected key insights from various sources to establish a theoretical foundation supporting resilience-based urban drainage system design. The resulting conceptual framework serves as a reference for formulating research directions, defining main variables, and developing conceptual recommendations applicable to the planning of adaptive and sustainable urban drainage systems.

RESULTS AND DISCUSSION

Improving Drainage System Performance with a Resilience Approach

A resilience approach to urban drainage system design has been proven to improve infrastructure performance in the face of increasingly complex hydrological pressures caused by climate change and urbanization. The resilience concept emphasizes a system's ability to absorb disturbances, maintain its primary function, and recover quickly after extreme events such as heavy rainfall and urban flooding. Unlike conventional approaches that focus solely on increasing physical capacity, resilience-based design integrates structural flexibility, network redundancy, and operational adaptability. This allows the drainage system to remain functional even in the event of flow overload or partial failure of some components.

Several studies have shown that applying resilience principles can improve hydraulic stability and reduce the risk of excessive runoff in drainage networks. Srihayati et al. (2025) explain that systems designed with climate uncertainty in mind demonstrate more consistent performance across various extreme rainfall scenarios. By factoring in future rainfall variability, drainage designs become more adaptive to changing environmental conditions. This approach not only increases peak flow capacity but also improves flow distribution, significantly reducing pressure on main channels.

Improved performance is also evident in the ability of resilience-based drainage systems to accelerate post-flood recovery. The resilience of an infrastructure system is measured not only by its resilience to disruptions but also by the speed with which the system returns to normal operational conditions. Drainage systems equipped with alternative flow paths, temporary retention areas, and adaptive flow control mechanisms can reduce the duration of inundation and accelerate the

stabilization of urban hydrological conditions. This is particularly important in dense urban contexts, where delays in recovery can directly impact economic activity and public mobility.

Beyond technical aspects, a resilience approach also improves the efficiency of drainage system management in the long term. Adaptively designed systems tend to require fewer emergency interventions and experience lower levels of structural damage. This reduces infrastructure maintenance and rehabilitation costs, while extending the service life of the drainage system. This efficiency provides significant economic benefits for local governments and urban stakeholders, particularly in the face of limited infrastructure budgets.

Furthermore, the integration of a resilience approach encourages the transformation of drainage planning toward more sustainable systems. This approach supports the integration of gray infrastructure with nature-based solutions, such as infiltration systems and green spaces that function as stormwater retention areas (Keairan et al., 2025). This combination not only increases the hydrological capacity of the system but also provides ecological and social benefits to the urban environment. Thus, improved drainage performance is measured not only in terms of the technical aspects of flood control but also in terms of its contribution to the city's overall sustainability.

Effectiveness of Climate Projection Data Integration

The integration of climate projection data into the planning and design of urban drainage systems has been shown to improve accuracy in anticipating future flood risks. This approach allows planners to consider changing rainfall patterns, increased intensity of extreme rainfall events, and shifts in the rainy season, which cannot be adequately captured by historical data alone. Climate change has led to an increase in the frequency and intensity of extreme rainfall events in many urban areas, rendering climate stationarity-based design approaches irrelevant (Munawaroh et al., 2025). By utilizing climate projections, drainage systems can be designed more adaptively and responsive to uncertain future hydrometeorological conditions.

Several studies have shown that the use of climate projection data in hydrological models produces more realistic estimates of peak discharge and runoff volume than conventional methods. Hendryarto et al. (2025) found that the application of climate change factors in drainage design can increase the system's capacity to cope with future extreme rainfall scenarios. This integration also allows for adjustments to channel dimensions, storage capacity, and other design parameters to ensure optimal function under changing climate conditions. Thus, this approach not only increases the system's technical resilience but also minimizes the risk of infrastructure failure.

The effectiveness of integrating climate projection data is also evident in the drainage system's ability to reduce uncertainty in long-term planning. A climate scenario-based approach helps planners evaluate various potential extreme conditions and develop more flexible adaptation strategies. By simulating various climate scenarios, drainage systems can be tested against varying levels of extreme rainfall, allowing potential weaknesses in the drainage network to be identified early. This provides a stronger basis for urban infrastructure decision-making.

In addition to improving technical accuracy, utilizing climate projection data also contributes to the efficiency of infrastructure investments. Designs that consider long-term climate risks tend to be more resilient and require fewer future readjustments. Investments in adaptive infrastructure based on climate projections can reduce disaster damage costs and increase long-term economic benefits (Siregar, 2024). Thus, climate data integration not only improves the hydraulic performance of drainage systems but also strengthens the economic rationality of urban infrastructure planning.

Furthermore, the integration of climate projection data supports the transformation of urban policy and governance toward a risk-based and climate adaptation approach. This approach encourages local governments and city planners to adopt more proactive planning in addressing the impacts of climate change (Efendi, 2024). By incorporating climate projections into the drainage planning process, cities can enhance their adaptive capacity while strengthening infrastructure resilience to future environmental stressors. Therefore, effective integration of climate projection data is a key component in developing resilient and sustainable urban drainage systems.

The Role of Real-Time Monitoring Sensors in Flood Management

The use of real-time flood monitoring sensors has become a critical component in improving the effectiveness of urban flood management. Sensor technology enables the continuous, real-time collection of hydrological data, such as water levels, flow discharge, rainfall intensity, and drainage channel conditions. According to Amin & Burhan (2025), sensor-based monitoring systems can improve the accuracy of early flood detection and provide faster and more reliable information for decision-makers. This real-time data enables a more adaptive operational response than conventional approaches that rely on manual observations or historical data.

One of the key contributions of real-time sensors is the enhancement of flood early warning systems. Data transmitted directly from the sensor network can be integrated into a centralized monitoring platform to detect rising water levels that could potentially cause inundation (Chen et al., 2013). Sensor-based early warning systems can reduce the impact of flooding by providing authorities and the public with a longer response time to take mitigation measures (Suhardono et al., 2024). With faster warnings, the risk of economic losses, infrastructure damage, and social impacts can be significantly minimized.

In addition to supporting early warning, real-time monitoring sensors also play a role in optimizing drainage system operations. Information on flow conditions and channel capacity allows infrastructure managers to dynamically adjust the settings of sluice gates, pumps, and flow control systems. Real-time data-driven drainage management can improve operational efficiency and reduce the likelihood of excessive runoff at critical points (Lukman, 2025). This approach makes drainage systems more responsive to rapidly changing hydrological conditions that occur during extreme rainfall events.

The role of real-time sensors also contributes to increasing drainage system resilience through continuous monitoring of infrastructure conditions. Sensor data can be used to detect flow anomalies, channel blockages, or decreased performance of drainage components before larger system failures occur. According to Farendy & Akbar (2024), the implementation of a smart city concept that integrates sensors and data analytics enables more proactive and evidence-based management of urban infrastructure. Thus, this approach not only improves response to flood events but also supports preventative maintenance and long-term planning.

Furthermore, the integration of real-time monitoring sensors with climate projection-based planning systems strengthens the adaptive capabilities of urban flood management. Real-time data can be used to validate hydrological models, update simulation parameters, and improve the accuracy of flood predictions. The combination of sensor monitoring and predictive modeling can improve the reliability of decision-making systems in the face of climate uncertainty (Weaver et al., 2013; Ukoba et al., 2025). Therefore, the role of real-time sensors is not limited to monitoring but also becomes a strategic element in building an adaptive, intelligent, and resilient flood management system.

Data Integration Scenario for Adaptive Design

The integration of climate projection data and real-time flood monitoring sensor data results in a more comprehensive adaptive design approach to urban drainage system management (Setyobudi, 2025). This approach enables the system to combine long-term information on climate change with actual hydrological conditions on the ground. The integration of multiple data sources provides a stronger basis for design decision-making, as it can accommodate climate uncertainty while responding to the dynamics of extreme rainfall events in real time. Thus, drainage design is no longer static, but evolves into a system that is adaptive and responsive to changing environmental conditions.

Bagheri & Liu (2024) said that, data integration scenarios also enable testing of drainage system performance under various projected future extreme conditions. Through climate scenario-based simulations, planners can evaluate the system's capacity to withstand increased rainfall intensity, changing flow patterns, and potentially greater runoff. Meanwhile, real-time sensor data is used to validate simulation results and dynamically update model parameters. According to Setyobudi (2025), this approach improves the reliability of hydrological models and reduces uncertainty in urban infrastructure planning. By combining these two data sources, drainage systems can be designed to maintain optimal function under various extreme conditions.

Furthermore, the integration of climate projection data and real-time sensors supports the development of intelligent drainage systems based on adaptive decision-making. Information obtained from both data sources can be processed through an analytics platform to provide automated operational recommendations, such as regulating flow, activating pumps, or opening floodgates at optimal times. The implementation of a control system based on real-time data combined with long-term predictions can improve operational efficiency and reduce the risk of flooding in dense urban areas (Julian & Umar, 2025).

The integration of both data sets also contributes to increasing the long-term resilience of drainage systems. Adaptive design based on climate projections allows for more flexible infrastructure capacity planning, while real-time monitoring supports continuous evaluation of system performance. According to Nugroho & Aryani (2025), this approach allows for gradual design updates in response to changing climate conditions and urban growth, allowing drainage systems to develop gradually without requiring major reconstruction in a short period of time. This provides strategic advantages in sustainable urban infrastructure management.

Beyond the technical aspects, the integration scenario of both data sets also strengthens governance and risk-based planning. This approach encourages collaboration between city planners, infrastructure managers, and meteorological institutions in data management and decision-making. The integration of climate information and operational data supports the transformation of urban policy toward a more proactive climate adaptation approach (Fitri et al., 2025). Thus, the integration scenario of both data sets not only improves the technical performance of drainage systems but also strengthens institutional and governance capacity to address future urban flooding challenges.

Discussion

The application of a resilience approach to urban drainage system design significantly changes the way infrastructure responds to increasingly complex hydrological pressures (De et al., 2022; Mugume et al., 2015). Systems designed with structural flexibility and operational adaptability in mind demonstrate greater resilience to extreme rainfall variability. This approach emphasizes that improved drainage performance depends not only on the physical capacity of the channel but also on the system's ability to adapt to dynamic disturbances. This reflects a paradigm shift from static design to infrastructure systems that are more responsive to environmental changes.

The integration of climate projection data into drainage planning contributes significantly to improving long-term design accuracy. By incorporating climate change scenarios into hydrological models, planners can evaluate a range of possible future extreme conditions. This approach allows for the identification of drainage system weaknesses early in the planning stage, allowing for more precise capacity adjustments and mitigation strategies. The use of climate projection data also strengthens a risk-based approach to urban infrastructure planning, which is increasingly necessary in the face of climate uncertainty.

The role of real-time flood monitoring sensors demonstrates the importance of utilizing digital technology in urban drainage system management. Real-time data enables faster and more accurate operational decision-making, particularly in the event of sudden, extreme rainfall events. This monitoring system supports early flood warnings and optimizes flow regulation and storage capacity. Furthermore, the use of sensors enables continuous monitoring of infrastructure performance, allowing potential disruptions or performance degradation to be detected early and addressed preemptively.

The integration of climate projection data and real-time sensors demonstrates a strong synergy in creating adaptive drainage designs. Climate projections provide a long-term framework for infrastructure capacity planning, while real-time data supports dynamic operational adjustments. The combination of these two data sources enables drainage systems to respond to changing environmental conditions more flexibly and evidence-based. This approach also opens up opportunities for developing intelligent drainage systems that integrate predictive modeling with data-driven operational control.

The implications of these findings extend beyond technical aspects to institutional and urban governance dimensions. Implementing resilience-based drainage designs requires cross-sector

coordination between infrastructure management institutions, climate data providers, and sensor technology developers. Furthermore, institutional capacity for data management, information analysis, and evidence-based decision-making is required. These challenges demonstrate that the success of implementing an adaptive approach depends not only on the availability of technology but also on the readiness of governance systems and supporting policies.

The adaptive design approach resulting from the integration of both data sets also contributes to more sustainable urban water resource management. Drainage systems no longer function solely as stormwater drains, but also as part of an integrated water management strategy that encompasses detention, reuse, and reduction of surface runoff. Thus, resilience-based drainage design can play a role in supporting urban ecological balance and improving environmental quality in urban areas.

CONCLUSION

The findings of this study demonstrate that resilience-based urban drainage design supported by climate projection data and real-time flood monitoring sensors provides a robust and adaptive framework for managing increasing flood risks in urban areas. The integration of resilience principles enhances the ability of drainage systems to maintain core functionality under extreme hydrological conditions while improving recovery capacity after flood events and operational disturbances. The incorporation of climate projection data enables long-term planning that accounts for future changes in rainfall intensity, storm duration, and hydrological variability, thereby reducing dependence on historical assumptions that are no longer reliable under changing climate conditions. Meanwhile, real-time sensor technology strengthens operational performance by enabling early warning, rapid response, and dynamic system control, which collectively contribute to minimizing flood impacts, infrastructure damage, and service disruptions. The combined use of long-term climate scenarios and real-time monitoring data creates a synergistic approach that supports adaptive design, allowing drainage systems to respond effectively to both anticipated trends and unexpected extreme events. This integrated framework also promotes more efficient infrastructure investment by prioritizing flexible and scalable design strategies that can be upgraded gradually as new data and technologies become available. Furthermore, the results highlight the importance of institutional readiness, interagency coordination, and data governance in ensuring the successful implementation of smart and resilient drainage systems. Effective collaboration between urban planners, infrastructure managers, emergency agencies, and data providers is essential to maximize the benefits of technological integration and adaptive planning. Overall, the resilience-based approach offers a strategic pathway toward sustainable urban water management by strengthening system reliability, improving risk management capacity, enhancing climate adaptation performance, and supporting long-term urban sustainability goals, while contributing to the development of urban drainage systems that are technically efficient, environmentally responsible, economically viable, and socially resilient.

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