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Flash flood assessment for economic losses in an urban basin of the São Paulo metropolitan region – Brazil

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ABSTRACT

Megacities in developing countries frequently experience severe flooding, generating significant social and economic impacts. Assessing flood scenarios and their consequences is essential to support evidence-based mitigation and adaptation strategies that reduce exposure and vulnerability. This study evaluates flash-flood scenarios in the Aricanduva River catchment, located in the metropolitan region of São Paulo, Brazil. The 102.5 km² catchment is fully urbanized, highly flood-prone, and characterized by a population density of approximately 7,400 inhabitants per km², with January presenting an average monthly precipitation of 292.1 mm. The objective of this study is to estimate flood-related economic losses and quantify the socioeconomic vulnerability of the population. Flood hazard maps were generated using the CADDIES cellular automata–based hydraulic model under extreme precipitation events, employing a LiDAR-derived digital terrain model aggregated to 10 m resolution. Simulated flood extents and water depths were combined with census-based socioeconomic data and information on public infrastructure to identify exposed assets, residential units, income levels, and socioeconomic classes. Economic losses were estimated using depth–damage functions relating floodwater depth to proportional losses in buildings, contents, and infrastructure. Results indicate that losses associated with household and commercial contents represent the largest share of total damage, followed by infrastructure and structural losses. Average damages per exposed building were estimated at approximately US$ 1,244 for construction, US$ 4,089 for contents, and US$ 1,599 for infrastructure, while maximum sector-level losses reached US$ 1.27 million, US$ 2.12 million, and US$ 1.01 million, respectively. Although higher-income classes exhibit greater individual losses, total damage is concentrated in lower-income sectors due to their higher spatial prevalence, highlighting the importance of integrating high-resolution flood modelling with socioeconomic data for urban flood-risk management.

KEYWORDS: Flood damage assessment; Socioeconomic vulnerability; Megacities; Flood risk management

1 INTRODUCTION

Flood risk arises from the interaction between hazard, exposure, and vulnerability, and effective flood management therefore requires integrated assessments of these components (IPCC, 2014). In rapidly urbanizing regions, particularly in Latin America, informal settlements, weak land-use regulation, socioeconomic inequalities, and deficits in basic infrastructure significantly increase exposure and vulnerability to flooding (Der Sarkissian et al., 2022). As a result, populations in megacities such as São Paulo remain highly susceptible to recurrent hydrometeorological disasters, especially where urban expansion has outpaced the implementation of adequate mitigation and adaptation measures (UN-Habitat, 2020).

The Metropolitan Region of São Paulo exemplifies these challenges, where intense rainfall combined with dense urban occupation, topographic constraints, and widespread impervious cover results in frequent flash floods and riverine flooding (Borba et al., 2016). Within this region, the Aricanduva River catchment stands out due to its high flood recurrence and demographic density. Flood events in this catchment regularly cause population displacement, damage to infrastructure, traffic disruption, and considerable economic losses (Simas, 2017; Haddad & Teixeira, 2015), highlighting the need for detailed and spatially explicit flood hazard assessments.

Recent advances in flood modelling, supported by LiDAR-derived digital elevation models and computationally efficient algorithms, have improved the representation of flood dynamics in urban environments (Vashit & Singh, 2024). Cellular automata–based models, such as CAFlood, offer an efficient alternative for simulating flood scenarios in densely urbanized catchments, where detailed topography plays a key role in flow propagation. When integrated with socioeconomic data, these models enable the estimation of direct economic losses and the assessment of community vulnerability (Merz et al., 2010).

In this context, the Aricanduva catchment provides a valuable case study for combining high-resolution flood modelling with census-based socioeconomic information. By integrating extreme rainfall scenarios, automated hydraulic modelling, and economic loss estimation through depth–damage functions, this study contributes to a more robust understanding of flood impacts in megacities of the Global South and supports evidence-based flood-risk management and urban planning strategies.

2 METHODOLOGY

2.1 Study area

The Aricanduva catchment is located in the eastern portion of São Paulo, Brazil, covering approximately 102.5–103 km² of highly urbanized territory (Figure 1). The catchment is characterized by dense built-up areas, limited natural vegetation, and a history of recurrent flooding. These conditions make it a representative setting for studies focused on hydrological processes and flood dynamics in megacities.

The climate of the region is classified as humid subtropical (Köppen), with an average annual temperature of around 19 °C. Seasonal variability is marked: temperatures range from 17.2 °C in July to 23.5 °C in February, while rainfall varies from 32.3 mm during the dry month of August to 292.1 mm in January, the peak of the wet season (INMET, 2020). The average annual discharge of the Aricanduva River is about 5.6 m³/s, and its channel width ranges from 13.3 m near the headwaters to 18.3 m near the outlet.

In addition to its hydrological relevance, the catchment presents significant socioeconomic vulnerability. With a population density of roughly 7,400 inhabitants/km^2 (IBGE, 2022), flash flooding events pose substantial risks of displacement, injuries, and economic losses (Simas, 2017). The area is also well monitored with rainfall, streamflow, and water-level measurements collected at 10-minute intervals over a 10-year period. This extensive monitoring network provides a robust basis for detailed flood modelling and risk assessment.

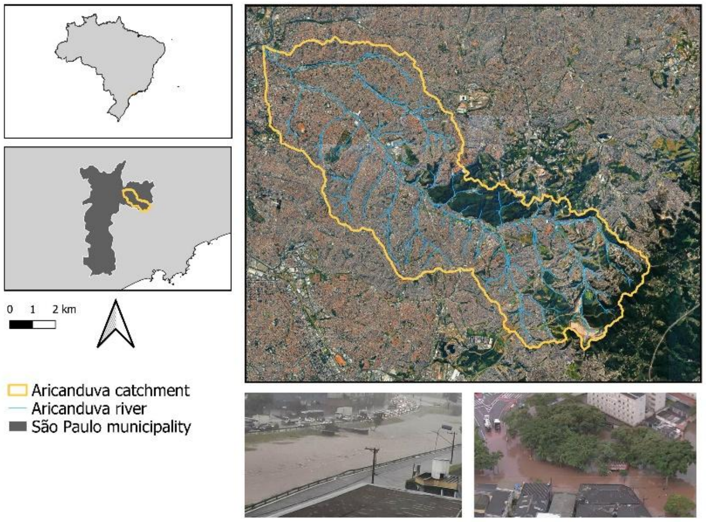

Figure 1: Aricanduva catchment location and pictures of flooding events

2.2 Flood modelling and mapping

Flood modelling for the Aricanduva catchment was conducted using hydrological time series, spatial rainfall interpolation, and two-dimensional hydraulic simulations. Hydrological data were obtained from the telemetric network of the São Paulo Metropolitan Region Flood Warning System (SAISP), which provides rainfall intensity and water level measurements at 10-minute intervals. For this study, one historical rainfall event was selected based on its magnitude and documented impacts on the catchment. The event happened on 2017-04-06, with 84 mm of total rainfall depth and 66 mm/h of peak rainfall intensity. Water depths recorded at four stream gauges distributed across the basin were used to support model assessment, while rainfall data from 12 gauges were interpolated using inverse distance weighting (IDW) with a power coefficient of 2.

Surface flooding dynamics were simulated using the Cellular Automata Dual Drainage System (CADDIES), also known as CAFLOOD a two-dimensional hydraulic model based on Weighted Cellular Automata (WCA2D). The model operates on a grid using a Von Neumann neighborhood structure and applies a ranking technique to determine the volume of water moving between cells. Flow propagation follows the diffusive-wave approximation of the Saint Venant equations combined with Manning's equation, providing a physically based upper limit for intercell flow exchange. Although the simplification omits inertial terms found in full hydrodynamic models, it offers a practical balance between accuracy and computational efficiency, particularly suitable for shallow and slowly varying flows in dense urban environments such as Aricanduva.

The model requires inputs including a digital elevation model (DEM), spatially averaged precipitation, and inflow or water-level boundary conditions. Given the catchment's 103 km² urbanized extent and high imperviousness, precipitation was aggregated to 10-minute intervals for simulation. A single Manning roughness coefficient was applied across the domain, and numerical stability parameters, such as timestep limits, tolerance thresholds, and iteration limits, were maintained at standard recommended values.

2.3 Economic valuation of affected assets and goods

The economic valuation of affected assets exposed to flooding in the Aricanduva River catchment considered damages related to building structures, goods and basic public infrastructure. To this end, data regarding hazard and exposure were integrated using geoprocessing procedures implemented in QGIS. These procedures included the extraction and association of hazard data, i.e. flood maps obtained from hydrodynamic modelling, socioeconomic indicators and the estimation of the number and type of buildings per area, obtained from the Brazilian Census of 2022 (IBGE, 2022). The workflow was structured to integrate flood-depth raster produced by flood modelling with Census and building-footprint layers, enabling a spatially explicit assessment of economic exposure.

For the socioeconomic indicators, Census data provide information on the average household income per census sector. Based on this information, sectors were classified into socioeconomic classes according to income thresholds commonly used in Brazil. These thresholds are expressed in multiples of the national minimum wage, a legally defined monthly income reference used for socioeconomic classification. At the time of analysis, one minimum wage corresponded to approximately R$ 1,412 per month (≈ US$ 270, considering the current conversion rate of R$ 1 ≈ US$ 0.193). The resulting classes were defined as: A (more than 20 minimum wages), B (10–20 minimum wages), C (4–10 minimum wages), D (2–4 minimum wages), and E (less than 2 minimum wages). Additionally, the Census microdata allow the identification of the location and type of each building, which were aggregated at the sector level and categorized as residential or non-residential buildings by summing their occurrences within each sector.

At the end of the workflow, each census sector contained integrated information on flood-depth values, total residential and non-residential buildings, average income, associated socioeconomic class and percentage of the sector area affected by the flood.

Based on the standardized data for each census sector, the estimation of building damages was carried out by cross-referencing the affected built-up area corresponding to each socioeconomic class (standardized according to the construction type defined by NBR 12.721/2006 with the basic unit construction cost provided by the Civil Construction Industry Union (updated in March 2025) for each construction standard category (Table 1).

In addition to structural damages, economic losses associated with the contents of each building were also considered. For this purpose, we used an adaptation of the study by Cançado (2009), presented in PDAU-RMGV (2021), which establishes content costs according to socioeconomic class. These values were updated using the Extended National Consumer Price Index (IPCA) for March 2025 (Table 1).

Table 1: Values of construction and goods' content according to different economic classes

Economic class	**Building standard**	**Category (NBR 12.721/2006)**	**Basic Unit Cost (US$/m²)**	**Content value (US$)**
A	High	R1-A	677.32	26975.16
B	Normal	R1-N	543.05	11313.45
C	Low	R1-B	453.35	3487.91
D and E	Popular	RP1Q	464.05	2723.89

Finally, the estimation of the proportion of damages to buildings and their goods' contents as a function of flood depth was based on Equations 1 and 2, proposed from the work of Machado (2005) and adapted by PDAU-RMGV (2021), where h represents the flood-depth.

$$PercentualDamage_{building} = 0.0125h + 0.0819 \tag{1}$$

$$PercentualDamage_{goods} = 0.2183\ln(h) + 0.4986 \tag{2}$$

As for the damages concerning the public basic infrastructure, according to data from the World Bank, based on actual flood occurrences in Brazilian states, losses in basic infrastructure represent between 12.5% and 30% of the total damage costs. To ensure a more conservative risk assessment, a percentage of 30% of the total estimated losses will be adopted.

3 RESULTS AND DISCUSSION

The flood extent simulated by the CADDIES model for the analyzed event in the Aricanduva catchment is presented in Figure 2. The results indicate that the model is able to realistically represent the basin's hydrodynamics, with well-defined river channels and clear representation of urban features such as buildings, street layout, and detention basins constructed as flood mitigation measures. High flood-depth values within some areas reflect water accumulation in detention basins, confirming that these structures are explicitly accounted for in the model framework. A critical assessment and validation of CADDIES for the Aricanduva catchment, including the event analyzed in this study, is provided by Benso et al. (2024).

Despite the presence of detention basins, Figure 2 shows that these structures are insufficient to fully attenuate flooding during events of this magnitude. Floodwaters still extend over large portions of the basin, particularly in downstream areas (highlighted by the red zoom in Figure 2), where flood depths outside the main channel reach approximately 2 to 4 m. Similar limitations of detention-based mitigation measures under extreme rainfall conditions have also been reported in other studies of highly urbanized basins, where storage capacity is often exceeded during high-intensity storms (e.g., Bhusal et al., 2023). In the Aricanduva catchment, these downstream areas also coincide with higher concentrations of commercial buildings and higher average income levels, increasing the potential for significant economic losses.

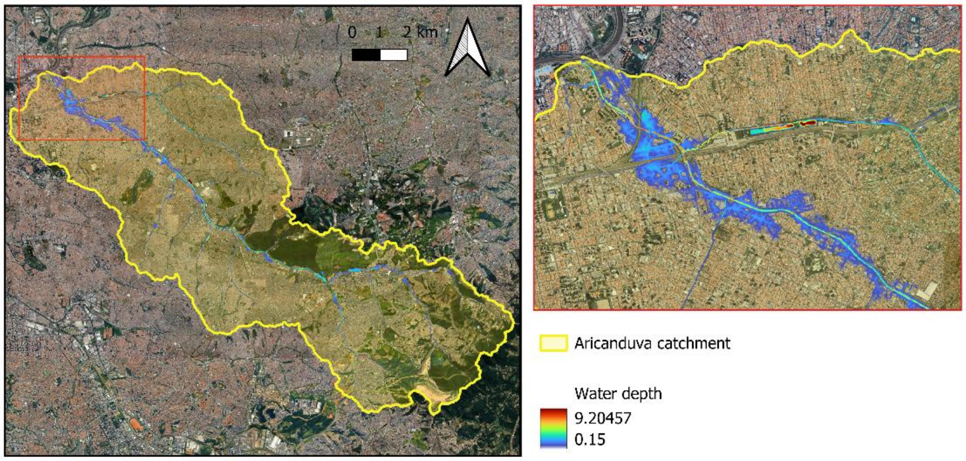

Figure 2: Flood extent and water depth obtained through CADDIES - in the right, it is shown a zoom in the most affected part of the catchment

By intersecting the simulated flood extent with 2022 Census data for the city of São Paulo, restricted to the Aricanduva catchment, economic losses associated with structural damage, infrastructure impacts, and losses of goods within buildings were estimated as a function of flood depth. Aggregated results for the entire basin are shown in Table 2. Losses related to goods and contents represent the largest share of total damages, followed by infrastructure and, finally, building structures. This damage hierarchy is consistent with findings from flood loss assessments in Europe and Asia, where contents often account for a substantial proportion of total urban flood losses, particularly in areas with moderate to high water depths (Merz et al., 2010). At the census-sector scale, maximum estimated losses reached US$ 1.28 million for construction damage, US$ 2.13 million for goods, and US$ 1.02 million for infrastructure, while several sectors experienced negligible losses.

For a more detailed assessment at the building level, average damages per structure (including residential and commercial buildings) were calculated across all census sectors. The mean losses were US$ 1,255 for construction, US$ 4,126 for goods, and US$ 1,615 for infrastructure per building. Figure 3 presents the distribution of individual building losses by census sector and socioeconomic class. As expected, individual losses related to construction and goods are higher for class B, reflecting the higher asset values associated with this group. These are followed by classes C, D, and E, with relatively small differences among the latter classes. Similar patterns have been documented in international studies, where higher-income groups exhibit larger per-asset losses, while lower-income groups tend to experience smaller individual losses but higher cumulative impacts due to greater exposure (Kreibich et al., 2014). Infrastructure losses remain nearly constant across socioeconomic classes, reflecting the relatively homogeneous provision of basic urban infrastructure across income groups in large cities.

Table 2: Statistics of economic damages for the Aricanduva catchment

	Economic damages (mi US$)		
	Construction	**Goods**	**Infrastructure**
Total	1123.03	3693.76	1444.45
Average	0.03	0.11	0.04
Min	0.00	0.00	0.00
Max	1.28	2.13	1.02
Standard deviation	0.09	0.16	0.07

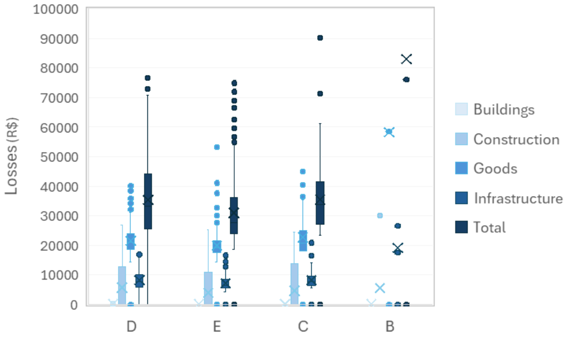

Figure 3: Flood damages per economic class and losses' type in the Aricanduva catchment. Conversion rate: R$ 1 ≈ US$ 0.193

Although class B exhibits the highest individual losses, class D accounts for the largest total losses at the catchment scale, as it is the most numerous socioeconomic group in the Aricanduva basin. This finding underscores the importance of population distribution in shaping aggregate flood impacts and aligns with international evidence showing that middle- and lower-middle-income groups often bear a disproportionate share of total urban flood losses (Winsemius et al., 2016).

Figure 4 focuses on sectors where total losses exceed US$ 1.94 million, classified here as extreme losses. While Figure 4 does not reveal a strong spatial pattern, Figure 4 shows that extreme losses are predominantly concentrated in downstream areas of the catchment. These sectors correspond to locations with higher simulated flood depths outside the river channel or detention basins (Figure 2) and a higher density of commercial establishments. Comparable spatial clustering of extreme flood losses in downstream or low-lying urban areas has been reported in studies of large cities worldwide, emphasizing the combined role of hazard intensity and economic concentration in amplifying flood risk (Hallegatte et al., 2013). This spatial variability reflects the combined effects of local flood depth, building density, and socioeconomic characteristics, as also observed in other large metropolitan areas (Jongman et al., 2012; Tellman et al., 2021).

Overall, the results highlight that flood risk in the Aricanduva catchment is governed not only by hydrological processes but also by the spatial distribution of socioeconomic assets and urban infrastructure. While detention basins provide localized benefits, they are insufficient to prevent significant losses during extreme events, particularly in economically dense downstream areas. These findings reinforce international evidence advocating for integrated flood risk management approaches that combine structural measures with land-use planning, asset-level protection, and targeted adaptation strategies to reduce exposure and vulnerability in megacities.

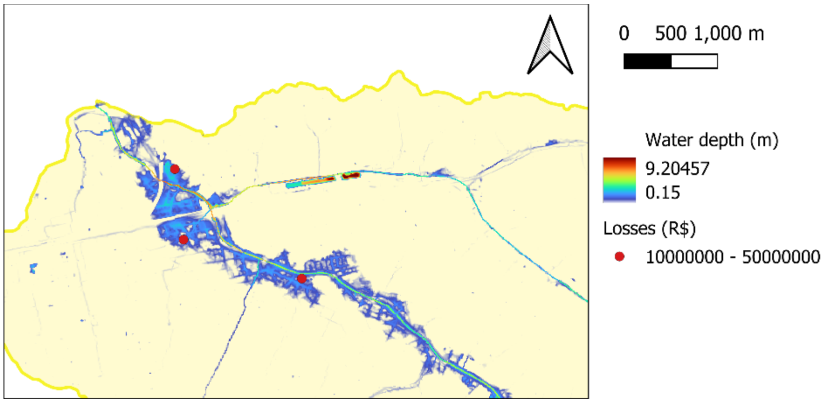

Figure 4: Zoom in the three most damaged points

4 CONCLUSION

This study highlights the value of integrating high-resolution two-dimensional flood modelling with socioeconomic data to support detailed flood impact assessments in highly urbanized catchments. The application of the CADDIES model in the Aricanduva basin successfully represented key hydrodynamic processes, including channelized flow, floodplain inundation, and the effects of detention basins. By combining simulated flood depths with census-based indicators, the results show that losses associated with household and commercial goods constitute the largest share of total damages, followed by infrastructure and structural impacts. While higher-income classes present greater individual losses, total damages are concentrated in lower-income classes due to their greater spatial extent and population density. These findings reinforce the importance of coupling physical flood modelling with socioeconomic vulnerability indicators to inform urban planning and flood risk management strategies.

Nevertheless, this study is limited to the estimation of direct tangible damages and does not account for indirect flood impacts. Losses related to disrupted economic activities, reduced mobility, loss of working hours and income, as well as health-related effects that impair labor capacity were not considered. Such impacts can significantly increase the overall cost of flooding in urban areas. Future research should aim to incorporate these indirect and intangible dimensions, potentially through the integration of economic, mobility, and public health data, to provide a more comprehensive assessment of flood risk and its socioeconomic consequences.

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