NEURAL NETWORKS FOR URBAN FLOOD PREDICTION: ENHANCING SMART CITY PLANNING AND DISASTER MITIGATION

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Abstract. *Urban floods bring social, economic, and environmental challenges, especially in cities that have grown rapidly. This study compares how Barcelona, Singapore, and Curitiba apply smart city technologies to predict and mitigate floods. Neural networks such as LSTM and CNN were analyzed, integrated with sensor, satellite, and environmental monitoring data, assessing their effectiveness when combined with urban planning and green solutions. While Barcelona monitors irregularities in real time through cameras with artificial intelligence; Singapore combines convolutional neural networks with rain gardens and other natural alternatives; and Curitiba uses an LSTM model capable of identifying complex hydrological patterns even with limited historical data. Analyzing these scenarios demonstrates that aspects such as data quality, integration with urban infrastructure, and adaptation to local conditions are fully connected to the efficiency of predictions. The results indicate that combining nature-based solutions and predictive technology allows for a reduction in population vulnerability, especially in risk areas, and supports public policies by providing evidence. The lessons from these international experiences offer valuable input for Brazilian cities that wish to implement similar flood management strategies.*

Keywords: Smart Cities, Urban Floods, Artificial Intelligence, LSTM, Flood Mitigation

Introduction

Urbanization in Brazil results from a long process of growth in urban centers, accelerated particularly in the 20th century through industrialization and the modernization of rural activities. Agricultural mechanization reduced the demand for labor, driving migration and rapid expansion of cities and metropolises. Much of this growth occurred in a disorderly manner, often without proper planning, leading to the occupation of areas naturally prone to flooding and placing populations at risk. Floods not only cause significant material damage but also exacerbate social and economic inequalities in affected regions. Therefore, urban management strategies must consider infrastructure, territorial organization, and environmental factors. In this context, tools that anticipate risks and support effective public policies are essential, paving the way for innovative solutions based on technology and data analysis, such as smart cities. This study presents a comparative analysis of Barcelona, Singapore, and Curitiba, cities representing different stages of smart city development, to examine how they apply artificial intelligence and neural networks to mitigate urban flood impacts.

Floods disproportionately affect vulnerable populations, who often occupy high-risk areas, causing disruptions to public services, housing damage, and increased exposure to waterborne diseases (Maricato, 2011). Economically, they generate significant costs due to transportation interruptions, losses in local commerce, and decreased urban productivity (He et al., 2021). Environmentally, changes in precipitation patterns associated with climate change make extreme events more frequent and less predictable, heightening hydrological risks in urban basins (IPCC, 2022).

Barcelona, Singapore, and Curitiba were selected as case studies due to their representation of distinct yet complementary models of intelligent urban development. Barcelona excels in integrating urban planning with digital infrastructure, Singapore is a global reference in data-driven predictive management, and Curitiba illustrates the Brazilian context, characterized by sustainable innovation and typical infrastructure challenges of developing countries. Given these complex urban challenges, smart cities offer a strategic alternative to improve resilience and reduce urban risks.

The smart city concept involves collecting large volumes of sensor data, processed through artificial intelligence to monitor, predict, and provide real-time alerts on urban risks, thereby supporting informed governmental decision-making.

Neural networks are promising tools for monitoring large areas and anticipating flood events, supporting public services in protecting populations and mitigating disasters. Recurrent neural networks, especially LSTM and GRU[1] architectures, are particularly effective at identifying complex patterns and nonlinear dependencies in time series, which are essential for hydrological predictions using diverse data sources.

Traditional hydrological and statistical models, such as linear regression and ARIMA[2], have long been used for flood forecasting. While useful, they struggle to capture nonlinear dynamics and the complex interactions among multiple meteorological and hydrological variables (Mosavi, Ozturk & Chau, 2018). In Brazil, irregular and limited high-quality historical data further constrain the reliability of these models in local contexts.

Predictive models alone are insufficient. Accurate forecasts require sensor networks, up-to-date meteorological data, and reliable geospatial information. Integrating these technologies yields more robust results, offering public managers practical support for preventive action. By comparing international smart city approaches, this study aims to identify replicable practices to guide the development of public policies and neural network–based forecasting systems in Brazilian urban contexts.

This article presents a comparative study on the practical applications of neural networks in flood management. By examining Barcelona, Singapore, and Curitiba, it seeks to identify an approach that balances forecasting efficiency with the structural, social, and economic impacts of implementation.

Objectives

The main objective of this article is to analyze and compare the application of smart city technologies in Barcelona, Singapore, and Curitiba, focusing on the use of neural networks for predicting and mitigating urban floods. It seeks to identify replicable practices adaptable to the Brazilian context. The study investigates how each city uses urban and environmental data in intelligent monitoring systems, evaluates neural networks—particularly LSTM and GRU models—in flood forecasting, and compares the effectiveness of public policies and infrastructures. It also identifies challenges and opportunities in implementing these technologies across different socioeconomic and environmental contexts, ultimately suggesting recommendations for adapting strategies to the Brazilian urban environment.

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[1] GRU (Gated Recurrent Unit) and LSTM (Long Short-Term Memory) are types of recurrent neural networks designed to capture long-term dependencies in sequential data, making them especially suitable for time-series forecasting such as hydrological modeling.

[2] Linear regression and ARIMA (AutoRegressive Integrated Moving Average) are traditional statistical methods used for forecasting time-series data, with ARIMA being particularly suited for modeling temporal dependencies and trends.

Development

This study conducts a comparative analysis of the implementation of smart city technologies aimed at predicting and mitigating urban floods in Barcelona (Spain), Singapore, and Curitiba (Brazil). The selection of these cities reflects diverse urban contexts and stages of technological development, as well as social, natural, and economic (infrastructure) factors, allowing the identification of effective practices adaptable to the Brazilian context.

Barcelona: Real-Time Monitoring with Artificial Intelligence

Barcelona has established systems for monitoring and alerting against urban floods, integrated into municipal management. Studies from the RESCCUE project show that the city conducts 1D/2D hydrological modeling and urban resilience assessments, feeding holistic tools for impact analysis and critical services, and enabling predictions in current and future scenarios. These methodologies support the definition of operational thresholds and the activation of emergency plans when critical levels are forecasted (Russo et al., 2020).

The LIFE BAETULO project, developed in partnership with neighboring municipalities such as Badalona, has implemented integrated multi-risk alert systems that combine local sensors, data analysis platforms, and population notification applications. Recent pilot projects have explored artificial intelligence techniques—including computer vision algorithms with cameras—to improve flood forecasting and early detection by identifying abnormal changes in water levels, still in the experimental phase. These solutions operate continuously and represent a consolidated model for flood and other urban climate risk prevention and response in the Barcelona metropolitan area (Climate-Adapt, 2022; Ajuntament de Barcelona, 2025; El País, 2024).

Singapore: Flood Forecasting with Convolutional Neural Networks

Singapore employs an advanced approach to flood prediction and mitigation, utilizing convolutional neural networks (CNNs[3]) to identify critical areas and enhance the accuracy of hydrological forecasts (Li & Stouffs, 2024). The city's abundant urban data, coupled with a well-established technological infrastructure, enables deep learning models to process large volumes of environmental information, improving responsiveness to extreme weather events.

The Active, Beautiful, Clean Waters (ABC Waters) initiative, developed by the Public Utilities Board (PUB), integrates technological and nature-based solutions, such as rain gardens, bioretention areas, and multifunctional reservoirs, reducing surface runoff and improving water quality (PUB, 2022; IGES, 2022). In addition, Singapore maintains an extensive drainage network with over 8,000 km of canals and 17 reservoirs, reinforcing its capacity to handle heavy rainfall (Channel News Asia, 2024).

The integration of AI modeling, hydraulic infrastructure, and ecological solutions positions Singapore as one of the world's most advanced examples of intelligent urban water management, particularly in the context of climate change.

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[3] Convolutional Neural Networks (CNNs) are deep learning models designed to automatically detect spatial patterns and features in grid-like data, such as images or environmental maps, making them useful for tasks like flood prediction.

Curitiba: Application of LSTM Neural Networks for Flood Forecasting

Curitiba faces major challenges in addressing urban floods due to disorderly land occupation, soil impermeabilization, and insufficient drainage infrastructure. To mitigate these impacts, researchers at the Federal University of Technology – Paraná (UTFPR) developed a pioneering project in 2023 using LSTM (Long Short-Term Memory) recurrent neural networks to forecast urban flooding based on satellite data, meteorological reanalyses, and historical rainfall and flow records (Dos Santos & Gomes-Jr, 2025).

Funded by development agencies such as CNPq and CAPES, the system was implemented in critical areas of the Belém and Atuba river basins, where recurrent flooding significantly affects mobility and public health. The LSTM model demonstrated high accuracy in detecting complex spatiotemporal patterns, outperforming traditional regression-based and simple neural network methods.

Designed for future integration with Curitiba's Civil Defense alerts, the system can provide forecasts up to three hours in advance, improving emergency response efficiency. This research highlights the strategic potential of deep learning in building smart and resilient cities, particularly in urban areas with limited drainage infrastructure.

Global Trends in Smart Technologies for Urban Flood Mitigation

The comparative analysis of the three cities highlights complementary approaches to urban flood forecasting. Barcelona stands out for its use of AI-enabled video surveillance cameras for real-time monitoring, enabling rapid responses to extreme weather events (El País, 2024). Singapore combines convolutional neural networks with nature-based solutions, demonstrating effective integration between technology and green infrastructure (Li & Stouffs, 2024). Curitiba applies LSTM neural networks, proving that advanced techniques are feasible even in urban contexts with limited infrastructure (Dos Santos & Gomes-Jr, 2025).

These experiences underscore the importance of integrating technological innovation, urban planning, and environmental sustainability. The development of robust predictive models relies on real-time data availability and supportive policies that foster collaboration among research centers, governments, and technology companies. Additionally, engaging the population through educational programs and participatory systems has proven essential for the success of smart cities in addressing extreme hydrometeorological events.

Results and Discussion

Comparing the use of neural networks in smart cities worldwide is essential to understand how technological strategies adapt to specific social, economic, and environmental contexts. In Barcelona, integrated monitoring and alert systems, such as the LIFE BAETULO project, employ local sensors, hydrological modeling, and artificial intelligence to forecast extreme events and activate preventive responses (Climate-Adapt, 2022; Ajuntament de Barcelona, 2025). In Singapore, convolutional neural networks (CNNs) combined with green infrastructure—such as rain gardens and retention areas—enable more precise forecasts and sustainable mitigation strategies (Li & Stouffs, 2024). In Curitiba, LSTM (Long Short-Term Memory) neural networks analyze satellite and hydrological data, surpassing traditional statistical models even when historical series are incomplete (Dos Santos & Gomes-Jr, 2025). This comparison underscores essential aspects such as forecast accuracy, anticipation capacity, integration with existing urban systems, and the social and economic impacts of the implemented

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solutions.

To facilitate visualization and comparison of the approaches, Table 1 presents the main characteristics, accuracy, and limitations of each city.

Table 1. Comparison of Flood Forecasting Technologies in Barcelona, Singapore, and Curitiba

City	Technology	Accuracy	Integration with infrastructure	Limitations
Barcelona	AI in cameras	High	Moderate	Limited coverage, depends on interpretation
Singapura	CNN + green infrastructure	Very high	High	Requires large volume of data
Curitiba	LSTM	Medium-High	Low	Lack of sensors and incomplete historical series

As shown in Table 1, Singapore demonstrates higher accuracy and integration due to the combination of CNNs with green infrastructure, while Curitiba illustrates that LSTM is applicable even in contexts with limited data, though dependent on the availability of sensors and reliable historical series. Barcelona stands out for real-time monitoring, enabling rapid responses to extreme events, although it is limited in sensor coverage.

Spatial Analysis and Impacts

Beyond technical effectiveness, intelligent systems have significant social and operational impacts. Figure 1 shows the neighborhoods of Curitiba most susceptible to flooding, based on a survey conducted with community participation (Plural, 2023). This visualization highlights that irregular occupation and the lack of adequate infrastructure increase population vulnerability.

In Barcelona, real-time monitoring enables the swift closure of risk areas and immediate signaling, minimizing material and social damage. In Singapore, the integration of CNNs with green infrastructure allows rain gardens and urban reservoirs to absorb part of the stormwater, reducing impacts in densely urbanized areas and preventing disruptions to transportation and local commerce (Li & Stouffs, 2024). Curitiba, despite its limitations, benefits from LSTM by identifying complex patterns in hydrological data, providing actionable information to municipal authorities.

Figure 1. Map of Curitiba neighborhoods most susceptible to flooding (Plural, 2023)
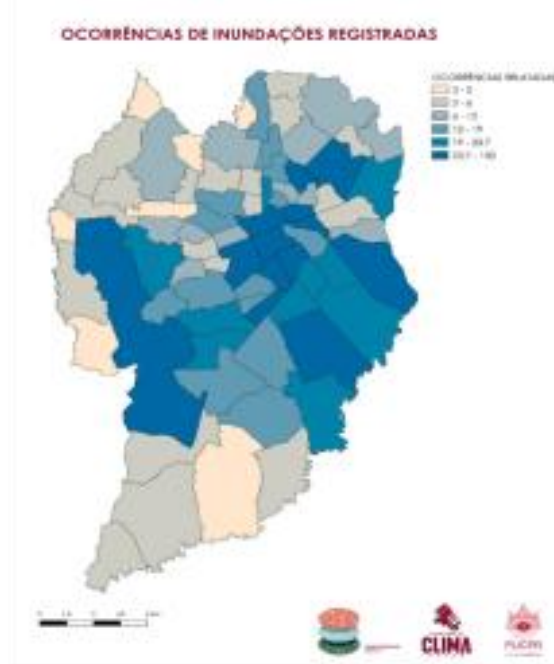
Forecasting and Observation

To evaluate forecast effectiveness, comparative graphs can be constructed between predicted and observed water levels in each city, allowing the measurement of indicators such as accuracy, anticipation capability, and model reliability. In the case of Curitiba, the LSTM-based neural network model outperformed traditional statistical models, especially during high-intensity events. However, significant margins of error were still identified in areas with limited sensor coverage, highlighting the importance of data density and quality for improving forecasts.

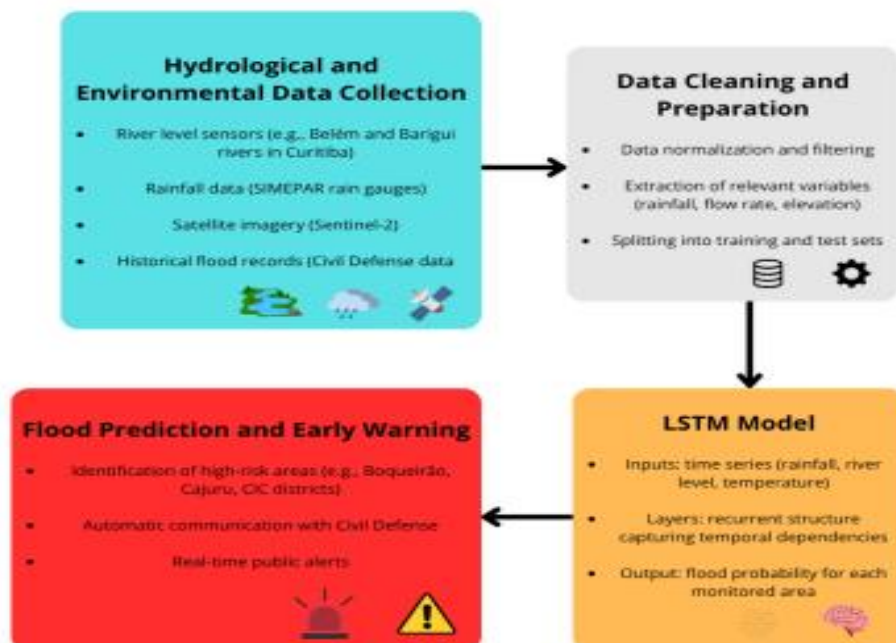Figure 2. Flowchart of the LSTM Model for Flood Forecasting in Curitiba

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Figure 2 illustrates the data flow of the LSTM model, from the collection of hydrological and sensor data, through processing in the neural network, to the issuance of preventive alerts. This integration allows public managers to make proactive decisions, minimizing damage to the population and reducing urban disruptions.

Integration of Technology and Green Infrastructure

Experiences around the world show that the combination of predictive technology with nature-based solutions increases urban resilience. In Singapore, the use of CNNs alongside rain gardens and urban reservoirs demonstrates the synergy between flood forecasting and environmental mitigation (Li & Stouffs, 2024). In Barcelona, real-time information reinforces the effectiveness of preventive measures. In Curitiba, the adoption of LSTM, combined with potential retention areas, could further enhance the effectiveness of preventive actions.

Figure 3. Construction and evolution over time of a green garden in Singapore (Petschek et al., 2024)

Lessons for the Global Context

The study suggests several recommendations for cities worldwide. First, the availability of high-quality data is fundamental; distributed sensors and complete historical series increase the reliability of models. Second, the integration of technology with green infrastructure enhances risk mitigation. Additionally, local aspects must be considered and respected, such as social inequality, economic limitations, and urban occupation patterns. Finally, a combined model of LSTM, strategic sensors, and small retention areas proves to be replicable and effective, contributing to the reduction of structural, social, and economic impacts in medium-sized Brazilian cities.

Conclusion

This comparative study showed that the application of smart city technologies and neural networks in flood forecasting adopts diverse approaches, with varying levels of effectiveness depending on the urban and technological context. In Barcelona, the use of intelligent cameras equipped with artificial intelligence stands out, focused on real-time monitoring of rivers, reservoirs, and tunnels, enabling rapid responses to abnormal changes. In Singapore, the integration of convolutional neural networks (CNNs) with green infrastructure,

such as rain gardens and retention areas, results in highly accurate forecasts and sustainable mitigation solutions. In Curitiba, LSTM networks were applied to the analysis of hydrological data and satellite imagery, showing good performance even with limited sensor coverage and gaps in historical series. From this comparison, it becomes clear that the combination of predictive technologies and nature-based solutions significantly contributes to increasing urban resilience, and that adapting these strategies to the Brazilian context, while taking into account social inequalities, budget constraints, and urbanization patterns, can meaningfully reduce the impacts of floods.

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