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VULNERABILITY TO URBAN FLOODING: A GEOSTATISTIC APPROACH FOR RISK ANALYSIS

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Lucas Guimarães da Silva[1], Rodrigo Cesar da Silva[2], Willian José Ferreira[3], Jackes de Pabllo Pereira Tiburcio[4], Thiago Moura Figueredo[5] and Marcelo dos Santos Targa[6]

ABSTRACT
Extreme precipitation events have caused significant disruptions to social systems, leading to considerable environmental impacts and directly affecting the lives of communities. This study investigates the vulnerability of São José dos Campos (SJC), in the Paraíba Paulista Valley, Brazil, to flooding, exploring the relationship between flood records, geographic characteristics, and disorderly urban occupation. The analysis integrates altimetric and precipitation data, using geoprocessing techniques and the Local Moran Index to examine the spatial correlation between altitude and flooding. Among the results, a significant autocorrelation was observed between altitude and flood records, with greater vulnerability in low-lying areas, in addition to a 62% reduction in flood events between 2009 and 2018, associated with mitigating interventions. The findings indicate that topographic characteristics and intense precipitation increase the risk of flooding, reinforcing the need for planning policies and improvements in drainage infrastructure to strengthen urban resilience. The study also highlights the need for public policies aimed at sustainable urban planning and adaptation to climate change. In this scenario, continuous investments in monitoring technologies and participatory governance are essential for mitigating risks,

[1] Master in Environmental Sciences
University of Taubaté (UNITAU)
E-mail: eng.lucasguimaraes15@gmail.com
ORCID: https://orcid.org/0000-0003-3776-295X
[2] Doctor in Natural Disasters
University of Taubaté (UNITAU)
E-mail: rodrigo.peb@gmail.com
ORCID: https://orcid.org/0000-0002-9721-6988
[3] Doctor in Spatial Geophysics
University of Taubaté (UNITAU)
E-mail: willian.jferreira@unitau.br
ORCID: https://orcid.org/0000-0003-4636-868X
[4] Master in Environmental Sciences
University of Taubaté (UNITAU)
E-mail: jackespabllo@gmail.com
ORCID: https://orcid.org/0009-0009-5618-5159
[5] Master's student in Environmental Sciences
University of Taubaté (UNITAU)
E-mail: thiago.mfigueiredo@unitau.br
ORCID: https://orcid.org/0009-0000-2573-4017
[6] Doctor in Agronomy
University of Taubaté (UNITAU)E-mail: mtarga@unitau.br
ORCID: https://orcid.org/0000-0002-4140-3493

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protecting the most vulnerable communities, and promoting a balanced coexistence between urban development and socio-environmental sustainability.

Keywords: Urban Planning. Risk Management. Land Use. Environmental Sustainability. Climate Extremes.

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INTRODUCTION

Disasters resulting from extreme precipitation events have disrupted social systems, causing environmental damage and directly impacting the lives of populations (Bathrellos et al., 2018). Among the most frequent on a global scale are floods and inundations, phenomena in which excess water exceeds the capacity of water bodies, causing overflows in adjacent areas, especially in lowland regions (Handayani et al., 2020). Studies indicate that, in urban areas, floods have caused significant damage to infrastructure, interfered with economic activities, and affected the safety of communities (Wang et al., 2020). Therefore, understanding the factors and dynamics that intensify these events is essential to plan more resilient cities and minimize the risks and impacts of extreme hydrological events. In recent decades, flooding in urban basins has been aggravated by the disorderly expansion of cities and the reduction of green areas, which reduces infiltration capacity and intensifies surface runoff (You, 2023). Surface impermeability and urban growth affect natural drainage and increase the frequency and extent of flood events, making risk management even more challenging (Rentschler et al., 2023). In Brazil, many municipalities face major challenges with flooding, especially in metropolitan areas, due to their high vulnerability to extreme hydrological events (Coutinho et al., 2018). This vulnerability is amplified in sensitive areas, such as riverbanks and hillsides, where environmental protection and urban planning standards are often disregarded (Brasil, 2024). In the state of São Paulo, the Paraíba do Sul River Basin (BHRPS) exemplifies this situation, given that its geomorphological complexity — marked by flat areas and steeply sloped regions — makes it particularly susceptible to flooding and landslides during heavy rainfall (Silva et al., 2020).

Analyzing the spatial and temporal distribution of floods in the BHRPS, especially in urban areas such as São José dos Campos (SJC), requires methods that integrate historical data and geoprocessing tools. According to Bathrellos et al. (2018), detailed information on local-scale flood occurrences, combined with these tools, are essential for planning and managing vulnerable areas, in addition to supporting strategies that reduce the impacts of these events and the exposure of communities.

Despite the advances, there are still gaps in the spatial understanding of floods in SJC, as there is a lack of analyses that integrate historical, topographic, and precipitation data to generate localized risk maps. This study aims to answer the following questions:

which areas of SJC are most susceptible to flooding, and how can integrated analysis of this data contribute to identifying and mitigating these risks?

From this perspective, the objective of this study is to identify areas most susceptible to flooding in SJC, using geoprocessing and spatial analysis techniques. Aligned with the 2030 Agenda for Sustainable Development, especially Goal 11 — which promotes inclusive, safe, resilient, and sustainable cities —, the research seeks to provide support for urban planning and flood risk management. In this way, it contributes to the development of preventive and mitigating strategies that reduce the impacts of flooding and increase the region's safety in the face of extreme hydrological events.

MATERIALS AND METHOD

STUDY AREA

This study focuses on the municipality of São José dos Campos (SJC), located in the Metropolitan Region of Vale do Paraíba and Litoral Norte (RMVPLN), state of São Paulo. As the largest city in the RMVPLN, with a population of 697,428 inhabitants and a population density of 634.4 inhabitants per km² (IBGE, 2024), SJC has great economic, technological, and scientific importance for Brazil.

The municipality is located on the axis between São Paulo and Rio de Janeiro (Figure 1) and is one of the main industrial and research hubs in the country, standing out, especially in the aerospace, technological, and innovation areas (Ferreira et al., 2023a). In addition, it is recognized for its quality of life and advanced infrastructure, with a diversified and growing service sector, which integrates areas with strong potential for expansion.

According to Köppen-Geiger, the climate of SJC is classified as humid subtropical (Cfa), with rainy summers and relatively dry winters. The average annual temperature is 20.9°C, with significant seasonal variations that influence the rainfall regime and humidity (Ferreira et al., 2023a). The average annual precipitation is approximately 1,400 mm, with the wettest months concentrated between December and February when monthly precipitation can exceed 200 mm due to high temperatures and humidity brought by the Atlantic tropical air mass (Ferreira et al., 2020b). The winter months, especially from June to August, are drier, with average monthly precipitation ranging from 30 to 60 mm, and are marked by the influence of cold and dry air masses, which contribute to a drop in relative humidity.

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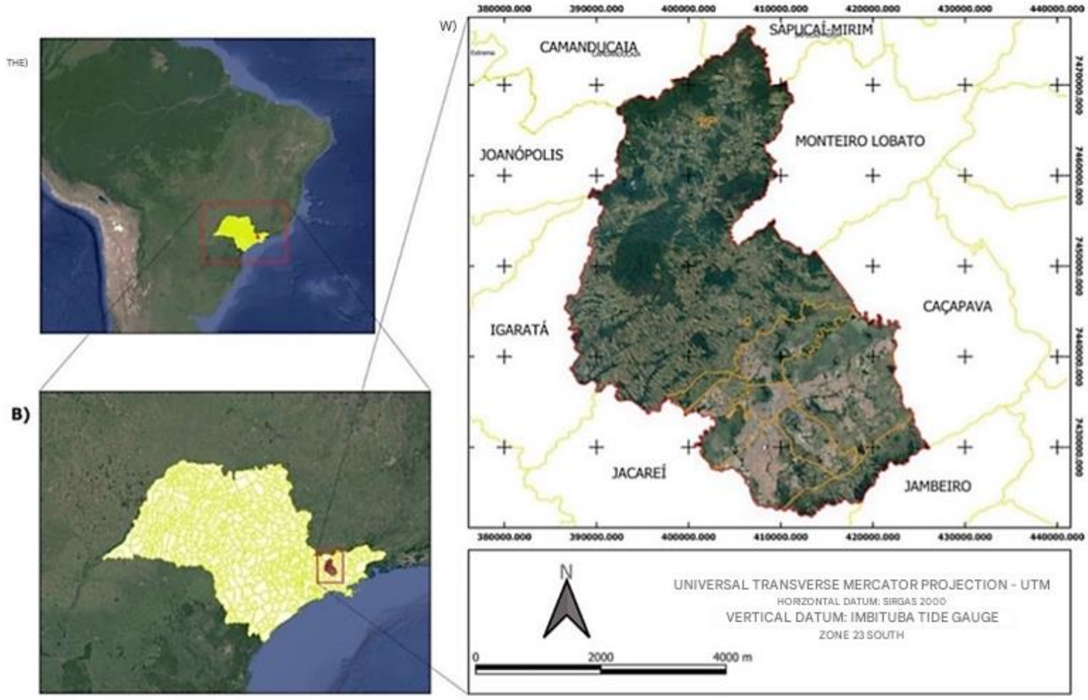
Figure 1. Geographical location of Sao Jose dos Campos, Sao Paulo, Brazil.



Source. Prepared by the authors.

The predominant soils in SJC are argisols, latosols, cambisols, and gleysols, with vegetation cover that varies between savanna and dense ombrophilous forests (Ferreira et al., 2020). According to Camargo et al. (2011), its relief is composed mainly of hills and mountains, located in the north and southeast regions. On the other hand, the south and parts of the east have broad and tabular hills, while the lowland areas, especially along the Paraíba do Sul River, stand out for forms of aggradation, such as alluvial plains and river terraces.

The altitude in the municipality varies from 535 meters, in the alluvial plain of Paraíba do Sul, to 2,082 meters, at Pico do Selado, located to the north, in the district of São Francisco Xavier (Prado; Abreu, 1995). This altimetric distribution can be seen in Figure 2, which presents the hypsometric map of SJC, highlighting the different slopes of the slopes. The map illustrates the variation in elevations in the municipality, indicating areas of greater susceptibility to erosion and flooding, especially in low-lying areas with gentle slopes.

Given its physical, climatic, and socioeconomic characteristics, SJC presents favorable conditions for the analysis of vulnerability to urban flooding, since the combination of intensive occupation of the alluvial plains, accelerated urban growth, the predominance of soils with low infiltration capacity, and the rainfall regime concentrated in

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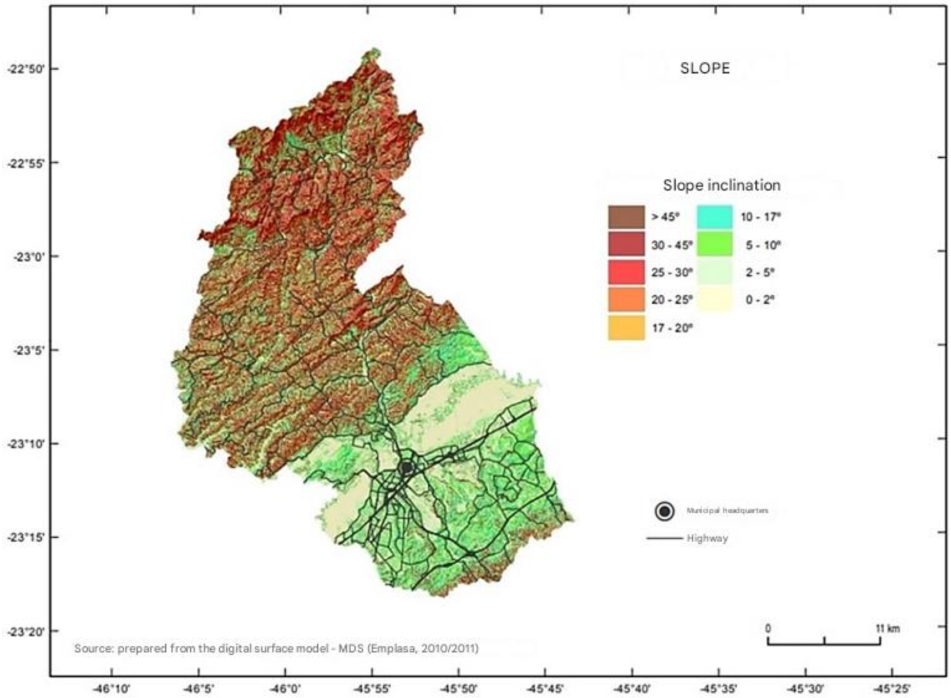
the summer months makes the municipality particularly susceptible to extreme hydrological processes, requiring detailed studies to identify and mitigate the associated risks.

Figure 2. Geographical location of Sao Jose dos Campos, Sao Paulo, Brazil.



Source. Prepared by the authors.

ANALYSIS AND SELECTION OF FLOOD EVENTS

Following a four-step process, flood events with consistent data were selected to avoid irrelevant information that could compromise the results. The steps included: (I) flood data collection; (II) geocoding, filtering, and georeferencing; (III) spatial analysis; and (IV) assessment of flood susceptibility.

The first step, data collection, covered information on floods, morphometric characteristics, and precipitation. Seven main sources were consulted: (I) Mineral Resources Research Company (CPRM); (II) Department of Water and Electric Energy (DAEE) of São Paulo; (III) Municipal Coordination of Civil Defense and Protection (COMPDEC) of SJC; (IV) Brazilian Agricultural Research Corporation (EMBRAPA); (V) Brazilian Institute of Geography and Statistics (IBGE); (VI) National Institute for Space Research (INPE); and (VII) Municipal Government of SJC.

In the second stage, of geocoding, filtering, and georeferencing, the flood occurrences recorded between 2009 and 2018 by the Civil Defense of SJC were selected. Each occurrence was analyzed individually, and, according to the methodology proposed by Ozkaia and Akyrek (2019), those without sufficient data for georeferencing were

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discarded, in order to minimize possible bias errors and ensure the accuracy of the results. The approved occurrences were organized in a database in the QGIS 3.4.3 software.

In the third stage, of spatial analysis, the georeferenced occurrences were combined with altimetry and precipitation data, allowing a detailed analysis of the factors involved. The Local Moran Index, as described by Parsian et al. (2021), was used to identify patterns of spatial concentration of floods and improve the susceptibility analysis.

Finally, the fourth stage, assessing susceptibility to flooding, considered common scenarios in SJC defined by the Civil Defense, such as "flooded house", "flooding" and "flood", which represent typical problems of urban flooding in Brazil. Each occurrence was examined in terms of land use and cover, enabling the identification of critical points of vulnerability to flooding.

APPLICATIONS OF GEOPROCESSING AND PRECIPITATION DATA

For georeferencing and geocoding of flood occurrences, Google Earth Pro was used, generating KML files based on records from the Municipal Coordination of Protection and Civil Defense, according to the method of Castro (2018). These data were converted to GeoPackage in QGIS 3.4.3, standardized in SIRGAS2000 Datum and UTM projection, and imported into GeoDA for spatial autocorrelation analysis.

Altimetric data were extracted from the Digital Surface Model (DSM) of the Mineral Resources Research Company (CPRM, 2022). Using the r.reclass and r.report algorithms of QGIS, the slope was calculated to identify patterns in the flooded areas. These data were integrated into the geographic database to calculate the Local Moran Index (LMI) and analyze the average altitude of the events.

Rainfall was obtained from the station of the Department of Water and Electric Energy (DAEE, code E2-099) and from estimated precipitation maps (CHIRPS v.2, 1981–2023), which combines satellite and meteorological station data, with a resolution of 5 km (Funk et al., 2015). To evaluate precipitation extremes, meteorological extreme indices (ETCCDI) were used, with the Climpact v.3 software (Alexander; Herold, 2016). The extreme rainfall indicators considered were: Rx1day, which indicates the maximum amount of precipitation in a single day (mm); Rx3day, which represents the maximum amount accumulated in three days (mm); Rx5day, the maximum amount in five days (mm); and R30mm, the number of days with precipitation equal to or greater than 30 mm (days).

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To account for flood events, records that occurred on the same date were consolidated into a single entry. The analysis of these events was then performed using geoprocessing techniques, considering essential variables, such as altimetry and precipitation, in addition to the flood records themselves.

GEOSTATISTICAL ANALYSIS: LOCAL MORAN SPATIAL AUTOCORRELATION

To assess the spatial dependence between flood records and altimetry, the IML was applied, according to the spatial autocorrelation model proposed by Anselin (1995). This index is a statistical tool that measures the spatial correlation between a specific area and its neighboring regions, indicating how geographic characteristics, such as altitude and flood occurrence, may be spatially grouped.

The IML scatter plot allows these correlations to be classified into four main categories (Luzardo et al., 2017): Q1 represents areas where high values are close to other high values (high-high); Q2 indicates areas where low values are close to other low values ixos (low-low), both denoting positive autocorrelation. Q3 (high-low) and Q4 (low-high) indicate negative autocorrelation, where high values are close to low values and vice versa.

In the interpretation of the results, values close to zero indicate the absence of spatial correlation, while values closer to -1 or +1 reflect negative and positive autocorrelation, respectively (Costa et al., 2007). The index is comparable to Pearson's correlation coefficient, with intensity classified as low (0 to 0.25), moderate (0.25 to 0.50), considerable (0.50 to 0.75), and high (0.75 to 1).

RESULTS

The results of this study provide an analysis of the relationship between flood records and geographic and anthropogenic characteristics in SJC, covering the period from 2009 to 2018. The following findings highlight the spatial distribution of flood events, the influences of land use and occupation, and the impact of mitigating interventions, composing a framework that justifies the importance of integrated policies for flood risk management.

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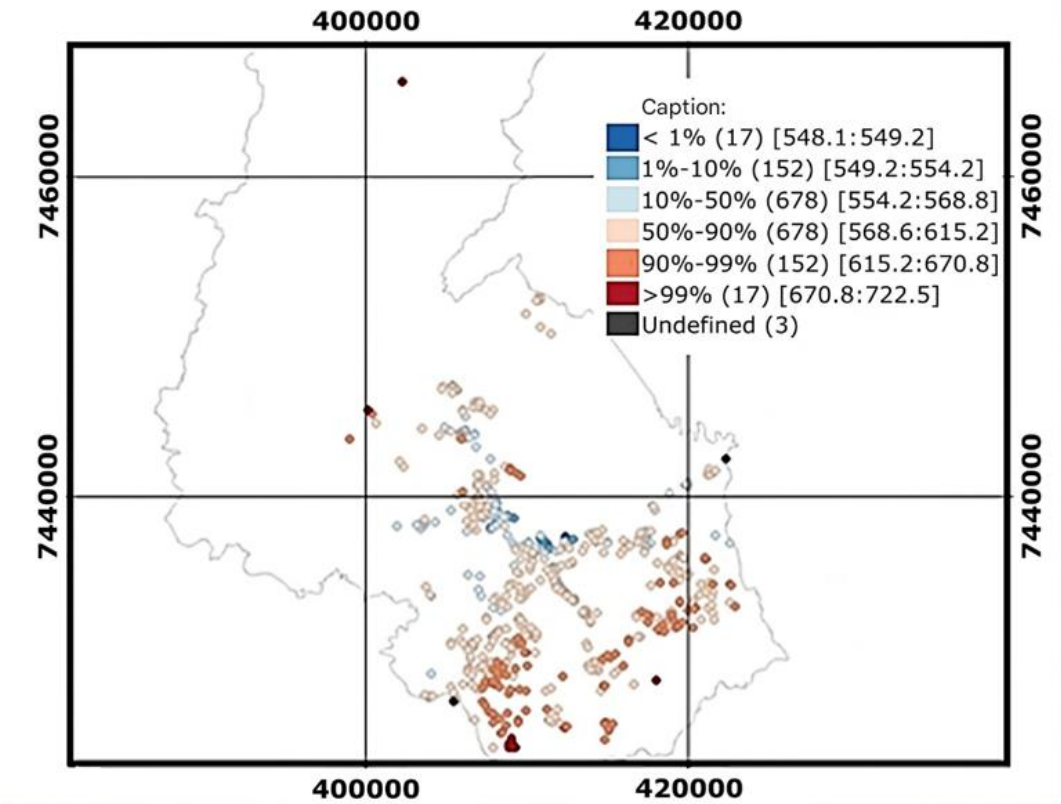
MAPPING OF FLOOD RECORDS

During the study period, 1,697 flood events were recorded by the Civil Defense in SJC, with a greater concentration in low-lying areas and close to bodies of water (Figure 3). This high incidence highlights the vulnerability of the municipality, especially in disorganized urbanized regions, where irregular occupations amplify the risk of flooding. This initial mapping provides a basis for identifying critical areas and the impacts of unplanned urbanization, which compromises the city's response to heavy rain events.(Santos; Haddad, 2014; Marchezini *et al.*, 2018).

Figure 3. Spatial distribution of flood events recorded in SJC between 2009 and 2018.



Source Authors.

In SJC, approximately 19.9% of the area has a slope of less than 8%, a condition that favors the accumulation of water and, consequently, the occurrence of floods, especially in flat or gently sloping regions close to bodies of water. This scenario demonstrates that disorderly urban growth contributes to the intensification of flood events, since the lack of drainage infrastructure compromises runoff and worsens the vulnerability of communities. Studies by Santos et al. (2016) and Alcântara (2022) highlight that the absence of effective land use policies amplifies economic losses and increases risks to the safety of populations. In this sense, urban governance strategies that prioritize sustainability and resilience are essential to reduce vulnerability and strengthen the response to extreme events. The correlation between low altitude and flood frequency in SJC is confirmed by the combined analysis of Figures 2 and 3. The hypsometric map (Figure 2) highlights areas with altitudes below 615 meters, predominantly in river floodplains, which are more susceptible to water accumulation during periods of heavy rainfall. Fig. 3 reinforces this observation by highlighting the concentration of flood events in these areas. This association between slope and flooding highlights the need for specific interventions, such as improvements in drainage systems and restrictions on new occupations in risk regions, aiming to mitigate the impacts of topographic characteristics combined with disorderly urban growth.

The analysis reveals that SJC shares vulnerabilities with other Brazilian cities susceptible to flooding, such as Blumenau and Brusque, in Santa Catarina, and Duque de Caxias, in Rio de Janeiro (Momo et al., 2016; Neves et al., 2019). In these cities, the combination of unfavorable topographic characteristics and urban pressure without adequate drainage infrastructure favors the occurrence of frequent floods. This recurring pattern demonstrates that the problem is nationwide, indicating that mitigation strategies can be replicated and adapted to the particularities of each location.

However, for SJC, it is recommended to adopt strategies already successfully implemented in other cities, adjusting them to local specificities. Measures such as restrictions on occupations in floodplain areas, expansion of the drainage system, and continuous monitoring of risk areas are examples of policies that can be adapted. Such actions contribute to urban resilience and more sustainable land use management, minimizing the impacts of floods and promoting the safety of the population.

SPATIAL AUTOCORRELATION BETWEEN ALTIMETRY AND FLOODING

The analysis with the Local Moran Index (IML) identified a significant spatial autocorrelation between altitude and flood records in the municipality of São José dos Campos ($p < 0.05$). A total of 962 events with spatial dependence were considered, while 735 records were discarded due to the random behavior of the flood points since the statistical significance did not reach the 95% confidence level ($p > 0.05$). The analysis revealed that areas with similar altimetric characteristics are more vulnerable to flooding, especially those located in low-altitude areas and close to bodies of water.

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The results indicated a clear pattern of positive autocorrelation, as evidenced by the IML value of 0.857, which confirms the spatial dependence between the variables analyzed. This correlation shows that areas with similar topography, with low altitude values, concentrate the majority of flood occurrences, reinforcing the direct influence of the altimetric configuration on the hydrological behavior of the region. In particular, quadrants Q1 (high-high) and Q2 (low-low) were those that concentrated the majority of events, demonstrating a significant spatial relationship between altitude and flooding.

Among the most notable locations are the areas located near the Cambuí stream, in the neighborhoods of Sapé I, Vila Guarani and Jardim do Lago, all in the eastern part of SJC. These locations experienced 415 flooding events, strongly influenced by the average elevation of 568 meters and insufficient drainage infrastructure, which increases the risk of flooding during periods of heavy rainfall.

Another critical point identified was the Mirante do Buquirinha, located in the northern region of SJC, in the Buquirinha district. This area recorded the highest number of flooding events, due to the recurring overflow of the Buquira River, whose levels fluctuate between 3.20 and 3.50 meters during periods of heavy rainfall. The vulnerability of the location is aggravated by the combination of low altitude, rugged terrain, and insufficient drainage infrastructure, factors that increase the susceptibility to both flooding and landslides. Figure 4 illustrates the increase in water volume, which results in the overflow of the Buquira River and causes damage in the neighborhoods of Mirante do Buquirinha, Taquari, and Costinha.

Figure 4. Impacts of the increase in water volume due to the overflow of the Buquira River, in SJC.

Source. Civil Defense of SJC (2023).

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Furthermore, specific interventions, such as the removal of housing in risk areas, had a direct impact on reducing flood events. Between 2009 and 2018, the number of occurrences fell from 60 to 23 events, representing an approximate decrease of 62%. These actions included the removal of homes located in critical zones and the unblocking of drainage systems, corroborating the effectiveness of structural mitigation policies. The case of Mirante do Buquirinha illustrates the relevance of these interventions, where the removal of vulnerable homes resulted in significant risk mitigation.

These results emphasize the need to incorporate specific land use regulations and urban planning strategies that consider altimetric and hydrological characteristics when allocating drainage infrastructure and defining risk zones. The approach adopted in this study reflects the importance of structural interventions and land use adjustments to reduce the impacts of urban flooding, in line with previous studies, such as those by Belisário et al. (2019) and Camargo et al. (2011).

PRECIPITATION PATTERNS AND IMPACT ON FLOODING

Accumulated precipitation data show that most heavy rainfall in SJC occurs between October and March, with a significant peak in January (Ferreira et al., 2020). This seasonal pattern of heavy rainfall in the summer months increases the risk of flooding, especially in areas with limited drainage infrastructure and disorderly occupation, as discussed in previous studies by Marengo and Alves (2005) and Silva et al. (2019). The correlation between periods of heavy rainfall and high frequency of flooding justifies the need for planned drainage infrastructure, as well as urban planning policies to mitigate disaster risks. The historical precipitation series between 1981 and 2023 (Figure 5) points to a declining trend in extreme precipitation events in SJC, evidenced by the R30mm, Rx1day, Rx3day, and Rx5day indices.

The R30mm index, which reflects the number of days with precipitation equal to or greater than 30 mm, presents a slope of -0.133 (p-value = 0.001), indicating a reduction in the frequency of days with intense rainfall, which can relieve pressure on drainage infrastructure and reduce the exposure of vulnerable areas. The Rx1day index, which measures the maximum volume of precipitation in a day, reveals a negative slope of -0.369 (p-value = 0.006), suggesting a decrease in the intensity of the most severe events, which can reduce flood peaks, although interannual variability keeps the risk present. The Rx3day and Rx5day indices, which represent the accumulated precipitation over three and five

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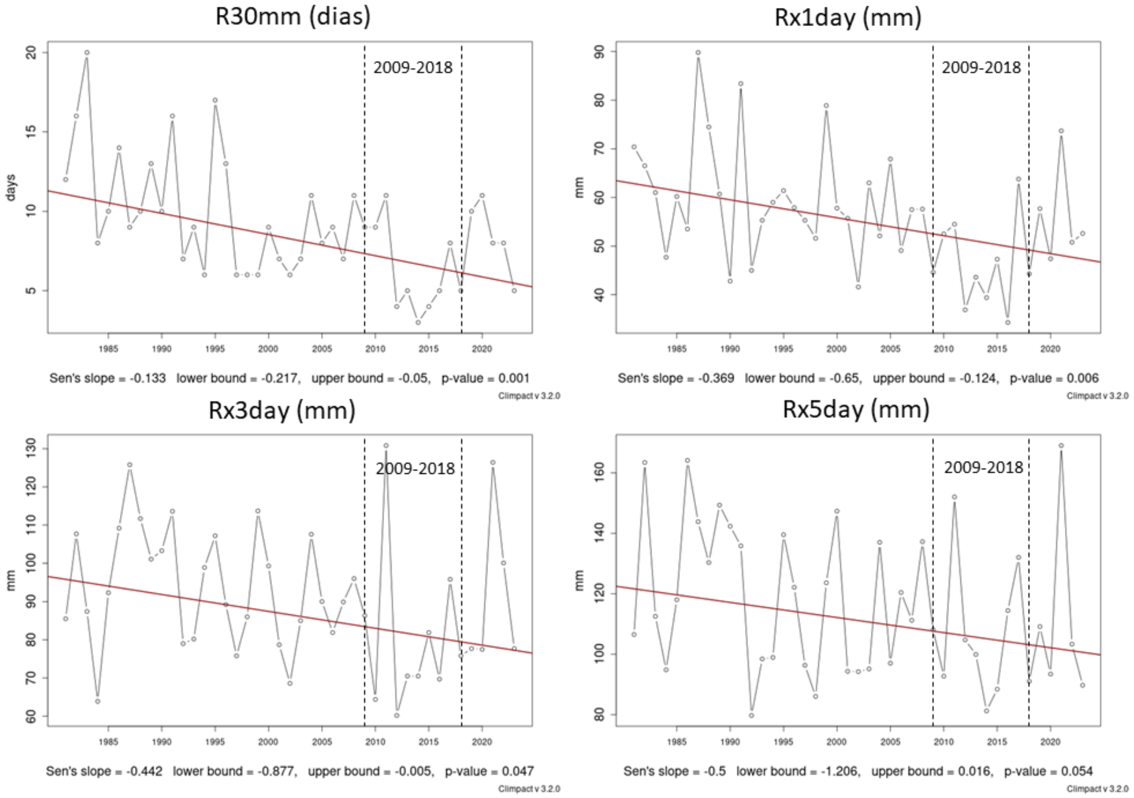
consecutive days, also show decreasing trends with slopes of -0.442 and -0.5, respectively. Although the p-value for Rx5day (0.054) presents lower statistical significance, both indicators suggest a reduction in the frequency and intensity of prolonged rainfall, which traditionally aggravates flood risks in dense urban areas.

Figure 5. Precipitation extremes (1981-2023), highlighting the indices R30mm, Rx1day, Rx3day and Rx5day.



Source. Authors.

DISCUSSION

The integrated analysis of altimetric and precipitation data made it possible to map the areas of SJC most susceptible to flooding and to understand the main factors that influence these events. The results identified a greater vulnerability in low-altitude regions and those close to bodies of water, especially in the eastern part of the municipality, where the drainage infrastructure is insufficient and the average altimetric elevation is 568 meters.

The Local Moran Index (LMI) revealed a significant spatial autocorrelation ($p < 0.05$) between altitude and flood records, with 962 spatially dependent events. Areas such as Sapé I, Vila Guarani and Jardim do Lago, close to the Cambuí stream, recorded 415 occurrences due to the combination of low altitude and poor drainage. Mirante do Buquirinha, in the northern region, had the highest flood records, related to the overflow of the Buquira River, whose levels fluctuate between 3.20 and 3.50 meters during heavy rains.

Historical precipitation data (1981-2023) indicated a declining trend in the frequency and intensity of extreme events, with reductions in the R30mm (-0.133, p = 0.001) and Rx1day (-0.369, p = 0.006) indices. Despite this partial relief, the persistence of intense events during the summer still represents significant risks, especially in areas already mapped as vulnerable.

These patterns reflect challenges observed in other locations, such as Guaratuba/PR and São Gonçalo/RJ, where soil sealing and the removal of riparian vegetation intensify the impacts of rainfall (Vieira et al., 2016; Silva et al., 2019). As in these contexts, the floods in SJC highlight the need for urban planning policies that incorporate topographic characteristics in land use planning and the allocation of drainage infrastructure.

Given these results, the importance of combining structural and nature-based solutions, such as buffer zones and permeable areas, to strengthen urban resilience is highlighted. Successful experiences in cities such as Curitiba and Blumenau demonstrate that integrated drainage systems and environmental awareness programs can reduce flood risks. Adapting these practices to the reality of SJC is essential to promote sustainable urban planning, aligned with SDG 11 (Resilient Cities) and SDG 13 (Climate Action).

Finally, this research has limitations, such as the reliance on Civil Defense records, which may not include underreported events, and the restricted time frame (2009-2018). Future studies should expand the analysis period and incorporate updated data, in addition to exploring remote sensing technologies and hydrological modeling to predict climate scenarios. Investigating the effectiveness of nature-based solutions represents a promising approach to mitigate flood risks in dense urban areas and prepare cities for future climate challenges.

CONCLUSION

This research investigated the relationship between flood records and geographic and anthropogenic characteristics in SJC, identifying areas of greater susceptibility and evaluating the effects of mitigating interventions between 2009 and 2018. The main finding was the identification of a significant spatial autocorrelation between altitude and flood records. The analysis with the Local Moran Index (LMI) showed that low-lying areas, especially close to water bodies, are particularly vulnerable to flooding, especially in the eastern part of the municipality, where drainage infrastructure is insufficient.

The contribution of this research lies in the application of an integrated methodology of spatial analysis and climate indicators, highlighting the relevance of considering topographic and seasonal variables in urban planning for disaster mitigation. These findings provide a basis for more targeted urban planning policies and investment decisions in drainage infrastructure in high-risk regions. This approach is aligned with Sustainable Development Goal (SDG) 11 of the 2030 Agenda, which aims to promote inclusive, safe, resilient, and sustainable cities. In addition, promoting environmental education programs that involve the community contributes to SDG 4, which seeks to ensure quality education and encourage sustainable practices.

The relevance of this research also connects to SDG 13, which reinforces the importance of action against global climate change. The SJC analysis, combined with studies from other locations, such as Guaratuba/PR and São Gonçalo/RJ, highlights that extreme weather events can intensify the risk of flooding, requiring adaptation measures and long-term policies. In line with Ferreira et al. (2023b), it is understood that strengthening institutional capacities and investing in climate monitoring and forecasting technologies are essential for an effective response to these events. Challenges. Furthermore, nature-based practices, such as the creation of buffer zones and the expansion of permeable areas, are in line with SDG 15, which calls for the protection and restoration of terrestrial ecosystems. These actions help maintain ecosystem services and the resilience of the territory, benefiting both the environment and the local population.

Future studies should expand the period of analysis, incorporating more recent data and assessing the effects of urban policies. The use of remote sensing technologies and hydrological modeling can refine the analyses and allow for more accurate projections for different climate scenarios. Investigating the effectiveness of nature-based solutions, such as the restoration of green areas, shows promise for mitigating risks in dense urban areas and can serve as a basis for the formulation of strategies that support the SDGs in an integrated manner.

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