# Resilience to cope with heavy rainfall events

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Floods in urban areas are becoming more common, primarily due to the increase in impervious areas and climate changes. The concept of resilience can provide the framework through which strategies and measures to mitigate the impacts of a flood can be developed, as resilience itself can be defined as the ability of a system to retain its functionality in the event of a disaster. In order to adapt to this new threat, a shift to a more resilient way of thinking must be considered, coping with increases in rainfall, temperature, and average sea level. This paper aims to define the theoretical concept of urban resilience as a quantifiable variable through key performance indicators (KPI). The KPI's were obtained by employing the methodology herein developed, in the course of this work, based on dynamic simulation of the performance of drainage systems in order to circumvent scenarios in which lack of data occurs.

**Keywords:** Urban Drainage; Floods; Climate Change; Urban Resilience; Heavy Precipitation Events.

## 1. Introduction

The increasing awareness of society to the potential hazards of climate change provides the perfect timing for establishing the concept of resilience as a tool to develop disaster mitigation strategies in cities. The definition of resilience depends on the area of study. Regardless, the capacity of a system to perform its functions when subjected to stress can be considered a comprehensive definition of resilience.

Population in urban areas has been increasing since the last century, especially in developing countries. As urban areas continue to expand as a result of population growth, it follows that an increase can be observed in impervious areas, on par with a reduction in infiltration and hydraulic retention time. All these factors can lead to poor performance in the drainage system and subsequently result in urban floods damaging properties and the environment, with general risk to human life. Data collected over the last few decades concludes that the number of fatalities due to floods has been decreasing, despite the number of events increasing.

As climate change becomes a reality, rainfall, temperature, and tidal levels are expected to rise, aggravating the current state of drainage systems and, therefore, resulting in an increase in flood events and their intensity in urban areas. Floods triggered by heavy rainfall, as well as poorly designed urban drainage, frequently occur in numerous regions of Brazil. The severity of these impacts, regarding floods in urban areas, are intensified by the illegal occupation of high-risk areas, a common factor that is transversal to multiple Brazilian cities.

Vitória is the capital of the state of Espírito Santo in Brazil, a region affected by frequent and intense floods. This coastal city has a predominantly flat landscape, high density of population, and is frequently exposed to heavy rains, in addition to a poorly designed urban drainage system. If the current forecast of climate change for South America proves to be accurate, a rise can be expected in the number and intensity of floods and their corresponding impacts within the city of Vitória.

## 2. Climate change

The industrial revolution in the eighteenth century was a milestone in technological development, industrialization and urbanization. However, it has since led to increased greenhouse gas (GHG) emissions which remain for extended periods of time in the atmosphere. Higher concentrations of greenhouse gases, as well as their prolonged lifetime, are responsible for increases in temperature, precipitation, the melting of polar ice caps and the subsequent increase in average sea level.

Carbon dioxide represents about ¾ of total emissions. Its concentration appears to be approximately 40% higher than the previous period of the industrial revolution, with a 35% increase in its concentration between 1990 and 2010 alone (IPCC, 2014). Most of the heavy rainfall events observed in the tropics are due to the monsoon system, whereby intense rainfall, associated with this phenomenon, is predicted to occur in South America, Africa, East Asia, South Asia, Southeast Asia and Australia (IPCC, 2014). Another phenomenon responsible for extreme precipitation events in Brazil is the South Atlantic Convergence Zone (SACZ) (Dos Santos and Fialho, 2017)

The frequency of extreme precipitation events due to monsoons is expected to increase, coupled with a foreseeable expansion of the affected areas, and furthermore the area covered by the SACZ is expected to move south, closer to the area in which the city of Vitória is located (IPPCC, 2014). As a result of climate change, an increase of 5% to 10% is expected in annual rainfall by 2040 (PBMC, 2014) along with an increase in the average sea level between 0.2 and 0.4 meters by 2050 or, in the worst case scenario, 1.3 meters by the end of the 21st century (Stead, 2014)

## 3. Resilience

The concept of resilience has an extensive history of applications in the fields of engineering, psychology, ecology, and risk management. Although present in multiple areas of application, the most influential modern theory of resilience is attributed, by several authors, to the ecologist Crawford Stanley Holling. Holling defines resilience as the ability of an ecological system to perform its functions, or persist in its tasks, when exposed to a shock or disturbance, and therefore, in this view, resilience would be a measure of the time interval that the system requires to restore itself to any steady state. This new definition contrasts sharply with the concept of resilience in engineering, since it originally presupposed a single state of equilibrium to which the system returned after a given stress (Holling, 1996)

Holling's (1996) notion of resilience evolved from a mere tool, meant to quantify the state of the system, to a holistic philosophy of approaching the problem. The notion of equilibrium and the means of quantifying resilience differs for each perspective of analysis, insofar as the equilibrium of a system can be seen as a single state (engineering), several states of equilibrium (ecological) or even equating the sheer lack of equilibrium (socio-ecological) (UN-Habitat, 2017).

In Meero et al. (2015), a wide range of literature was reviewed, encompassing the most important works in the area of resilience from 1973 to 2014, resulting in the observation of 25 different definitions of urban resilience and highlighting many inconsistencies and ambiguities throughout the publications. As such, there is significant difficulty in defining urban resilience, a challenge that may lie primarily in the characterization of "city" and "resilience" individually in different areas of study.

Urban resilience, in general, refers to a state of non-equilibrium, seen as a goal to be achieved, which can be reached through mechanisms of persistence, transition, and transformation, with particular emphasis on the ability to adapt on a given time scale. Urban systems are considered as emerging ecological systems, complex in nature, adaptive, and composed of four subsystems: regulatory networks for flow of materials, energy networks, urban infrastructures and socioeconomic dynamics (Meerow *et al.*,2016).

**Urban resilience**

It is important to note that cities are a combination of complex and interdependent systems of a socio-ecological nature, and understanding the links between the different systems involved is essential to develop a resilience plan that allows, to the largest possible extent, the proliferation of life with a satisfactory degree of functionality in the system, even when subjected to any shock or disturbance. Existing literature on the subject has so far encouraged an integrated, multi-level and multi-stakeholder approach, in order to obtain a level of resilience capable of withstanding different levels of disruption, with variable intensity, at different spatial scales. There is a recent trend towards producing international tools, indicators, and standards to allow for the measurement of urban resilience. Resilience is primarily a philosophy of approach to a theme of extreme importance in the development of urban studies (UN-Habitat, 2017).

By emphasizing the importance of engaging a broader spectrum of stakeholders, working in close cooperation in their effort to achieve sustainable urban development goals, the urban resilience approach has demonstrated a strong capacity to attract interest from global and regional actors in a collective effort. It should be noted, however, that guiding this vast network of partners, dispersed across multiple sectors and broadly different scales, requires strong coordination and interaction efforts.

## 4. Methodology

The methodology aims to characterize the different stages of a flood in order to obtain a measure of urban resilience. The IIRU (equation 3) calculates Urban Resilience as an aggregate of several indicators of performance (Barreiro, 2017). The steps followed in the methodology are as follows:

1. **Definition and characterization of the study area:** defining the limits and corresponding characterization of the study area (Bento Ferreira basin);
2. **Simulation of the 1D hydraulic model:** simulating the behavior of the drainage network, implemented via SWMM software design in Macedo (2017);
3. **Map of flooded areas**: determining the areas affected by the flooding volumes, as obtained in the SWMM model. Level contours are generated based on the dimensions of the manholes in order to understand the topographic profile of the city.
4. **Duration of the flood**: obtaining the duration of the flood based on data obtained from the SWMM model and a MATLAB routine. The duration of the flood divided into two installments. The SWMM model provides the first, based on flooding flows; the second is the time the given flood volume requires to return into the drainage system. The flow of an inlet located in low elevation areas is given by equations (1) and (2), formulated by the Arms Corps of Engineers of the United States of America, and these indicate that the hydraulic capacity of the inlets depends on the hydraulic load above the inlet (Sousa and Matos, 1990):

$$Q = 0{,}83\ P\ h^{\frac{3}{2}}\ para\ h \leq 0{,}12\ m \quad (1)$$

$$Q = 1{,}45\ A\ h^{\frac{1}{2}}\ para\ h \geq 0{,}42\ m \quad (2)$$

such that,

Q: Captured flow ($m^3/s$);

P: Outer perimeter of the grid, not including the space occupied by the crossbars (m);

H: Hydraulic load on the grid (m);

A: Grid floor area ($m^2$)

5. **Classification of urban resilience:** defining the urban resilience of the study area employing KPI (Table 1). Once the IIRU is determined, resilience can be evaluated under the classification model developed in Barreiro (2017) (Table 2). Performance indices are as follows:

Table 1: KPI employed

| |
|---|
| **$ID_V$ – Flooding volume (%):** $ID_V = \frac{flooding\ volume\ (m^3)}{total\ rainfall\ volume (m^3)}$ |
| **$ID_A$ – Flooded area (water height>5cm) (%):** $ID_A = \frac{Flooded\ area (m^2)}{Flood\ area (m^2)}$ |
| **$ID_A$ – Critical flooded area (water height>30cm) (%):** $ID_{AC} = \frac{Critical\ Flooded\ area (m^2)}{Flooded\ area\ (m^2)}$ |

**$ID_D$ – Flood duration(%):** $ID_D = \frac{Duration\ of\ the\ flood\ (hours)}{Duration\ of\ rainfall\ (hours)}$

**$ID_S$ –Affected services (%):** $ID_E = \frac{number\ of\ affected\ services\ (-)}{total\ number\ of\ services\ (-)}$

**$ID_T$ – Loss of traffic:** $ID_E = \frac{V - \sum P_i}{V}$

$$P_i = \rho_i \frac{Maximum\ legal\ traffic\ speed\ limit\ (km/h) - Penalty\ factor(km/h)}{Maximum\ legal\ traffic\ speed\ limit\ (km/h)}$$

- V (-) – Total number of roadways.
- $P_i$ (-) – Loss of potential traffic speed (-);
- Penalty factor (km/h) – Any roadway afflicted by a water height between 15 and 30 cm suffers a penalty of 20 km / h on the maximum speed otherwise permitted. If the height is greater than 30 cm, the road is considered to be closed (Pyatkova *et al*., 2019);
- $\rho_i$ – Roadway hierarchy weighting factor.

**IIRU – Urban resilience:** Represents the overall resilience of the city

$$IIRU = \frac{\sum(1 - \alpha \times ID)}{n} \quad (3)$$

- **n** – total number of KPI;
- **α -** Weighting factor of each KPI;
- **ID –** represents the KPI.

Table 2: Range of resilience through the IRRUI. Adapt: Barreiro (2017).

| |
|---|
| 90 < IIRU ≤ 100: Optimal Resilience |
| 70 <IIRU ≤ 90: Good Resilience |
| 50 < IIRU ≤ 70: Acceptable Resilience |
| 30 < IIRU ≤ 50: Insufficient Resilience |
| 0 < IIRU ≤ 30: Unacceptable Resilience |

## 5. Case Study: Bento Ferreira basin

**Defining the study area**

The city of Vitória is the capital of the state of Espírito Santo, located on the coast of the Southeast region of Brazil. Vitória is a coastal city, the territory of which is partly continental, with the remainder composed of an archipelago of thirty-three islands, comprising a total area of 93.38 km$^2$ where urban occupation is estimated to extend over approximately 50% of the territory (PMV, 2008).

Specifically, the study area is the Bento Ferreira basin (Figure 1 on the left), exposed to frequent flooding due to its geomorphological characteristics, extreme rainfall, and inefficient urban drainage network behavior (Figure 1 on the right). Coelho (2016) carried out a study based on the elevation, slope, and impervious area in order to identify areas of susceptibility to flooding, given that a large part of the Bento Ferreira basin coincides with areas of high flooding risk.

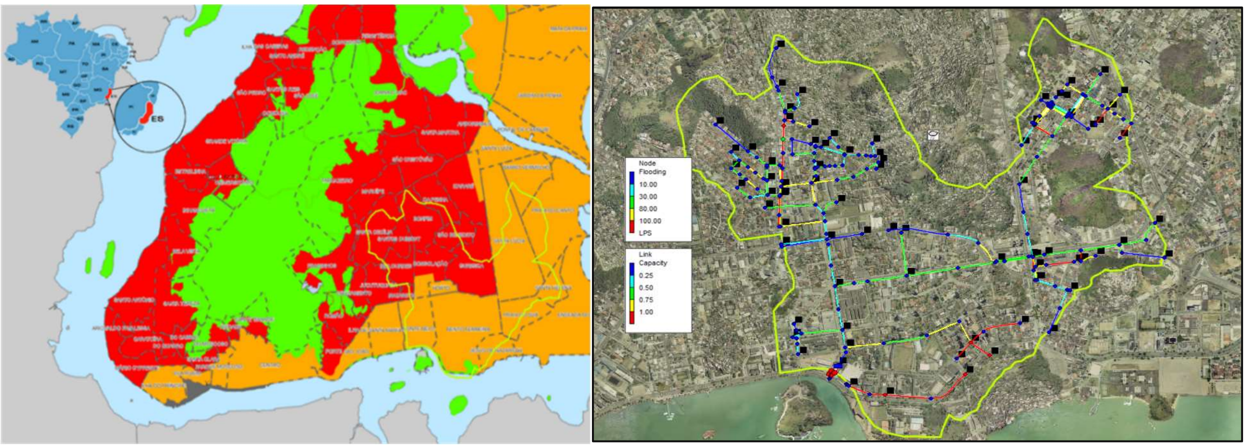

Figure 1: On the left: Location of the Bento Ferreira basin. On the right: Urban drainage model (SWMM)

**Scenarios**

A triangular hyetograph was used to evaluate the variation of precipitation, a method recommended in the PDDU (*Plano Diretor de Drenagem Urbana*). This method is used when the area of a basin is within a range of 1.5 to 5 km$^2$, since the results obtained are close to the observed values (PMV, 2008). The intensity of precipitation, for a given return period and duration, can be found in the Intensity-Duration-Frequency (IDF) curves designed for the city of Vitória (Pfrafstetter, 1982). The triangular hyetograph method (Figure 2) was developed by Yen and Chow (1980) (Tomaz, 2012). The tide values of the city of Vitória (Figure 3) are based on the reference system of the Brazilian Institute of Geography and Statistics (IBGE), developed by Macedo (2017).

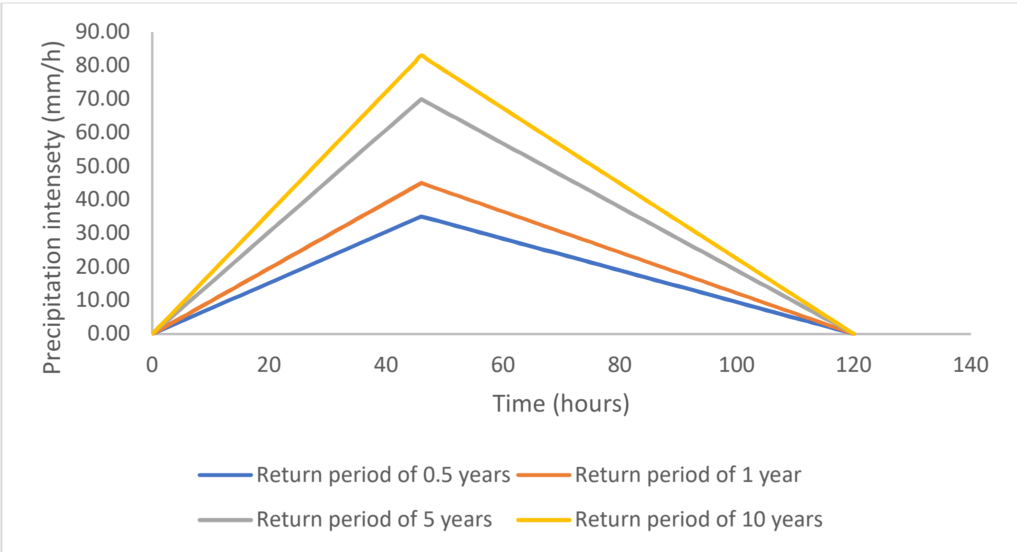


Figure 2: Triangular hyetograph for the four return periods.

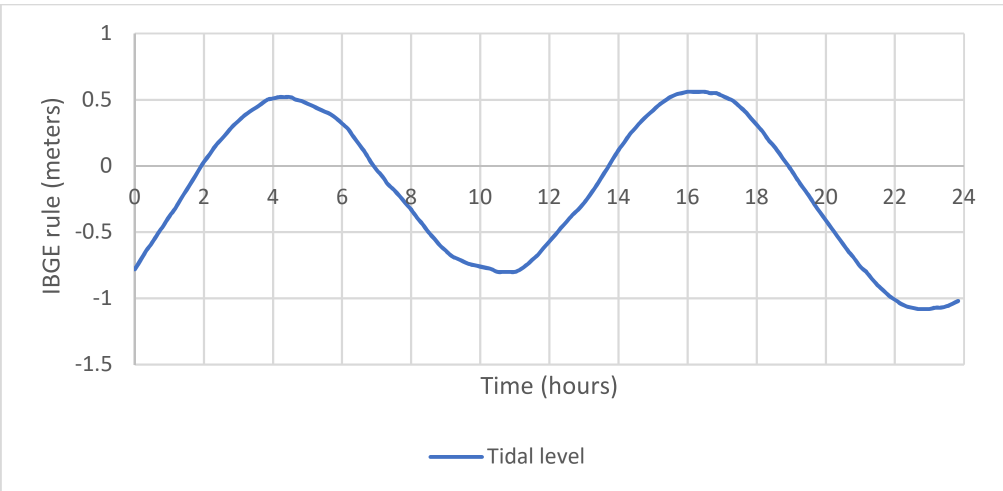


Figure 3: Tidal level of Vitória city

In order to apply the proposed methodology, the following scenarios are considered:

- **Scenario 1**: Simulation of the drainage model of Bento Ferreira basin, for four return periods associated with the current rainfall and tide level (Table 3);
- **Scenario 2**: Simulation of the drainage model of Bento Ferreira basin, accounting for the predicted values of precipitation and tidal level for an optimistic scenario of GHG emissions (10% of the increase in precipitation intensity, and an increase of 0.4 meters in tidal level) (IPPCC, 2014) (Table 3).

Table 3: Values of precipitation and tide level for the two scenarios.

| | **Scenario 1** | | | | **Scenario 2** | | | |
|---|---|---|---|---|---|---|---|---|
| **Return period (ano)** | **0.5** | **1** | **5** | **10** | **0.5** | **1** | **5** | **10** |
| **Intensity of precipitaion (mm/h)** | 35 | 45 | 70 | 83 | 38.5 | 49.5 | 77 | 91.3 |
| **Tide level (-)** | current | | | | current + 0.4 | | | |

## 5.1. Results

The first scenario had the explicit purpose of defining and evaluating the performance of the existing urban drainage system, regarding precipitation and current tide levels. For the smaller return periods, half and one year respectively, the system proved unable to handle the total flow generated, resulting in multiple points of flooding across several regions, yet the flood heights and flood durations were not considered to be severe. The expected rainfall when considering return periods of five and ten years, however, generates extensive flooding areas, up to 36% and 42% of the total flood area respectively, covering the districts of De Lourdes, Consolação, Bento Ferreira, Monte Belo and Santa Lucia (Figure 4). The most critical flood heights occurred in the neighborhoods of Bento Ferreira and Monte Belo, reaching 90cm and 75cm respectively. Regarding the duration of the flood, these events were estimated to persist for several hours due to the magnitude of the event (Table 4).

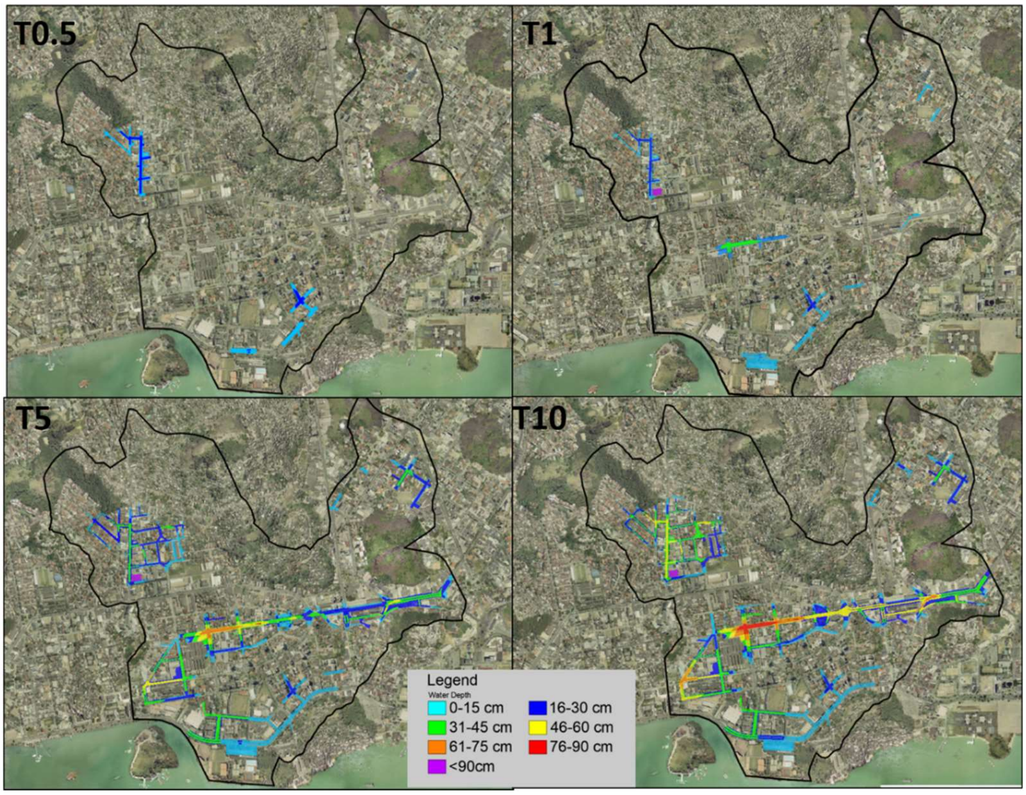


Figure 4: Flooding areas (first scenario).

Table 4: Summary of the results (scenario 1).

| Return period | Flooding Volume ($m^3$) | Flooded Area ($m^2$) | Flood Duration (hour) |
|---|---|---|---|
| **0.5** | 3109 | 21383 | 1.2 |
| **1** | 10624 | 83221 | 1.6 |
| **5** | 171234 | 236764 | 2.8 |
| **10** | 206863 | 274041 | 3.3 |

The second scenario introduces a 10% increase in rainfall intensity and an increase of 0.4 meters in the average sea level. The performance of the current urban drainage system, as would be expected, deteriorated, resulting in a general increase of flooding volumes across all simulations (Table 5). For the half-year return period, however, the increase in climatic variables did not appear to increase flooded areas, only flood heights (at the top left of Figure 5). For the remaining return periods, all variables in the analysis, namely flood area, height and duration of flooding, increased even further, such that it is possible to conclude the drainage system is neither capable of responding at a satisfactory level to a possible change in the rainfall regime, nor to the current one.

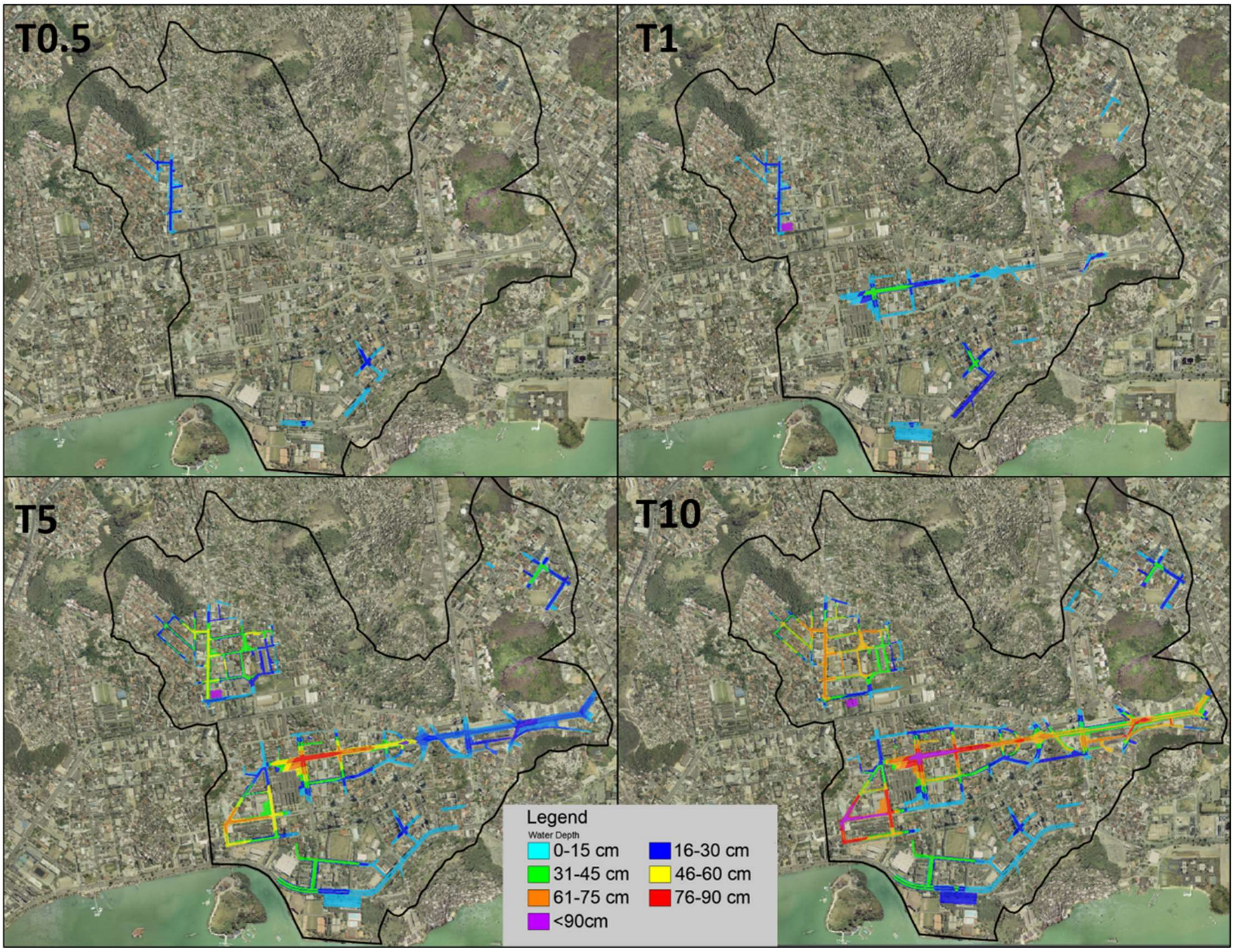

Figure 5: Flooding areas (second scenario).

Table 5: Summary of the results (scenario 2).

| Return period (year) | Flooding Volume ($m^3$) | Flooded Area ($m^2$) | Flood duration (hours) |
|---|---|---|---|
| **0.5** | 4419 | 24502 | 1.1 |
| **1** | 18621 | 84649 | 2.4 |
| **5** | 80907 | 262739 | 3.2 |

| 10 | **116245** | **312093** | **3.9** |
|---|---|---|---|

**Resilience**

Once the volumes, flood areas and the duration of the floods for a particular scenario are obtained, the KPI are calculated. The flood volume, flood area, and flood duration indicators are determined using the results obtained in the SWMM model, via the mapping of the flooded area and estimated duration of flooding, respectively. Regarding the KPI of affected services and loss of traffic capacity in the roads, additional information must first be gathered. In the following paragraphs, the required information for the definition of the missing KPI is described in greater detail. The services considered, for the calculation of the KPI were educational establishments, hospitals and clinics.

For the purpose of calculating the KPI, a given service is considered to be affected in case there is a flood of more than 30 cm in the adjacent area. The KPI for loss of traffic capacity depends on the maximum speed limit legally allowed in each road and the height of the flood afflicting it. The penalty factor was estimated by (Pyatkova *et al*., 2019). The PDU classifies motorway routes according to a hierarchy divided into four categories of roads: metropolitan, municipal, collector, and local (PMV, 2018). The defining attributes ascribed to each road in the hierarchy can be found in Table 6, and its spatial distribution in the Bento Ferreira basin is shown in Figure 6 on the left.

Table 6: Hierarchy of the roadway

| Roadway | Function (-) | Nº of lanes in each direction (-) | The maximum speed allowed (km/h) | Nº of each roadway in Bento Ferreira Basin | Roadway hierarchy weighting factor ($\rho_i$) |
|---|---|---|---|---|---|
| **Metropolitan** | Roadway for articulation between municipalities | 3 | 60 | 4 | 0.5 |
| **Municipal** | Internal municipal road | 2 | 40 | 0 | 0 |
| **Collector** | Routes connecting local roads with roads of superior hierarchy | 2 | 30 | 2 | 0.3 |
| **Local** | Circulation inside neighborhoods | 1 | 40 | 84 | 0.2 |

The occurrence of a flood in a given metropolitan road, where it would be otherwise possible to travel in any of three lanes at a maximum speed of 60 km/h, results in a more significant disturbance in the capacity of the system when compared to local access roads. Given the above assumption, the loss of capacity in the overall road system depends on the type of roadway affected. The flow of traffic is available, qualitatively, on the OpenStreetMap website repository, which contains GPS information (Global Positioning System) provided freely by the software's users, demonstrates the higher concentration of traffic flow in the roads classified as metropolitan, followed by the collecting routes and, ultimately, the roads within neighborhoods (local). So as to replicate the differing degrees of impact, on total loss of capacity, of the various roads, the weighting factors presented in Table 6 were considered.

**Urban resilience**

The first scenario manifests "good" and "acceptable" resilience for the return periods of half and one-year, respectively (Table 7). The deterioration from an acceptable state to an insufficient state, for the return periods of five and ten years, is due to the reduced capacity of the drainage system to drain the total volume of precipitation downstream. The percentage of flooding volume observed for the highest return periods, 37% and 46%, results in flooded areas of 36 and 42% of the total. For the latter scenarios, accounting for climatic changes, namely in regard to forecasts and tide level, was not observed to be sufficient to further aggravate the resulting classification of resilience. The values of flooding volume, flooded area, and duration of flooding increased, yet were not severe enough to reduce the final resilience score to a lower level.

Table 7: Urban Resilience classification

| | Scenario 1 | | | | Scenario 2 | | | |
|---|---|---|---|---|---|---|---|---|
| **Return period (year)** | 0.5 | 1 | 5 | 10 | 0.5 | 1 | 5 | 10 |
| **Flooding volume (%)** | **4%** | **10%** | **37%** | **46%** | **5%** | **16%** | **43%** | **51%** |
| **Flooded area (%)** | **3%** | **13%** | **36%** | **42%** | **4%** | **13%** | **40%** | **47%** |
| **Critical flooded area (%)** | **0%** | **17%** | **28%** | **58%** | **20%** | **27%** | **46%** | **58%** |
| **Flood duration (%)** | **59%** | **82%** | **140%** | **167%** | **54%** | **120%** | **159%** | **193%** |
| **Affected services (%)** | **0%** | **4%** | **32%** | **36%** | **0%** | **4%** | **12%** | **28%** |
| **Loss of traffic (%)** | **86%** | **86%** | **26%** | **23%** | **86%** | **77%** | **26%** | **23%** |
| **IIRU (%)** | **75%** | **62%** | **51%** | **39%** | **72%** | **53%** | **43%** | **33%** |
| **Resilience Behavior** | Good | Acceptable | Insufficient | Insufficient | Good | Acceptable | Insufficient | Insufficient |

## 6. Conclusion

As climate change effects become a reality, additional pressure is exerted on the correct operation of urban drainage systems. The increasingly vast impermeable areas, due to the expansion of cities, along with increased precipitation and average sea levels, provide a pessimistic scenario, given that drainage networks may not possess the capacity to accommodate the resulting increment in flows from the described factors.

The methodology aspired to the objective of characterizing the different stages of a flood through a simplified approach in order to determine urban resilience expeditiously. The obtained results do not possess a degree of accuracy such that rigorous analysis can be carried out at the level of the RESCUE project or the 100 Resilience Cites project. However, for any given situation where there is a severe lack of data, which does not allow for an exhaustive study, the proposed methodology renders it possible to carry out an initial or preliminary study of the behavior of urban resilience in the face of flooding events.

The results demonstrate a resilient behavior in both scenarios for the return periods of half a year and one year. The ability to respond to extreme rainfall events decreases for larger return periods, regardless of the scenario. Upon accounting for the climate change scenario (Scenario 2), an increase in flooding volumes, flooded areas, and flood duration followed, yet the resilience classification did not reflect any modification in score.

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