Supporting decision-making on urban flood control alternatives through a recovery deficit procedure for successive events

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Abstract

The occurrence of floods poses a challenge to cities, resulting in tragedies and losses in watersheds unprepared to receive massive amounts of water. Therefore, studies to define impacts caused by successive flood events are essential to quantify long-term losses and allow feasibility analysis of design alternatives to mitigate them. The financial losses caused by each event trigger successive recovery processes. Thus, it is important to identify areas with low resilience to guide public investment to prevent progressive degradation. This work presents a method to analyze successive flood events considering the recoverability of the region. To illustrate the method’s application, two case studies were performed, in the Mangue Channel and Acari River watersheds of Rio de Janeiro, regions with different recovery capabilities, to test the method in different conditions and check the criticality level of these areas in relation to resilience gaps. The watersheds were also evaluated regarding projects designed to mitigate rainfall events with return periods of 5, 10, and 25 years. Among the results were confirmation of the efficiency of projects designed for lower recurrence intervals in mitigating successive damages, showing that more frequent events (although less critical individually) can be of great importance in flood control strategies.

Keywords

decision support, flood damages, flood recovery, vulnerability

1 INTRODUCTION

Floods are acknowledged to be one of the most significant natural hazards (Jha, Bloch, & Lamond, 2012), responsible for causing major damages all over the world (UNISDR, 2011). The rising trend of flood losses and the large number of people affected by extreme events are mainly related to the intensification of urbanization, which puts pressure on the environment and increases the occupation of risky areas (Cannon, 2000; Price & Vojinovic, 2008). Climate change also may play an important role in this situation (Whitfield, 2012). These factors alter the conditions for coexistence of urban populations with the natural water cycle and challenge the management of flood risks, whose objective is mitigation of social, economic, and environmental impacts.
Flood risk is defined as the combination of a hazard—the probability of a flood event; exposure—the number and type of flooded areas or elements; and vulnerability—composed of susceptibility, cost of damage, and resilience (Kron, 2005; Sayers et al., 2013). The application of resilience theory to natural hazard management is relatively new, despite its long history in ecology and engineering (Berkes, 2007). According to Batica and Gourbesville (2016), there are five elements that comprise resilience: reflection, relief, resistance, response, and recovery. Thus, urban resilience is the capacity of the city to tolerate flooding and avoid physical damage and socioeconomic disruption (Lhomme, Serre, Diab, & Laganier, 2013; Liao, 2012).

The impact of flood events refers to all types of harmful effects on people (health and safety), properties, infrastructure, ecological systems, industrial production, and the economy in general. Flood damages can first be classified as direct or indirect and second as tangible or intangible (Messner et al., 2007). The level of direct and tangible economic damages is one of the simplest and most important indicators of the consequences of flood hazard (Granh & Nyberg, 2017).

Different models have been developed to evaluate flood losses. Naumann, Nikolowski, and Golz (2009) presented an engineering approach with synthetic depth-damage functions for different building types considering individual damage processes. Dottori, Figueiredo, Martina, Molinari, and Scorzini (2016) also proposed a synthetic flood damage model based on a component-by-component analysis of physical damage to buildings and tested their method through a case study in northern Italy. Deniz, Arneson, Liel, Dashti, and Javernick-Will (2017) developed two models for predicting direct economic losses for single-family residences based on the 2013 Colorado floods. Wijayanti, Zhu, Hellegers, Budiyono, and van Ierland (2017) estimated flood damage in Jakarta by means of a survey and compared these values with the damage estimated by a flood damage model. Oubennaceur, Chokmani, Nastev, Lhissou, and El Alem (2019) presented a probabilistic approach for flood risk management considering direct damage to residential building (structural and nonstructural damage, excluding damage to contents). Eckhardt, Leiras, and Thomé (2019) reviewed a wide range of documents to identify the existing methods to assess the economic costs of disasters and presented a critical analysis, proposing improvements, and avenues for research.

Flood damage models are site specific, which means they are valid only for the context for which they have been developed (Cammerer, Thielen, & Lammel, 2013; Scorzini & Frank, 2017). The transfer of the models in space should take into consideration the particularities of each place. Therefore, proposals for flood control projects need to evaluate the peculiarity of the region under study and the characteristics of the population. Solutions to urban flooding problems should include, in addition to conventional actions that modify the watercourse system, measures that conserve the environment and reduce damages through better coexistence of the population with floods. Early warning systems and prediction techniques, for instance, can be used to anticipate events (Ball et al., 2012; Golian, Yazdi, Martina, & Sheshangosht, 2015) and reduce their negative effects. Preventive measures can avoid the materialization of the risk (Behrouz & Alimohammadi, 2016), mitigation measures can reduce flood consequences in anticipation, and response measures can reduce losses when the event occurs.

Despite all the advances in designing flood controls and developing flood modeling, it is not possible to completely eliminate flood hazard and flood damage (Jha, Miner, & Stanton-Geddes, 2013; Kalyanapu, Judi, Mcpherson, & Burian, 2015; Moe & Pathranarakul, 2006) due to the economic and financial limitations associated with the costs of engineering works and the inability to predict meteorological events with precision and precedence. More than that, there is always a residual risk, since the flood event has a probabilistic character, which implies that it is always possible for a rare flood event to occur that exceeds the design flood (Plate, 2002). Therefore, there is a limit to what is reasonable to try to protect, which is associated with the cost of public works to mitigate the effects of floods compared to the losses to the socioeconomic system avoided by the protections implemented.

The concept of risk in hydrological analysis is usually expressed in terms of annual probability, that is, the probability that a flood of a given magnitude will occur, or be exceeded, in any year (McBain, Wilkes, & Retter, 2010). This definition is in line with the traditional expression of return period, which expresses the expected frequency of an event and defines the degree of safety associated with the project (Sayers et al., 2013). Often, due to the lack of measurements of water levels and discharges for flood events, especially in urban areas, the recurrence interval is associated with maximum rainfall depths (and their own return periods), to determine specific characteristics for the flood, such as water depths, flow velocities, and duration. This approach accepts that the rainfall recurrence interval is approximately comparable to that of the flood, which is not necessarily accurate, since previous rainfall events and soil moisture affect each flood event differently.

In Brazil, there is a standard recommendation for macro drainage and flood control projects, in which the
acceptable risk of failure of the project corresponds to floods with a return period of 25 years or more (Ministério das Cidades, 2012). This is to say that projects must consider 25-year average recurrence interval as a reference for the flood event to be avoided. This is a primary condition to request federal funds from the Ministry of Cities. If a project proposal uses sustainable urban drainage concepts, it is necessary and sufficient to respect this standard recommendation, which exempts a more detailed evaluation of the influence of probability on costs and benefits arising from implementation of the project. The lack of discussion about this problem makes it difficult to obtain more economical and effective solutions—and even to reach an effective sustainable drainage system. Sufficient space does not always exist in the urban network to implement significant works associated with higher return periods without major encumbrances and operational disruptions. On the other hand, the situation is often so critical in some areas that small and recurring disaster events can already cause severe flooding and significant damages (UNISDR, 2015). Besides this, economic and human losses from flooding can push households into a poverty cycle that is difficult to overcome (Vu & Ranzi, 2017).

Indeed, in many situations, reasons such as financial limitations, low priority for risk reduction, and so on can encourage the use of a design event with a lesser magnitude than that of the standard design project (Kalyanapu et al., 2015).

Given these facts, this study proposes an integrated method that combines: (a) the analysis of losses to the population affected by floods over a project horizon, rather than considering a single reference event; (b) the region’s recovery capacity, which is associated with the socioeconomic fragility of the population and its (in) capacity to recover from losses; and (c) optimization of the recurrence interval used in the design of the flood control project in a given region. Note that the main objective of the method lies in recovery from the damages borne by local residents (not by the government). Therefore, the considered losses are limited and do not represent the total losses associated with the event.

Although it does not include the losses to the public sector, this type of evaluation could indicate the best cost–benefit ratio by comparing flood risk mitigation projects sized for different recurrence intervals, as well as justifying the allocation of resources for project implementation, considering the socioeconomic fragility. The total value of the avoided losses suffered by residents and of the works proposed as solution, in each project configuration, for different return periods, can be analyzed to define an optimized alternative. Therefore, this paper discusses the concept of an optimal recurrence interval for the design of projects in a given region, supported by an exploratory study.

2 | METHODOLOGY

2.1 | Horizon of analysis

Intending to incorporate long-term effects in flood control assessment, we suggest that flood losses, and hence the socioeconomic fragility of the watershed, should be considered within a certain time horizon, when successive flood events may occur, instead of just considering a single reference event. This proposition allows estimating the annual average results (Kalyanapu et al., 2015; Li et al., 2016; Mohammadi, Nazaria, & Mehrdadi, 2014; Tariq, 2013) to approximate the reality of the basin, justifying the allocation of resources for the implementation of major drainage and flood control projects.

Through a random draw, sequences of rain events are defined based on their individual probabilities of occurrence, associated with reference return periods. In order to limit the sample and allow the calculation of the losses associated with specific events, reference return periods of 1, 5, 10, 25, 50, 100, and 500 years were adopted. Besides, a project horizon of 50 years was defined, based on the typical useful life of residential buildings in general (Miguez, Raupp, & Veról, 2018).

To compose the sequences, 10,000 events were drawn, resulting in 200 sequences of 50 years. These sequences were organized according to their level of criticality and divided into three groups: more favorable events (sequence F), medium events (sequence M), and more unfavorable events (sequence U). To obtain the representative sequence of each group, the mean number of events of each return period was calculated and these were distributed along the project horizon by random draw of their position.

2.2 | Hydrological and hydrodynamic modeling

The intensity of the design rainfall, associated with the reference events, was obtained through the intensity-duration-frequency equations (IDF’s) representative of the study areas (PCRJ, 2010). In turn, the rainfall distribution was based on the alternate blocks method from the Bureau of Reclamation (SCS, 1975).

These rainfall events were used in the hydrological and hydrodynamic model MODCEL (Mascarenhas & Miguez, 2002; Miguez et al., 2017) to produce flood maps. MODCEL was chosen because of its capacity to represent
surface runoff behavior, especially during flood events in urban spaces, associating these surface flows with storm drains and open channels. In addition, this model was used in previous works, developed in the watersheds related with the case studies, which allowed quickly reaching a reliable working base.

MODCEL considers that nature can be represented by dividing the watershed into homogeneous and interconnected compartments, called cells. The cells have a storage capacity and compose a quasi-two-dimensional flow network, from one-dimensional hydraulic relations linking neighboring cells. The main hydraulic relation is the dynamic equation of Saint-Venant, which can represent the flow in rivers, channels, and floodplains. Besides the hydraulic links, which allow the exchange of flow between cells, each cell receives a contribution of precipitation and performs internal hydrological processes to transform rainfall into runoff.

2.3 | Estimating losses

With the flood maps obtained from the hydrological and hydrodynamic modeling, the economic losses resulting from the reference events were evaluated through an adaptation and update of the study developed by Nagem (2008), who built depth–damage curves based on the original work of Salgado (1995). In this method, Nagem (2008) considered the costs associated with waterborne diseases, residential damage, house cleaning, material damage to vehicles, and diseconomies related to lack of mobility as the most significant impacts of flooding in urban areas. However, according to the results, damage to homes (structure + contents) and to vehicles accounted for approximately 96% of the total losses estimated. Given this fact, to simplify the measurement of losses and make the method more practical and applicable, only these damages were used in the analysis of the case studies developed here. Furthermore, since the losses are compared with the households’ recovery capacity, it is assumed that only damages that can be remedied or restored by the population in the basin should be considered, and they should be considered integrally. In the original method, since the main intention was to assess economic losses, a depreciation factor was applied to represent the real value lost. However, when considering that people have to replace lost goods, this paper did not consider depreciation.

The damage to residential properties was divided into damage to the building structure and to the building contents. The former corresponds to damage to all construction components, while the latter refers to damage to consumer goods found inside residences, such as furniture and appliances (listed in Table 1).

| Room        | Consumer goods       | Room       | Consumer goods       |
|-------------|----------------------|------------|----------------------|
| Living room | Two-seat sofa        | Master bedroom | Double box springs |
|             | Three-seat sofa      |            | Double mattress      |
|             | Center table         |            | Six-piece cabinet    |
|             | Shelf set            |            | Television           |
|             | TV stand             |            | Dresser              |
|             | Air conditioner      |            | Telephone            |
|             | Fan                  |            | Bedside table (two units) |
|             | Television           |            | Table lamp           |
|             | DVD player           |            | Alarm clock          |
|             | Micro sound system   | Kitchen    | Kitchen cabinets     |
|             | Computer             |            | Table set with four chairs |
|             | Computer desk        |            | Stove                |
|             | Coffee table         |            | Stove exhaust hood   |
|             | Telephone            |            | Electric oven        |
|             | Table lamp           |            | Microwave oven       |
| Dining room | Dining table set     | Refrigerator | Freezer             |
|             | with six chairs      |            |                      |
|             | Low storage cabinet  |            |                      |
| Single      | Single box springs   | Toaster    |                      |
| bedroom     | Single mattress      | Blender    |                      |
|             | Three-piece cabinet  | Food mixer |                      |
|             | Dresser              | Dish washer|                      |
|             | Bedside table        | Coffee maker|                    |
|             | Table lamp           | Washing machine |                |
|             | Service area         |            |                      |
|             | Alarm clock          |            | Iron                 |
|             | Writing desk         |            | Vacuum cleaner       |
|             | Chair                |            |                      |
|             | Fan                  |            |                      |

It is important to note that the damage estimation considered in this study is limited to damages supported by the population, and therefore it is representative of the socioeconomic fragility. Furthermore, damage to
buildings is more easily measurable and can generally indicate the criticality of flooding in the region. Despite this, there are other significant damages that are not counted, such as damage to urban infrastructure, which is the responsibility of the public sector and can represent a considerable portion of total flood losses by value.

### 2.3.1 Damage to residential buildings

The calculation of the damage to residential buildings used the standardization of the characteristics of the properties and the constructive standards according to the Brazilian technical standard NBR 12721/2005 (ABNT, 2005), which establishes criteria for the calculation of the basic unitary costs (BUC) of construction. In addition, this paper used the Brazilian Economic Classification Criterion (ABEP, 2015), which divides society into economic classes (A, B1, B2, C1, C2, and D–E, from highest to lowest) according to households’ purchasing power. The Brazilian technical standard NBR 12721/2005 (ABNT, 2005) presents four building types that are combined to the social status to determine the construction BUC associated with each cell of the model. Therefore, economic class A is associated with a higher standard building type while classes D–E are related to the lower standards.

Nagem (2008) also estimated the building damage percentage (BDP), based on the depth of flood reaching the building, through the flood depth × damage function, as originally developed by Salgado (1995). Like the construction BUC, the BDP varies with the building type.

Summing up, damage to residential buildings was calculated through Equation (1):

$$\text{CDRB} = \text{BUC} \times \text{BDP} \times \text{NHC} \times \text{AD} \quad (1)$$

where CDRB is the cost of damage to residential building ($); BUC is the basic unitary cost of construction ($/m^2); BDP is the building damage percentage; NHC is the number of households, considering the correction of the number of apartments by the average height of the neighborhood, since usually only the ground floor is directly affected by floods; and AD is the area of the standard house referenced to the household income (m²).

### 2.3.2 Damage to building contents

The type of contents, the quantity of goods, and the monetary value of the items vary according to socioeconomic status of each household. Thus, in order to quantify damages to building contents, a standard dwelling was defined by a survey of consumption items and their location and distribution in residences. From this survey, the authors defined the flood ranges that can damage each item and its replacement costs. In order to consider generally less expensive items, such as clothing, foodstuffs, and decorative items, among others, the final value was increased by 15%, as suggested by Nagem (2008).

Since the survey was carried out for a standard class of property, a multiplication factor (depending on the purchasing power of each social class) was applied for the other classes. For higher household incomes, this factor is greater than 1, increasing replacement costs, whereas for lower incomes, this factor is less than 1.

Finally, the damage to the contents was calculated through Equation (2):

$$\text{CDCR} = 1.15 \times \left( \frac{\text{CCSP}}{\text{SPA}} \times \text{MF} \right) \times \text{NHC} \times \text{AD} \quad (2)$$

where CDCR is the cost of damages to contents of residences ($); CCSP is the cost of the contents of the standard property ($); SPA is the standard property area (m²); MF is the multiplier factor; NHC is the number of households, considering the correction of the number of apartments by the average height of the neighborhood, since only the ground floor is directly affected by floods; and AD is the area of the standard house referenced to the household income (m²).

### 2.3.3 Damage to vehicles

Material damage to vehicles is counted for flood depths starting at 30 cm. Considering a basic vehicle, it is possible to estimate the cost of repairing the damage, associated with a certain range of flood depth, from a survey of repair shops. When the depth of flood reaches 100 cm, total loss occurs so the cost of this damage refers is the vehicle replacement cost.

Briefly, material damage to vehicles was calculated using Equation (3):

$$\text{CDV} = \text{NVH} \times \text{NH} \times \text{DC} \quad (3)$$

where CDV is the cost of damage to vehicles ($); NVH is the number of vehicles per household; NH is the number of households; and DC is the damage cost according to flood depth ($).

It should be noted that the use of the NVH variable is an approximation, resulting from a conceptual model. Some garages will be protected against flooding (by ramps or location above ground level), but it is
assumed that cars passing on flooded streets (not necessarily belonging to local residents) will suffer damage and this number will offset any cars not affected because they are parked in protected garages.

2.3.4 Total losses

The total cost of damage was obtained by adding up the portions of damage to residential buildings, their contents, and vehicles.

Using the losses associated with each reference event, the total losses in each sequence were calculated and the result was divided by number of years of the project horizon to obtain a base value for the expected annual loss. This value could be higher with the inclusion of other complementary items (and also possibly considering indirect losses), but we considered it to be representative of the total cost of losses, useful to evaluate the relevance of implementing flood control projects.

2.4 Recovery capacity

After major flood events, it is common for the recovery phase not only to rebuild the affected assets to restore their functions and services, but also to reduce vulnerability to flood risk and improve system resistance and resilience. Nevertheless, especially in developing countries, frequent (and therefore less severe) events may cause major losses despite theoretically having low impact. Thus, usually there is little or no action taken by the government to increase resilience, since these events are not considered of major importance. With the lack of public investment and focusing on the household losses, the recovery capacity is defined in this article as the monetary value that a particular social class can invest to recover and/or restore goods damaged by floods that affected their residences. This variable was established based on the concepts of average monthly household income and minimum income required to live. The average monthly household income corresponds to the income obtained through the sum of the monthly income of all residents of the household. The minimum income required corresponds to the opinion of the respondent about the value of the minimum monthly family income necessary to survive to the end of the month (Rosa, 2015).

Assuming that the cost of living of a family is equal to the minimum necessary income, it is possible to calculate the percentage of income available to a particular social class. When this percentage is equal to or greater than 100%, the population is not able to recover. If the percentage is less than 100%, the remainder of the income, called disposable income, can be used to recover and/or replace goods damaged by floods.

Another important consideration regarding the proposed model is the hypothesis that there is no previous specific savings related with the recovery capacity, which means that if in a given year no damages occur due to flooding, the family uses the disposable income for other purposes, such as leisure and other factors that improve quality of life. Therefore, in the computation of the recovery capacity, there is no reserve from previous years available for recovery and/or replacement of assets before they are damaged. Flood insurance can eventually be considered as a compensation to cover the lack of savings. However, no flood insurance is considered in this study, since it is not common to have this assurance in developing countries. These hypotheses allow simulating the most critical situation in terms of recovery capacity. Furthermore, when using potential savings for flood recovery, other social purposes (like leisure, travel, renovating houses, etc.) can be considered as indirect losses that would nullify the increase in the recovery capacity.

2.5 Recovery deficit

Combining and comparing the economic losses and the recovery capacity along the sequence of events, it is possible to understand and analyze the effects of successive floods through the recovery deficit, which represents the value still to be recovered, calculated according to Equations (4) and (5). When the recovery deficit in a given year is greater than zero, it implies there complete recovery was not achieved, so this amount should be recovered in subsequent years. In turn, values equal to zero indicate that complete recovery occurred.

\[
RD_i = \begin{cases} 
0, & \text{if } TL_i - RC \leq 0 \\
TL_i - RC, & \text{if } TL_i - RC > 0 
\end{cases}
\]  

(4)

\[
RD_i = \begin{cases} 
0, & \text{if } RD_{i-1} = 0 \text{ and } TL_i - RC \leq 0 \\
TL_i - RC, & \text{if } RD_{i-1} = 0 \text{ and } TL_i - RC > 0 \\
RD_{i-1} + TL_i - RC, & \text{if } RD_{i-1} \neq 0 \text{ and } RD_{i-1} + TL_i - RC > 0 \\
0, & \text{if } RD_{i-1} \neq 0 \text{ and } RD_{i-1} + TL_i - RC \leq 0 
\end{cases}
\]  

(5)

where \(RD_i\) is the recovery deficit in year \(i\); \(TL_i\) indicates the total losses in year \(i\); and \(RC\) is the recovery capacity.

Figure 1 summarizes the method proposed in this paper.
2.6 | Scenarios

The analysis of scenarios comprises original and projected situations. In the scenario that represents the current situation (without the implementation of any flood control project), flood depths were obtained directly from calibrated and validated models for the urban basins under study.

In the project scenarios, the effects of the implementation of projects designed for different return periods (in this case, 5, 10, and 25 years) were analyzed. However, the projects were not effectively developed and modeled. In this analysis, we assumed that, regardless of any project conception, they were able to completely eliminate losses associated with each of the events for which they were designed. That is equivalent to saying that each project was 100% effective for the return period considered in its conception. This simplification aims to optimize the analysis of scenarios, considering that for each return period, it is possible to combine several effective design alternatives. This choice implies not undertaking an economic feasibility assessment for each project, since it will not be possible to estimate the costs of implementation.

Finally, it is possible to compare the damage results for different scenarios over the project horizon, which allows the assessment of the importance of a given recurrence interval in the design of the flood control project.

2.7 | Case studies

To present the potential of the method, two contrasting urban watersheds located in Rio de Janeiro, Brazil, were chosen as case studies, namely Mangue Channel watershed and Acari River basin. The latter region is significantly poorer than the former one.

2.7.1 | Case study 1: Mangue Channel

Mangue Channel watershed, presented in Figure 2, has a drainage area of about 45 km² and contains traditional neighborhoods that frequently suffer from flooding.

There are five main watercourses that compose the Mangue Channel watershed, specifically Maracanã, Joana, Comprido, Trapicheiros, and Papa-Couve rivers. The basin empties into Guanabara Bay, through an artificial channel that gives name to the watershed.

The relief of this basin presents sharp gradients in the western and southwestern regions, where Tijuca Massif is located, followed by an almost flat urbanized area.

Based on the most recent national demographic census (IBGE, 2010), most of the area of the basin is occupied by economic class B2, which indicates an intermediate social status. Table 2 presents the percentages of the basin area associated with each economic class and its respective average monthly household income in Brazilian currency (US$ 1.00 = R$3.40). It is important to note that Brazilian demographic census shows average values of household income by census sector. Therefore, in average terms, no areas with social status A and D–E were identified in this basin. This means there may be households with average monthly income compatible with these social statuses, but on the average, these values do not define the census sector’s representative income.

The floods in Mangue Channel watershed are frequent, so several hydraulic works are being carried out (although not completely implemented), as proposed by the Municipal Sanitation Plan of the City of Rio de Janeiro (PCRJ, 2015). These works, designed for a return period of 25 years, according to the current standards (Ministério das Cidades, 2012), were not incorporated into the hydraulic and hydrodynamic modeling used in this study. The situation prior to this set of works was taken as a reference to estimate current losses.
2.7.2 | Case study 2: Acari River

Acari River basin has more than 140 km² of drainage area and contains poorer neighborhoods in the northern region of Rio de Janeiro. The Pavuna and Acari rivers are the tributaries of São João de Meriti River, which flows into Guanabara Bay.

Flood events are frequent in Acari River basin. The high degree of urbanization, with high rates of soil sealing, is a typical aggravating factor. Part of this urbanization also suffers from informal and irregular occupation, forming slum areas (popularly called favelas). In addition, the abrupt slope variation observed in this basin is determinant of the natural drainage conditions. The upstream areas are subjected to high flow velocities, resulting in low concentration times, high peak discharges, and strong propensity to carry sediments downstream. In contrast, downstream areas are subjected to low flow speeds, which favor the accumulation of upstream sediments, causing sedimentation and progressive reduction of flow capacity in the drainage system. Garbage collection is also deficient; so Acari River accumulates solid waste in several sections. Besides that, flow capacity problems exist at bottleneck points (cross section contraction), mainly associated with railway bridges, footbridges, and to a slightly lesser extent, road bridges, such as those of Avenida Brasil (BR-101) and Presidente Dutra Highway (BR-116).

The mathematical modeling of Acari River basin was divided into two parts: a detailed region modeled as cells covering most of the critical areas of the basin in terms of flooding (the lower and flatter areas), and a set of areas that were individually simulated and treated as boundary conditions.
conditions in MODCEL. The region detailed as flow cells is highlighted in Figure 3.

In contrast to Mangue Channel watershed, the demographic census indicates higher concentration of economic class C2 in Acari River basin, which suggests that the latter is significantly poorer than the former. Table 3 presents the percentages of Acari River basin area associated with each economic class and its respective average monthly household income.

3 | RESULTS AND DISCUSSION

The main results of applying the proposed method to the case studies are presented next.

3.1 | Average annual damage

The average annual damage for each sequence is obtained from the average of the total losses over the project horizon. This means that for each sequence, the losses of each cell were added over 50 years, resulting in a total loss value during the project horizon. This amount was then divided by 50 years, resulting in the average annual damage. Table 4 presents the results for Mangue Channel watershed and Acari River basin in the original scenario.

The losses in Mangue Channel watershed vary from R$970 to R$1,430 per residence, while in Acari River basin they vary from R$10,390 to R$10,850 per residence (showing high consequences for the household even for the most favorable sequence). These values indicate that Acari River basin is more vulnerable when considering the same sequences of events.
Therefore, it is possible to apply this method to different basins and to prioritize investments in one region instead of another, by comparing the results.

### 3.2 Percentage of loss reduction in project scenarios in relation to the original scenario

After defining the basin where the investments in flood risk mitigation projects should be allocated, it is important to evaluate the pertinence of the return period in terms of damage reduction for the chosen watershed. This can be analyzed by the percentage of loss reduction in each project's scenario in relation to the original scenario.

Figure 4 presents the results obtained for Acari River basin. In sequence F (most favorable events), no events with a return period of more than 10 years were randomly drawn here, so projects designed for 10 or 25 years have an efficiency of 100%. Besides that, for sequences M (medium events) and U (most unfavorable events), the results are positive in terms of damage reduction. Comparing projects designed for recurrence intervals of 10 and 25 years reveals no significant difference in results, and a cost–benefit analysis could justify the implementation of a 10-year return period project.

The evaluation of damage reduction can also be done by comparing damage maps for each scenario. In this case, it is also possible to perform the spatial analysis of the results and propose specific localized solutions that can complement the initially proposed project.

The results presented consider the evaluation of losses over a project horizon. However, they do not include the influence of the region’s recovery capacity yet. Therefore, other results obtained directly from the proposed method can be used to complement the analysis.

### 3.3 Recovery deficit curves

The recovery deficit curves can be constructed from Equations (3) and (4) for different sequences and scenarios.

Considering that the models developed for Mangue Channel watershed and Acari River basin have, respectively, 732 and 189 urban surface cells, it is impracticable to present all the recovery deficit curves in this work. Therefore, we chose the results obtained for emblematic sites of each basin to illustrate the potential of this type of analysis.

In Mangue Channel watershed, we chose a cell near Maracanã stadium (cell 86) and another one near Praça da Bandeira (a public square, cell 392). Both places present recurrent flood problems, with high damage and inconvenience to the population. The recovery deficit curves are exhibited in Figures 5 and 6, respectively. It can be observed that for the medium sequence of events, there is difficulty in recovering from the damage caused by the floods in the scenario without a flood control project. In the Maracanã vicinity, this recovery would be impossible without official intervention, since the recovery deficit is increasing over the project horizon in the original scenario. On the other hand, scenarios with implemented projects, even designed for a 5-year return period would benefit from a 10-year return period project.

| Sequence of analysis | Mangue Channel watershed | Acari River basin |
|----------------------|--------------------------|-------------------|
| Sequence F           | R$ 81.15                 | R$ 1,050.05       |
| Sequence M           | R$ 93.04                 | R$ 1,066.95       |
| Sequence U           | R$ 119.78                | R$ 1,097.01       |

**FIGURE 4** Percentage of loss reduction in project scenarios in relation to the original scenario for Acari River basin

**TABLE 4** Average annual damage

| Sequence of analysis | Average annual damage (in R$ millions) |
|----------------------|----------------------------------------|
|                      | Mangue Channel watershed | Acari River basin |
| Sequence F           | R$ 81.15                 | R$ 1,050.05       |
| Sequence M           | R$ 93.04                 | R$ 1,066.95       |
| Sequence U           | R$ 119.78                | R$ 1,097.01       |
**FIGURE 5**  Recovery deficit curve for cell 86, located near Maracanã stadium

**FIGURE 6**  Recovery deficit curve for cell 392, located near Praça da Bandeira
period, can mitigate losses in such a way that recovery over the project horizon becomes feasible. In the area near Praça da Bandeira, there are recovery deficit spikes that are compensated in the following years. With the projects, these peaks become less accentuated or nonexistent.

In Acari River basin, we chose a cell in the Parque Columbia neighborhood (cell 1402), an area with a mainly low-income population living in a very low-lying area. The recovery deficit curve for this cell is presented in Figure 7. As in the Maracana vicinity, it is possible to perceive the difficulty of recovering from losses. However, it is important to note that the results are even more critical here. Given the magnitude of the losses, the implementation of flood control projects is capable of significantly reducing the problem. However, even with the project designed for a 25-year return period, the population would be unable to completely recover from their losses over the project horizon, indicating the criticality of this region in social terms.

### 3.4 Maximum consecutive years for full recovery from damage

Another result that allows analyzing how the recovery of the basin occurs during the project horizon refers to the time for a given region to fully recover from the damages suffered, considering the occurrence of a sequence of events. For each sequence, we computed the maximum number of consecutive years elapsed before the recovery was complete. Considering the 50-year project horizon, the most critical situation is the one in which the population takes 50 years to recover or fails to achieve full recovery.
**FIGURE 8** Percentage of households in Mangue Channel watershed in each range of maximum consecutive years for full recovery from damage.

**FIGURE 9** Percentage of households in Acari River basin in each range of maximum consecutive years for full recovery from damage.

**FIGURE 10** Percentage of households in Acari River basin in each range of maximum consecutive years for full recovery from damage—project scenarios.
recovery over the project horizon. Note that this type of analysis refers to the number of years for recovery rather than reporting the year in which the recovery occurs as used in the previous results.

Therefore, this analysis can be used to compare the effects of a sequence of events in different basins. Figures 8 and 9 present the results comparing the proposed sequences of events for Mangue Channel watershed and Acari River basin, respectively. The former one has a higher income population, so it is easier to recover from flood losses, which explains the high percentage of households in the 0-year range. On the other hand, the population in Acari River basin has a lower income, which reduces the region’s recovery capacity. This explains why nearly 50% of households cannot recover at all from the first event that occurred in the project horizon (50-year range).

This analysis of the maximum number of consecutive years needed for full recovery from damage can also be used to evaluate the influence of different project scenarios. Figure 10 presents these results for Acari River basin. Projects designed for 5-year return period are already capable of eliminating the previous worst results, in which almost 50% of the population would be unable to recover fully from the first event in the sequence even after 50 years, proving their efficiency. It is evident that the results are even better with projects designed for return periods of 10 and 25 years, but only by completing the evaluation with the cost–benefit analysis could the optimal solution be determined.

4 | CONCLUSIONS

Growing concern with flood risk assessment can be seen in the literature reviewed, as well as in practical examples around the world. However, there is a shortage of studies that consider the impact of successive events on urban environments’ degradation and their influence on the affected population’s resilience. This aspect is important because since available income is limited, people have greater difficulty to recover from successively recurrent events, thus reducing their resilience.

Therefore, the purpose of this work was to integrate hydrodynamic modeling, calculation of flood damage, and a variable associated with recovery capacity, based on the income of the resident population in the watershed, to evaluate the urban degradation resulting from successive flood events accumulated in a certain time horizon, instead of considering a single reference event.

The applicability of the proposed method was verified through the case studies of Mangue Channel and Acari River. In addition to allowing the comparison of results for different basins, this approach can also be used for the analysis of project scenarios, in the search for an optimal solution for each region. To complement the results, it would be interesting to include the cost of implementing each project alternative to perform a cost–benefit analysis. It would also be relevant to take into account climate changes in the prospecting scenarios. These are the next steps to be developed.

Finally, the method can be used by public managers to decide on the allocation and prioritization of resources in a given project at a given place, since it incorporates the socioeconomic fragility of the affected population, giving additional information to support decision-making.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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