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# Urban Pluvial Flood Risk Assessment in Porto: A Multi-Criteria Spatial Analysis Considering Physical and Social Factors

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## Abstract

Urban rainfall flooding represents a growing challenge for cities, especially in the context of climate change. Identifying flood-prone areas is crucial for implementing effective monitoring, mitigation and prevention measures.

This study proposes a methodology for assessing the risk of urban pluvial flooding in the city of Porto, through a multi-criteria spatial analysis, where topographical, infrastructural, demographic and building elements were combined with physical and social factors.

The results make it possible to classify the different areas of the city into four levels of risk: low, medium, high and very high, and to prioritise the zones with the greatest risk, contributing to more efficient management of resources in the mitigation of urban pluvial flooding.

## Highlights

- Development of an urban pluvial flood risk assessment model.
- Identification of the territory at risk of flooding to support decision-making.
- Validation of the model using real data.

## Introduction

Urban rainfall flooding is a growing challenge for cities around the world, driven by factors such as urbanisation and climate change. The intensification of extreme weather events and soil sealing increase the frequency and magnitude of these events, respectively, resulting in socio-economic impacts and risks to the well-being and integrity of citizens (Qi, 2022).

Defining flood risk zones in urban areas, especially for pluvial floods, presents a significant challenge due to data scarcity, including limited historical flood inventories, incomplete information on urban drainage infrastructure, high sensitivity to rainfall data resolution (Ze, 2023) and the complex interaction between surface runoff and sewer network (Cea, 2022). Additionally, traditional physically based models often fail to account for the influence of social factors on flood risk (Qi, 2022), which refers to how different individuals or groups within a community experience, cope with, and recover from flood hazards, even when exposed to the same physical flood magnitude (Qi, 2022).

The literature review identified works where the application of multi-criteria spatial analysis (MCSA), that integrates different physical and social factors, is important for flood risk analysis in a context of incomplete or imperfect data. A study carried out in Wadi Al-Lith, Saudi Arabia (Elsebaie, 2023), using factors such as elevation, slope and rainfall, proved to be effective in identifying floods in watersheds with limited data. In Sanandaj, Iran, the MCSA combined geographical and urban vulnerability factors to produce flash flood risk maps that were consistent with the observed flooded areas (Ahmadi, 2022). In the Serafa river basin in Poland, integrating the Decision-Making Trial and Evaluation Laboratory

(DEMATEL) method with geospatial analysis proved to be useful for identifying flood-prone areas, even with incomplete public data (Natkaniec, 2024).

The municipal company Águas e Energia do Porto (AEDP), which is responsible for managing the rainwater infrastructure, rivers, and streams of the Municipality of Porto, developed this study to understand the risk factors associated with the managed territory, contribute to the monitoring plan and maintenance operations, ensure the protection of the community and promote resilient and sustainable urban development. Identifying areas prone to flooding and understanding the factors that contribute to the risk will help inform the implementation of prevention and mitigation measures and increase their effectiveness.

To assess the risk of urban pluvial flooding in a context of data scarcity and to promote sustainable city management, this study presents a methodology for assessing the risk of urban pluvial flooding, used for the city of Porto, considering both physical and social factors, through a MCSA. The aim is to provide a decision-making tool and risk management map in the context of urban planning and infrastructure management, helping to increase the city's resilience to extreme weather events.

## Methodology

The study focussed on the application of MCSA to the company's existing database and information made available by various public entities, similar to existing literature (Elsebaie, 2023; Natkaniec, 2024; Ahmadi, 2022; Qi, 2022): AEDP data on blocks, streets and drainage infrastructures; digital elevation model and georeferenced information with the typology of the city's buildings from Porto City Council; demographic and building data from Census2021, provided by the National Statistics Institute. In the end, the results were compared with flooding incidents recorded by the Porto Sapper Fire Brigade (BSP) between 2018 and 2023.

The MCSA was used to assess flood risk, considering physical and social factors, where risk was defined according to the physical exposure and social vulnerability of the location (Cea, 2022). QGIS software and its associated resources were used for this purpose.

### Physical Exposure

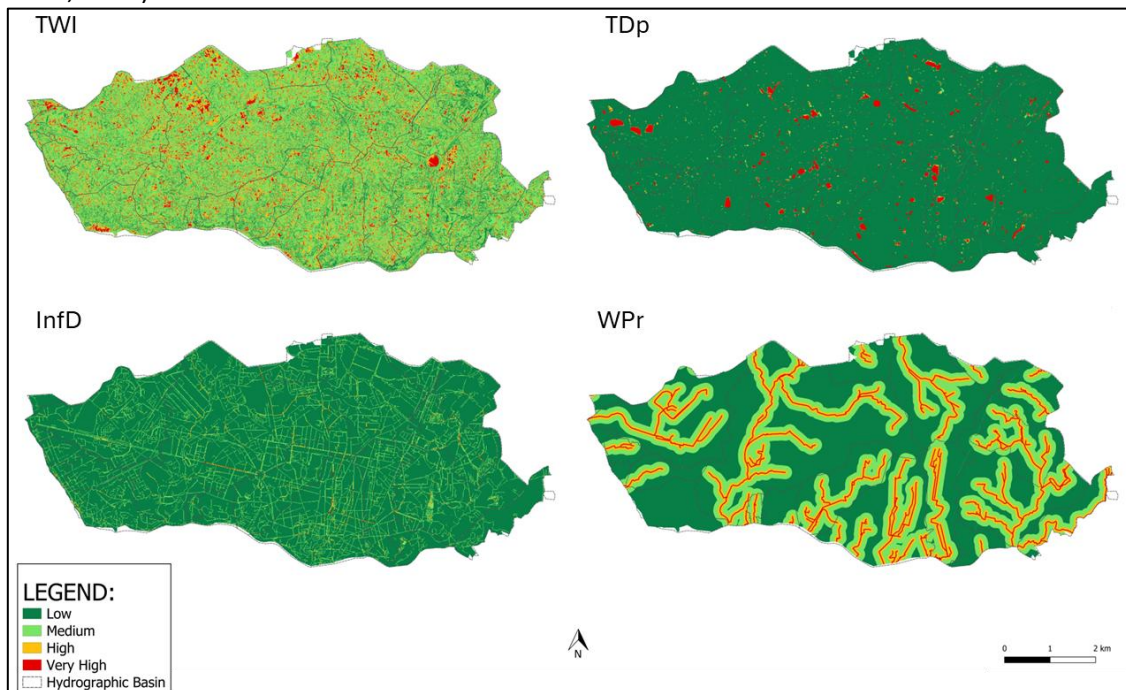
The Physical Exposure Index (PE) quantified the susceptibility of a given location to pluvial flooding based on its inherent physical and infrastructural characteristics (Qi, 2022). Its assessment included four indicators: the Topographic Wetness Index, the depth of terrain depressions, the density of storm water drainage infrastructure and the proximity to water lines. The results were normalized to a range of values between 1 and 4 and the DEMATEL method (Natkaniec, 2024) was used to determine the specific weight of the factors. The final value will be equal to the sum of the values for each factor, multiplied by their specific weight.

The Topographic Wetness Index (TWI) is a standard hydrological index that quantifies the influence of topography on the spatial distribution of soil moisture and surface water accumulation. It is calculated from a DEM and combines upstream contributing area with local slope. Areas with higher TWI values are more likely to become saturated and accumulate runoff, making them more susceptible to flooding (Elsebaie, 2023).

The depth of terrain depressions (TDp) act as natural storage areas for runoff (Elsebaie, 2023). Once the capacity of the formal drainage system is exceeded, these depressions will begin to fill, leading to surface ponding. This factor is a direct indicator of potential flood depth and extent (Omar, 2022). A higher TDp value indicates a deeper depression with a greater potential for water accumulation and, consequently, a greater risk of flooding.

The density of storm water drainage infrastructure (InfD) was calculated as the total length of drainage collectors per square meter. It was considered that a higher drainage density value is associated with the existence of more drainage infrastructures, enhancing the greater flow confluence to the site. Therefore, when drainage density increases, the InfD factor rating increases.

Proximity to water lines (WPr), as a significant factor in determining susceptibility to flooding, determines that areas closer to rivers or water lines generally present a greater risk of flooding (Ahmadi, 2022).



**Figure 1.** Results of Topographic Wetness Index (TWI), depth of terrain depressions (TDp), density of storm water drainage infrastructure (InfD) and proximity to rivers and streams (WPr).

### Social Vulnerability

The Social Vulnerability Index (SVI) measures the susceptibility of the population and built environment to the adverse impacts of flooding (Qi, 2022). The selection of indicators was guided by a review of the literature and tailored to the specific socio-demographic context of Porto and available data. It has been assessed based on proximity to critical infrastructure (SVI\_F1 in Figure 2), percentage of population aged over 65 and under 14 (SVI\_F2 in Figure 2), percentage of population living in the area (SVI\_F3 in Figure 2) and percentage of buildings built before 1945 (SVI\_F4 in Figure 2). Although there is no consensus on how social vulnerability should be measured, it is generally considered that it depends on the spatial scale, the local and regional social environment, the availability of demographic information and the resolution of the data (Qi, 2022).

For the selection of vulnerability factors, we considered that the flooding of streets around buildings or critical infrastructure affects the ability to deal with the damage caused and increases the impact of these events on citizens' daily lives. The percentage of elderly and young people shows the population that is most exposed to the risks of flooding because they potentially have less autonomy of movement and/or decisions. The percentage of residents seeks to reflect the areas with the highest number of residents and the percentage of old buildings represents the parts of the city with the highest number of historic buildings and, consequently, the most susceptible to damage.

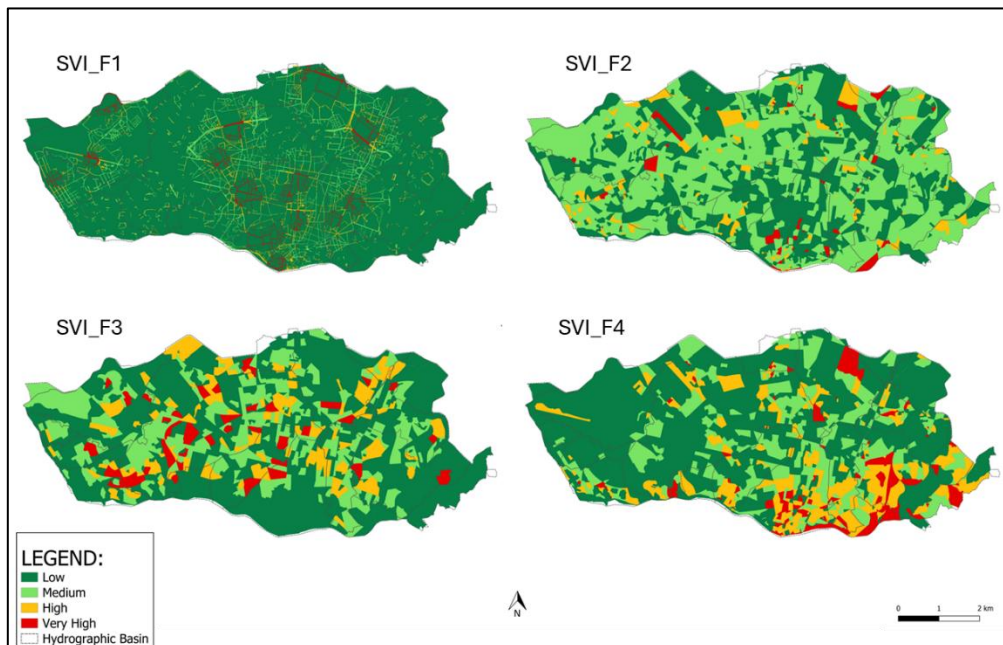
The SVI is calculated by combining all the social vulnerability indicators with equal weights, as an arithmetic mean. As was done when calculating the PE, the factor values were normalized to a range of values between 1 and 4.

### Urban Pluvial Flood Risk

The Urban Pluvial Flood Risk Index (RIPU) was calculated by multiplying the Physical Exposure (PE) and Social Vulnerability (SVI) indices. The rationale behind this multiplication is that low exposure and vulnerability to flooding would inherently result in the lowest overall risk (Qi, 2022). The final RIPU values are then categorized into four levels of risk: low, medium, high, and very high, providing a

comprehensive understanding of urban pluvial flooding and promoting the formulation of effective flood mitigation strategies (Qi, 2022).

The results obtained for PE, SVI and RIPU were intersected with the geospatial layer of the city's organization and the maximum value of each index were found for each block and street.



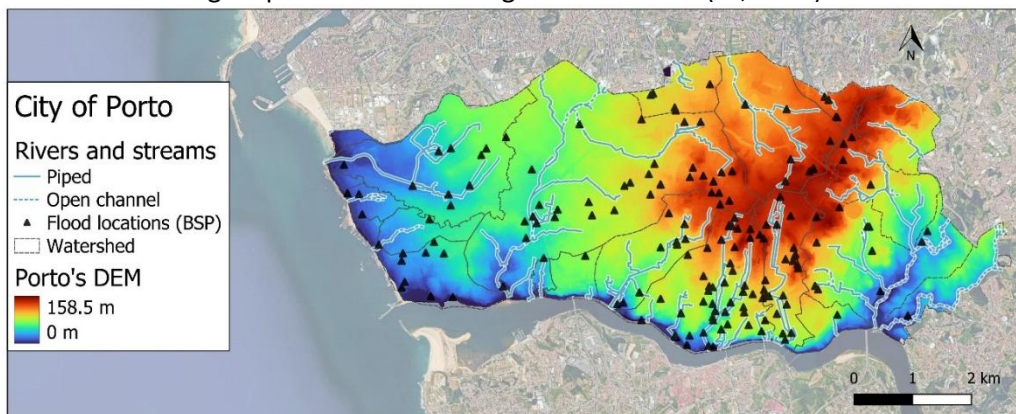
**Figure 2.** Results of proximity to critical infrastructure (SVI\_F1), percentage of population aged over 65 and under 14 (SVI\_F2), percentage of population living in the area (SVI\_F3) and percentage of buildings built before 1945 (SVI\_F4).

## Case study

The city of Porto, located in the north-west of Portugal, has a separate rainwater drainage system and a topography characterised by its steep slopes. At the same time, it has 4 rivers and 12 streams in its 41 km<sup>2</sup>, covering a length of 85 kilometres, of which 75% flows through a piped system, and around 16 kilometres in an open channel, according to the AEDP records. The climate, with wet winters and dry summers, regularly experiences heavy rainfall events which, with urban consolidation and climate change, contribute to an increased risk of flooding.

The historical and social characteristics of the city demand that its social dimensions, such as population density, the presence of historic buildings in vulnerable areas and ageing infrastructure, be considered in flood risk management (Cea, 2022).

The study aims to understand and quantify the city's susceptibility to pluvial flooding events, to subsidise decision-making on prevention and mitigation measures (Qi, 2022).

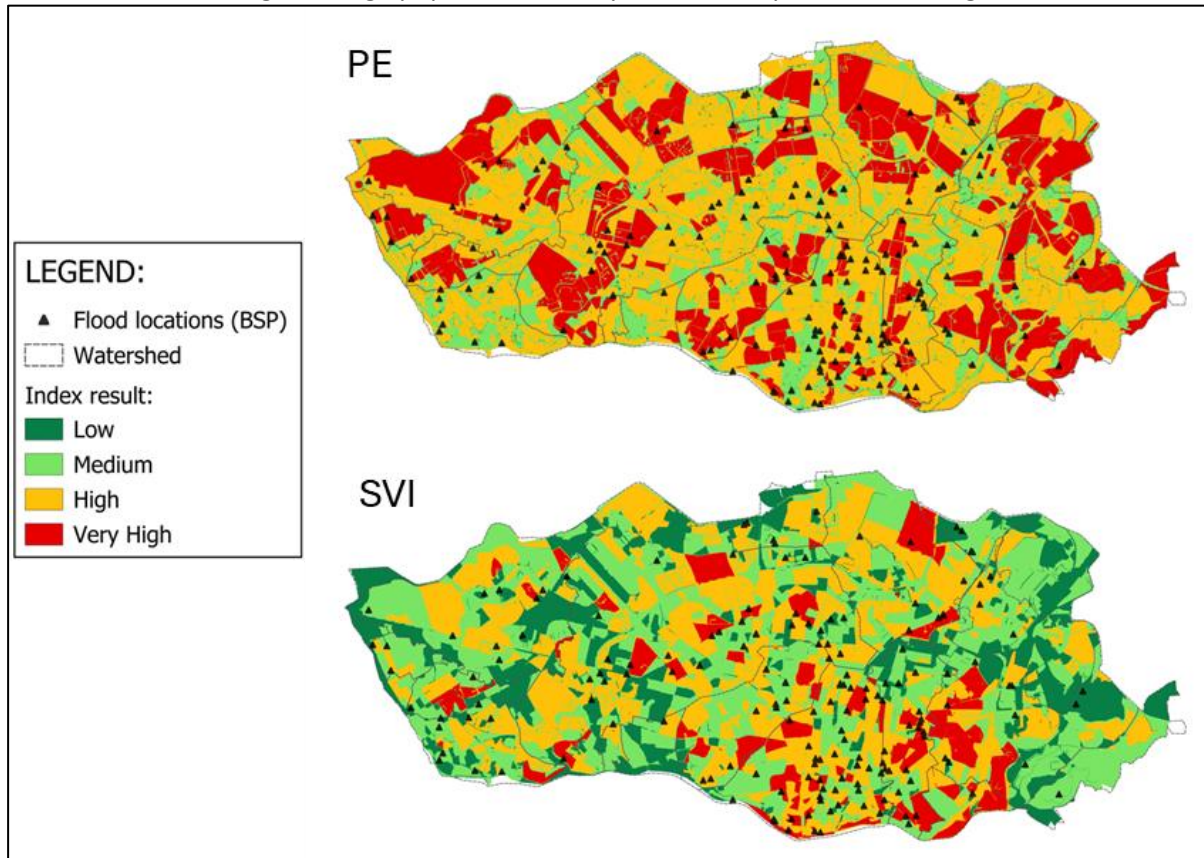


**Figure 3.** Representation of the study area of the city of Porto, illustrating its topography, hydrographic network and BSP flood records

## Results and discussion

The urban pluvial flood risk assessment model made it possible to identify the areas of the city most susceptible to flooding (Wang, 2023). The results show that 30% of the city of Porto has a very high propensity to flooding (PE), with 25% having a medium propensity (PE). The highest risk areas are mainly located in topographically depressed areas and close to water lines, such as Miragaia, Asprela and Campo 24 de Agosto.

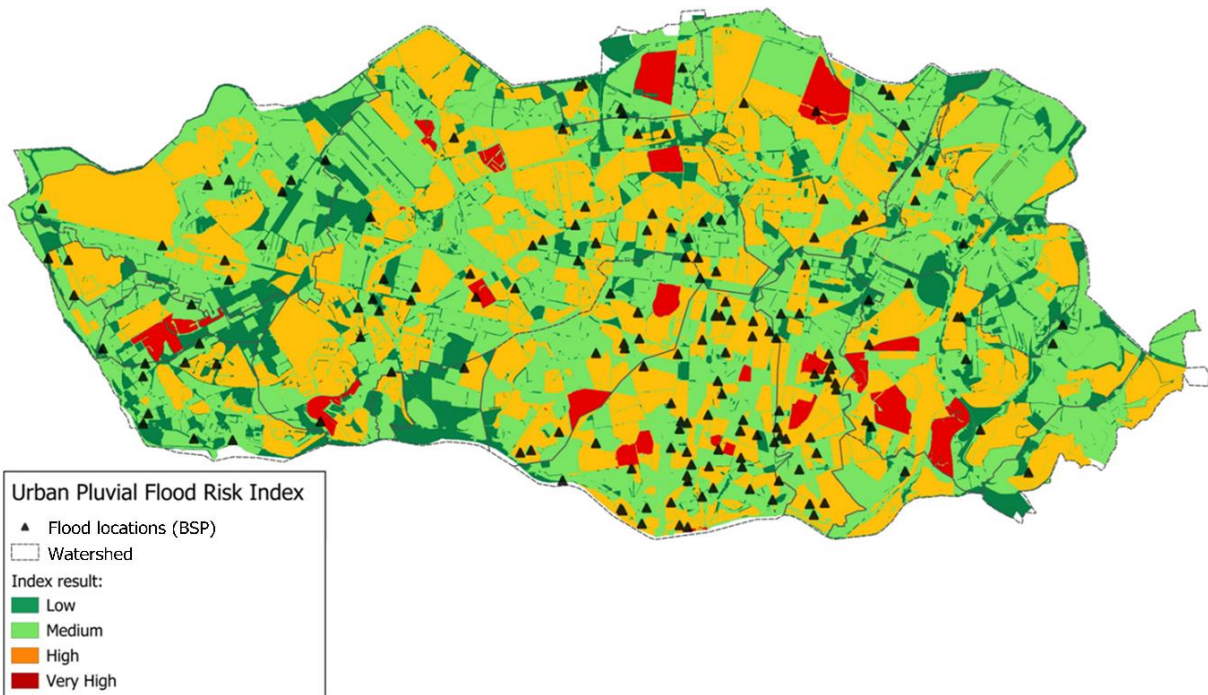
The social vulnerability assessment (SVI), based on indicators such as the percentage of elderly/young population, proximity to critical infrastructure and the age of buildings, revealed that 43 per cent of the city has high or very high social vulnerability. The zones with the highest social vulnerability include areas with old buildings and high population density, such as the parishes of Miragaia and São Nicolau.



**Figure 4.** Results of Physical Exposure (PE) and Social Vulnerability (SVI) for the city of Porto, compared with the locations that register flood between the year of 2018 and 2023.

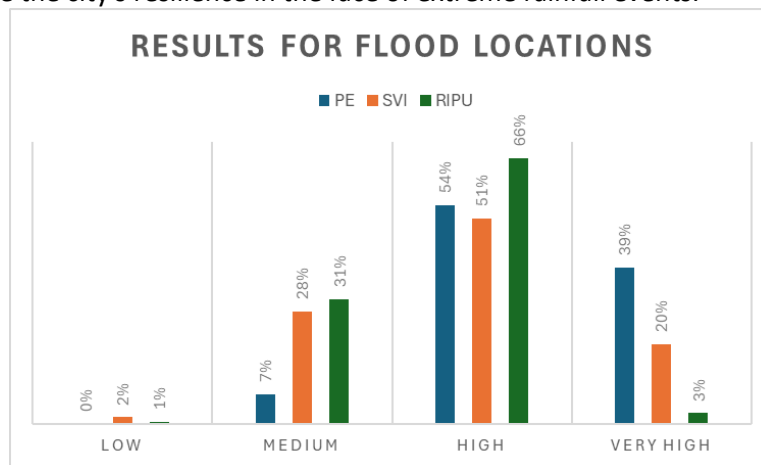
The urban pluvial flood risk index (RIPU) quantified the overall risk of flooding for each area of the city. The results indicate that 6.1 per cent of the city's area is at very high risk of flooding, with the maximum value being recorded in the Frio's watershed (river). The areas with a high risk of flooding correspond to 49.9 per cent of the city's area and are concentrated in the Granja, Massarelos, Picoto, Nevogilde and Asprela basins.

The validation of the model, carried out by comparing it with the occurrence records of the BSP, showed a strong correlation between the risk classification and the occurrence of flood events. Areas with high and very high risk concentrate most occurrences (69%) and 92 per cent of occurrences are in places with high or very high physical exposure, confirming the model's ability to identify areas of greater susceptibility to flooding. The integrated analysis of physical exposure and social vulnerability made it possible to classify the different areas of the city into four risk typologies, with different implications for the definition of monitoring plans and maintenance operations, mitigation measures and timeframes for action. Areas with high exposure and social vulnerability, such as the Carregal's area, are prioritised for the implementation of monitoring plans, mitigation measures and/or the preparation of the community and built heritage for extreme climate events.



**Figure 5.** The results of Urban Pluvial Flood Risk for the city of Porto, compared with the locations that register flood between the year of 2018 and 2023.

This study shows the importance of considering both physical and social factors when assessing the risk of urban pluvial flooding. The model developed, complemented by hydraulic modelling of the rivers, will enable careful prioritisation of mitigation measures to be implemented in the city of Porto, helping to increase the city's resilience in the face of extreme rainfall events.



**Figure 6.** Comparison of the percentage distribution of flood sites according to the Physical Exposure (PE), Social Vulnerability (SVI) and Urban Pluvial Flood Risk (RIPU) analyses.

## Conclusions and future work

The aim of this study was to develop a model to assess the risk of pluvial flooding in the city of Porto, considering both physical and social aspects, to provide support for prioritising the implementation of the monitoring plan, maintenance operations and mitigation measures for extreme climate events. Through the MCSA, factors such as topography, infrastructure density, proximity to water lines, population density, the percentage of elderly and young people and proximity to critical infrastructure were considered.

Based on this data, an urban pluvial flood risk map was drawn up, quantifying the risk of the different areas of the city in four risk levels: low, medium, high and very high. The results obtained suggest that the design of mitigation measures should consider both the physical exposure and the social

vulnerability of the locations to reduce the impact of floods and increase the environment's capacity to recover from these events.

The validation of the model, using the occurrence records of the BSP, demonstrated its ability to identify the areas of greatest exposure and risk. At the same time, the reliability of the results allows them to be used as a complement to hydrological and hydraulic analyses developed for urban watercourses and contributes to accurately prioritizing interventions in the territory and the type of mitigation measures to be implemented.

One of the limitations of our study is the fact that we only focused on rainfall flooding, ignoring the occurrence of river flooding and/or sea overtopping. Therefore, future work could combine rainfall, river and sea flooding in the assessment of urban flood risk. At the same time, the reliability of the data used should be improved in future studies, particularly the resolution of the city's subsections and its digital elevation model.

## Acknowledgement

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