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Original Research Article

Flood Impacts in Sprawling Landscapes: integrating urban drainage, open spaces and land use in the process of urban planning

Beatriz Cruz Amback[*1], *Matheus Martins de Sousa*[2], *Aline Pires Veról*[3], *Marcelo Gomes Miguez*[4]

[1]Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Av. Athos da Silveira Ramos, 149 - Ilha do Fundão, Rio de Janeiro, Brazil
e-mail: beatrizamback@gmail.com

[2] Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Av. Athos da Silveira Ramos, 149 - Ilha do Fundão, Rio de Janeiro, Brazil
e-mail: matheus@poli.ufrj.br

[3] Programa de Pós-Graduação em Arquitetura, Universidade Federal do Rio de Janeiro, Av. Athos da Silveira Ramos, 149 - Ilha do Fundão, Rio de Janeiro, Brazil
e-mail: alineverol@fau.ufrj.br

[4] Programa de Engenharia Ambiental, Universidade Federal do Rio de Janeiro, Av. Athos da Silveira Ramos, 149 - Ilha do Fundão, Rio de Janeiro, Brazil
e-mail: marcelomiguez@poli.ufrj.br

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ABSTRACT

Floods are strongly related to lack of proper spaces in cities. This work aims to assess the potential aggravation of floods in a sprawling area if open spaces are lost and not used in a multifunctional way to accommodate stormwaters in the urban developing process. An exploratory approach is used, focusing on a critical case study, where both environmental and social fragilities are severe. Five developing scenarios were built and simulated using a hydrodynamic tool for comparison purposes, intending to show the importance of integrating urban drainage, urban open spaces and land use and occupation planning. Results show that the tendency of worsening the situation is alarming, if no land use planning measures are taken. This study highlights the need to recognize the crucial role of open spaces in flood mitigation and to plan these spaces in advance, integrating natural water demands and ordering a safer future city occupation.

KEYWORDS

Hydraulic risk reduction, Urban floods, Open spaces, Urban expansion, Land use planning, Urban planning.

INTRODUCTION

Cities are a complex system, composed of a series of interconnected equally complex subsystems that, with different levels of importance, interact with nature and its own dynamics that provide a support capacity to the city functioning. Urbanization modifies land use and cause severe transformation in the natural landscape, altering environmental processes and triggering socioenvironmental issues that hinder urban sustainable development, which is aggravated by

[*] Corresponding author

climate change [1], [2]. The urban development, especially when cities are less compact and urban sprawl prevails, provokes an increasing demand of natural resources, which can accelerate the environmental degradation, generating losses both for the urban population and the affected ecosystems [3].

One of the main challenges that cities face nowadays are the urban floods – which are greatly related with the urban land use modifications [4]. Processes related to urbanization, such as surface paving, deforestation and artificialization of river courses, disturb the hydrological cycle, increasing runoff generation, flood volumes, flood peaks and flow velocity [5]. Floods are not a solely natural disasters, since they can be affected by the way the watershed is modified by anthropic process. They can trigger social and economic impacts, affecting other systems that compose the city in a cascade effect [6]. Some of these consequences are the loss of material goods, structural damages, urban infrastructure degradation, interruption of urban services, landslides, among others [7]. It is noteworthy that the higher the social (and environmental) vulnerability, the greater is the relative losses caused by these events [8].

Floods are strongly related to the lack of proper spaces in cities to manage stormwater dynamics effectively. Since urban development produces more runoff volumes flowing faster, the natural drainage system is not able to manage stormwaters. Moreover, if traditional urban drainage systems are implemented to substitute or complement natural flood paths, they tend to transfer floods downstream. Relying on traditional stormwater management, which prioritize the rapid evacuation of water, rather than its accommodation inside the urban environment, often demonstrates inefficiency due to escalating demands of urban expansion for larger capacity structures [9]. As a result, the traditional urban drainage solutions, commonly referred as grey infrastructure, require increasing investments. Besides being susceptible to failure, the lack of attention to the environmental quality prevails.

Conversely, if a city is planned to accommodate water, in a preventive and proactive approach, it is possible to minimize the effects of urbanization over the water cycle, incorporating a more sustainable and resilient perspective to urban drainage design [10]. This approach seeks to encompass the preservation of natural dynamics, societal demands and economic viability, which constitute the three pillars of sustainability [11]. The emphasis on defense systems has been replaced by the incorporation of water as a resource in the development of cities [12], through solutions that value the presence of water in cities and enhance its potential as catalyst for spatial, social and cultural development [13].

Although floods may not be a persistent concern in cities, as they only occur during rainfall events, the drainage system should be considered as a structuring element to the territorial planning process, since its failure can potentially affect almost all the other systems in the city [14] Therefore, conducting a conscient land use planning is essential for designing resilient cities, preparing its territory to be safely occupied, by integrating the open space system with urban drainage solutions in a preventive way [15]. This approach does not negate the necessity for grey solutions but allows the combination of traditional drainage infrastructure with complementary sustainable actions, that often makes use of the open space system.

Open spaces perform a crucial role in cities, accumulating social and environmental functions; therefore, it is fundamental that a city disposes of a quality open space system [16]. Nevertheless, consolidated urban areas often lack open spaces, limiting possibilities for sustainable drainage-focused interventions [6]. On the other hand, urban developing areas can offer more open spaces and a greater potential to safely accommodate floods. However, without proper planning, these spaces in expanding areas may decrease fast [17] and they are very difficult to be reversed after occupied. It is noticeable that open spaces are frequently (and improperly) seen as future buildable areas, when proper planning does not define a functional open space system as part of a vital city.

One of the potentials of open spaces is the incorporation of Blue and Green Infrastructure (BGI), which consists of a network capable to provide urban and environmental services connecting blue (water bodies) and green (vegetated) spaces to the built environment [18]. It is the interpretation of blue and green elements combined in an integrated manner that can deliver effective services for the city, aiming to maintain a balanced relationship between society and nature by promoting biodiversity, conservation and social benefits, among others [19]. BGIs can be composed of natural or constructed landscape elements and some examples are rivers, natural reserves, detention and retention ponds, wetlands, rain gardens, and bioswales [20].

These solutions should accompany multifunctionality, whenever possible, to fulfill their role in urban qualification and optimize the uses of the open space system. According to Kim & Song [21], the benefits of BGI can be divided into economic, ecological, and social categories. Ecological benefits include flood control, biodiversity enhancement, habitat protection, carbon capture, and improvement in water quality. Economic benefits encompass increased urban space attractiveness, local economic growth, enhanced productivity of local workers, and increased urban land value. On the social front, aspects like aesthetics, accessibility, public safety, and improvements in physical and mental health can be cited.

Recognizing the importance of open spaces in urban planning and, in the sequence, in urban drainage interactions, is necessary. Actions in urban planning aimed at flood mitigation should integrate green and blue spaces in cities in a multifunctional manner, ensuring qualified open spaces providing temporary storage for urban floods, while other essential urban functions are not overlooked. By embracing this approach, cities can optimize land use efficiency and promote sustainable development while simultaneously addressing flood risk.

In this context, this work aims to assess the potential aggravation of floods in a sprawling area if open spaces are lost and not used in a multifunctional way to mitigate floods in the urban developing process. Departing from this recognition, a set of useful guidelines can be proposed to reverse negative effects of urban growth.

MATERIALS AND METHODS

This work undertakes an exploratory approach, comparing different urbanization and design scenarios on a particularly critical case study to show the importance of integrating urban drainage, urban open spaces and land use in the process of urban planning and consequent development. Two different types of urban growth patterns were considered: a tendential expansion – characterized by a non-controlled urban growth; and a controlled expansion that considers the stormwater dynamics. Additionally, two intervention alternatives were designed: one composed basically by concentrated high-capacity infrastructure, what is a commonly used approach associated with tendential growth, reacting to this inadequate urban sprawl; the other combining the first design alternative with BGI interventions, trying to better accommodate and proactively integrate natural stormwater needs into urban system responses. The first scenario, in fact, is associated with a formal municipal stormwater plan and, because of this, the second design alternative introduces a complementary approach, considering that the first scenario is probably going to occur.

Five different scenarios (S1, S2, S3, S4 and S5) were designed and compared to the current situation of the watershed (S0), intending to support the proposed discussion, which considers that planning urban growth, while considering the stormwater dynamics occurring in the proposed urban design patterns, is a pathway to build cities that are more functional and safer from floods.

The proposed scenarios are composed of different combinations of the urban growth patterns and design alternatives. Scenarios 1 and 2 consider different urban expansion patterns, without including any design intervention: S1 corresponds to the expected tendential growth and S2 to the controlled expansion. These two scenarios intend to support the investigation about how urban growth is directly associated with the increase of urban flooding consequences. The other three scenarios include design interventions, combined with the two different urban development models. S3 simulates the design alternative that corresponds to the official proposal of the municipal government to mitigate floods in the watershed, without considering any urban expansion – that is, it shows the effectiveness of the official municipal proposal in the current situation. S4 merges S1 and S3, including the official design alternative and the tendential expansion – in this case, S4 shows how the effectiveness of the project decay with an inadequate urban expansion pattern. Finally, S5 combines the controlled expansion, the official proposal and the complementary BGI actions in urban open spaces – this combination shows the probable best combination, both in terms of urban expansion and design alternatives and the expected result should be able to show that BGI interventions combined with controlled urban growth sustain the flood control results. If this expectation is verified, we can confirm the hypothesis that urban open spaces can be a valuable resource to control urban floods, if associated with BGI approach in the context of urban planning process.

The scenarios were evaluated using a hydrodynamic simulation tool, assessing the impact of the different urban growth patterns and design alternatives in urban floods. The methodological procedures are represented in **Figure 1**.

In the particular case of this work, the model called Urban Flow Cell Model - MODCEL **[22]** was used. This choice was made, in practical terms, because this model is tailored to represent urban floods, using the flow-cell concept **[23]** and it was developed by the research group that developed the study presented here. However, the model choice is not a constraint to the method – other models can be equally used.

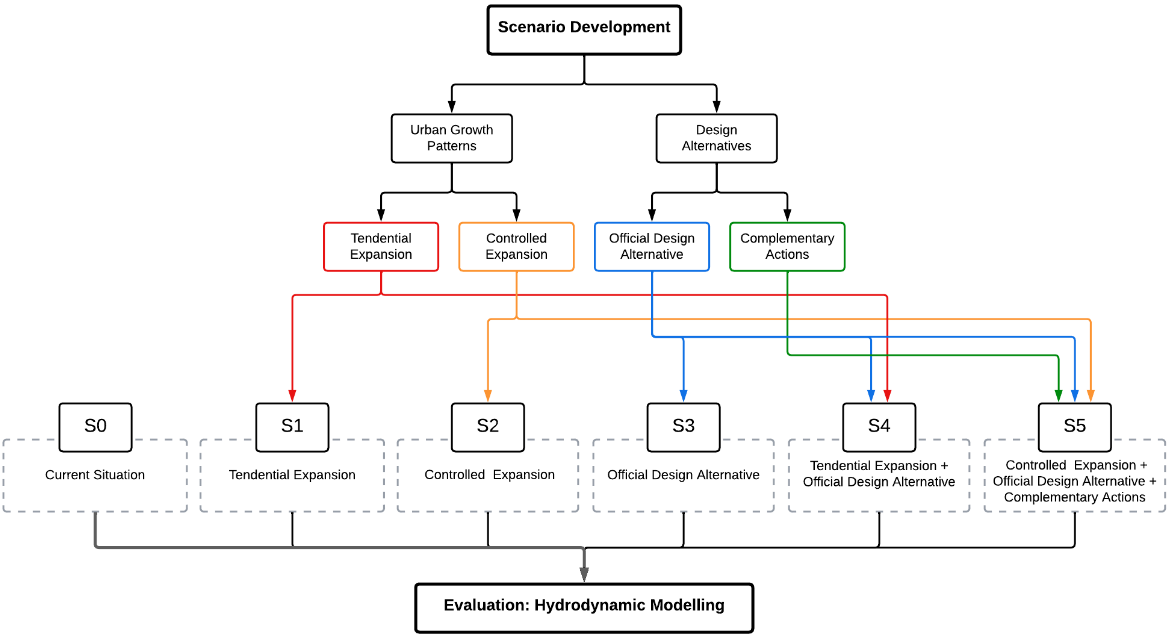

Figure 1. Methodological Flowchart.

Urban Growth Patterns

Both expansion scenarios consider a 20-year horizon. Urban growth was estimated by arithmetic projection regarding two parameters: the expansion of the urban fabric and the growth of the areas occupied by lots. In this sense, it was possible to predict a sprawled horizontal growth of the urban area and or its densification. The disposition of the new population in the territory involved two distinct approaches, resulting in the development of two urban growth patterns: a and a controlled compact expansion. Both take into account the parameters established by the Zoning Law in force.

Tendential Expansion. This approach considers the outcome of a tendential urban expansion if the historic growth pattern of this watershed is reproduced in the future. In other words, it estimates a sprawling, with a horizontal growth of the urban fabric. All of the zones that are permitted residential use can be fully occupied, if the population growth is sufficient, regardless of the environmental fragility. In this hypothesis, there is no control regarding occupation of flood prone areas, slopes or riverbanks, as well as no regulation or protective measures to maintain open spaces to accommodate stormwater dynamics.

Controlled Expansion. Consists of a sustainable approach in land use planning. In this situation, the urban expansion is conducted by premises that seek balance between natural and constructed spaces. To build this scenario, the natural susceptibility to floods is mapped and urban expansion is avoided inside the identified flood prone areas, even if the current zoning law permits its occupation. The new population can be accommodated through the verticalization of some areas, optimizing the urban infrastructure use and maintaining open spaces available in cities, but respecting the limits of verticalization attributed to each zone. The implementation of new housing developments is preferred in empty lots in consolidated urban areas, avoiding the establishment of new allotments (and the consequent sprawl that consumes natural resources and territory space). The parameter utilized to determine the ideal quantity of open space in the urban environment is the UN-Habitat guidelines, which recommends that cities allocate 15 to 20% of their area for public open spaces [24].

Design Alternative

Official Design Alternative. The official proposal of the municipal government to mitigate floods in Rio de Janeiro, as they occur today, is published in the Rio de Janeiro Stormwater Management Master Plan (PDMAP) [25]. For the Watershed chosen as Case Study, the project includes large-capacity reservoirs and interventions in the riverbed. It is important to notice that this design alternative is an evolution from the usual channelization approach, since it considers the necessity of storing stormwaters to reorganize the flood flows.

Complementary Actions. This project consists of the incorporation of blue and green spaces in a flood mitigation project, combining the official design alternative with BGI solutions to achieve greater efficiency in flood reduction and a better organization of the urban areas, to guide the future development. It is important to stress that within the BGI solution, one floodable park was proposed by the Municipality, in an official action added to complement PDMAP actions. Furthermore, all these strategies guarantee not only risk reduction but also provides quality multifunctional spaces for the population alongside with promotion of ecological functions, integrating stormwater management with many other functions that are vital to the cities – like providing green areas, opportunities to increase urban biodiversity, recreation, cooling, among others.

Evaluation

The proposed scenarios were evaluated with the support of a hydrodynamic model capable of mapping floods in urban areas. MODCEL [22] was originally conceived in 1990, based on the concept of flow-cells and has been continually developed since then.

The whole watershed is represented to show urban and natural landscape in a combined way, defining of complex flow network that integrates surface flows, river flows and subterranean storm drains in a pseudo-three-dimensional approach. Additionally, the model also performs hydrological procedures for transforming rainfall into runoff.

The basic elements of MODCEL are the cells and the connections (or links) between them. The cells act as homogeneous compartments, representative of elements of the natural territory, urban landscape elements, and hydraulic structures. The cells can vary in size depending on the desired level of model precision and the specific characteristics of the area being analyzed. Their shape and dimensions are determined manually, considering the topography and the distribution of urban elements. Notably, cells within the same model can also differ in size, reflecting the heterogeneity of the landscape.

While the cells function as storage elements, their links represent hydrodynamic functions occurring between them, reproducing the flow patterns found in the urban scenario, calculated by known hydraulic laws, such as the dynamic equation of Saint-Venant. Consequently, the behavior of each cell is influenced by the cells to which it is connected, reflecting the interconnected nature of urban and hydrological systems.

The cells are configured based on predefined types: channel, storm drains, urban plains, reservoirs, natural plains, among others. Information such as surface area, storage area, terrain elevation, runoff coefficients, and urbanization patterns are assigned to the cells. The connections between cells can also be configured according to their type, including river, plain, spillway, orifice, gallery, micro-drainage, pumps and flapgates, among others. Depending on the type of connection, different coefficients and physical information are introduced in the model set-up.

The results of the simulations provide information such as water depth in each cell, discharges, and flow velocities between each two cells.

CASE STUDY: PIRAQUÊ-CABUÇU WATERSHED

The proposed exploratory method was applied in the Piraquê-Cabuçu Watershed, in the municipality Rio de Janeiro, Brazil. Originating from the upstream areas Pedra Branca Massif, the Piraquê-Cabuçu river flows through a stretch of 12km and covers a drainage area of 108 km², outflowing into the Sepetiba Bay. It is a particularly critical site, where environmental and social fragilities are severe. In addition to that, the area is experiencing an ongoing heavy urban expansion.

Historically, the western portion of Rio de Janeiro, where the watershed is located, has been an agricultural and industrial hub from the 15th to the 18th centuries. However, with urbanization in the latter half of the 20th century, driven by road access and real estate speculation, the region witnessed great increase in population. Government initiatives in the 21st century further fuelled development in this region, especially due to megaevents like the 2014 FIFA Worldcup and the 2016 Olympic Games, both held in Rio de Janeiro, which fostered transportation investments. However, this process was also marked by lack of sufficient public investment in urban infrastructure.

This watershed encompasses two distinct Administrative Regions: AR XVIII (Campo Grande) – upstream - and AR XXVI (Guaratiba) - downstream. Campo Grande is a densely populated urban hub that contrasts with Guaratiba, a less urbanized area, yet experiencing significant population growth, indicative of potential landscape transformation. This recent significant growth is explained by new routes of transportation that were opened in the south region of the watershed.

In terms of socio-economic conditions, the Social Development Index (SDI) provides a useful metric for comparing the watershed to the broader city. The SDI, derived from census data, considers factors such as education, income, and sanitation. The average SDI for the city of Rio de Janeiro is 0.61. In comparison, the districts of Campo Grande and Guaratiba score 0.57 and 0.49, respectively. For context, a wealthier neighborhood like Copacabana achieves a significantly higher score of 0.73. While Campo Grande exhibits a relatively higher SDI compared to its neighboring districts due to its role as an urban centrality, its score remains below the city's average, reflecting persistent socio-economic challenges. Guaratiba, being a less urbanized and more peripheral area, demonstrates even lower socio-economic indicators.

The general low elevations, mild slopes and soil composition in the downstream portion of this watershed contribute to the occurrence and permanence of floods. Additionally, the region faces other environmental challenges, including water pollution, deforestation, river sedimentation and degradation of water quality, mainly due to improper wastewaters disposal. The population exposed to floods is also socially vulnerable; therefore, displaying little recovery capacity after these events, which is something not secondary and also alarming.

Figure 2 shows the location of the Piraquê-Cabuçu Watershed in Rio de Janeiro/Brazil, as well as some relevant roads and landmarks. It also shows two satellite images of a portion of the watershed, corresponding to the urban subdivision of Jardim Maravilha, in the district of

Guaratiba, in two different years – 2004 and 2022-, highlighting the transformation that the landscape went through in this 18-year time frame. It is worth pointing out that Jardim Maravilha is one of the most critical locations in this watershed regarding floods, and the tendency of expansion of this region indicates the worsening of this situation, since it represents further degradation of the environment and increase in exposition.

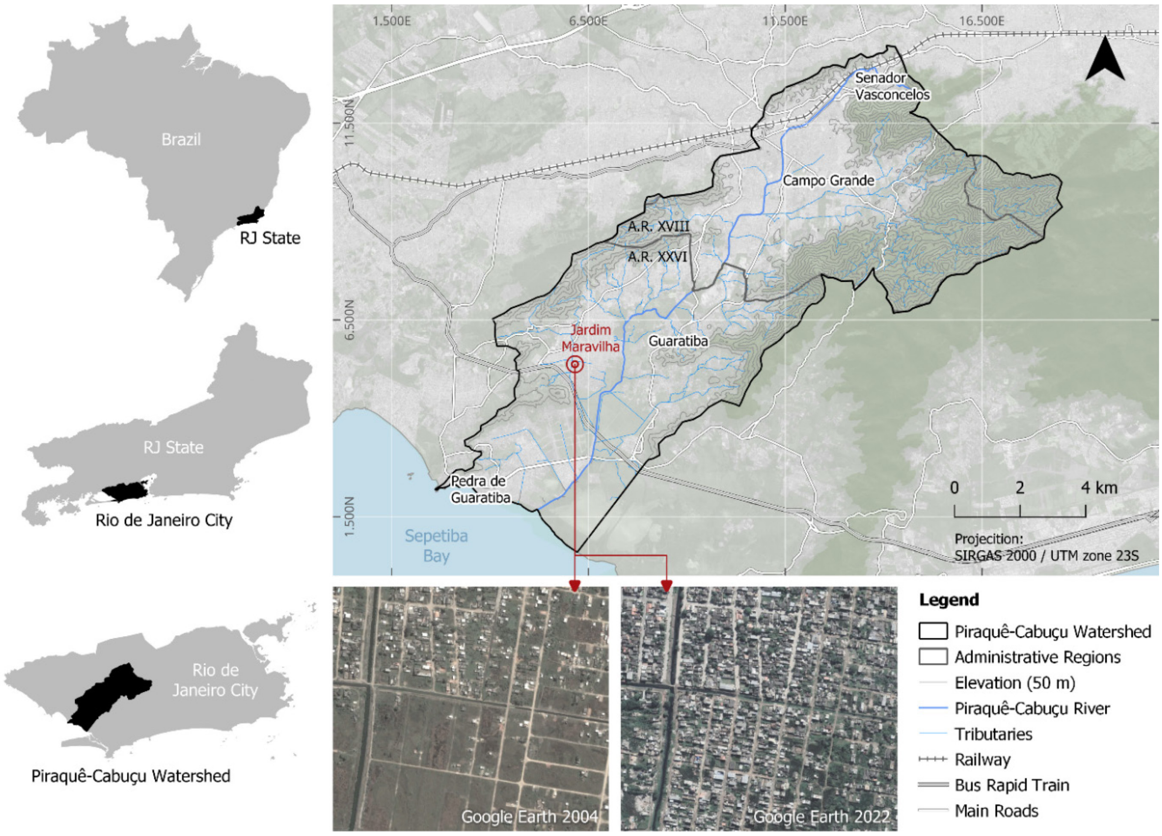

Figure 2. Location of the Piraquê-Cabuçu Watershed.

The Piraquê-Cabuçu Watershed covers 13 urban planning zones, established by two distinct zoning laws. The AR XVIII (Campo Grande) operates under Complementary Law No. 72, of 2004 [26], while the AR XXVI (Guaratiba) is governed by Decree 322, of 1976 [27]. Figure 3 shows the zones in this Watershed as well as the flood prone areas mapped according to the IPhySF application. In this analysis, it is possible to identify areas where urbanization is allowed, if not already urbanized, but that are also environmentally fragile – which can represent a risk to the population exposed. The delimitation of susceptible areas considered the territorial units where the index got score over 0.6 (out of 1) – this threshold implies in the joint consideration of areas that received scores related to high (0.6-0.8) and very high (0.8-1.0) susceptibility to floods.

The Residential zones identified in AR XVIII are ZR-1, ZR-2, ZR-3 and ZR-4. ZRs 1 and 2 allow a maximum height of three floors, while ZR-3 accepts four floors, and ZR-4 accepts up to eight floors. Regarding uses, ZR-4, which is in a more central location, tolerates a greater variety of activities besides residential use, concentrating greater diversity of commercial and service uses, while ZR-1 is restricted to residential and single-family use (favoring urban sprawl). The Commercial and Service zones in this AR are ZCS-1 and ZCS-2, located side by side. ZCS-2 allows a height of up to eight floors, while ZCS-1, and establishes heights of only four floors.

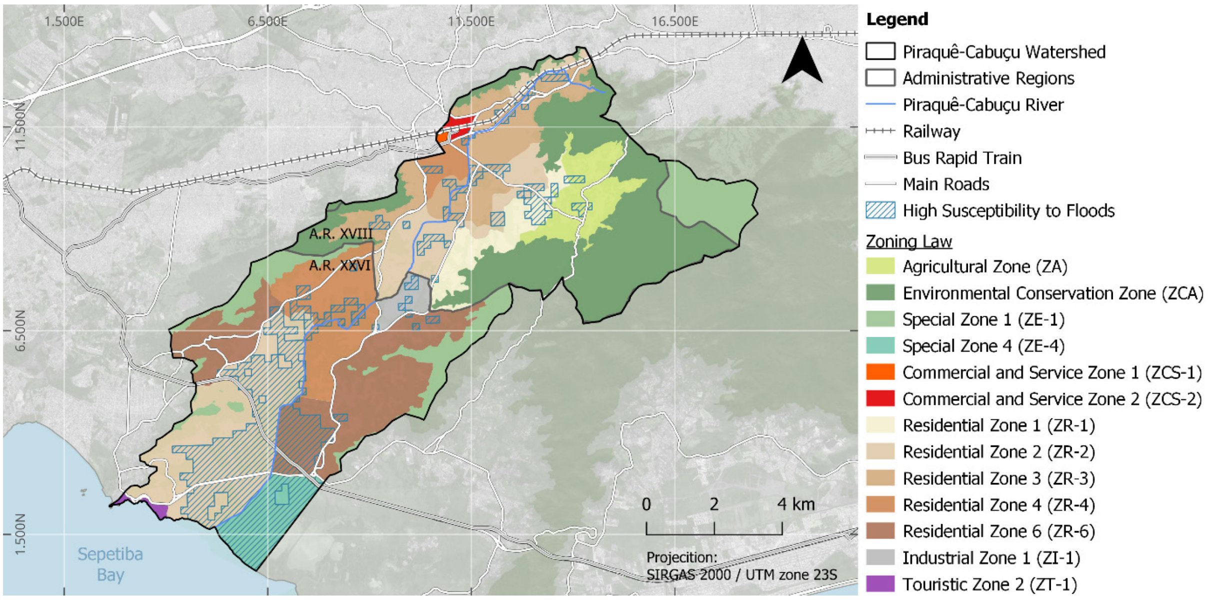

Figure 3. Zoning Law and Susceptibility to floods in Piraquê-Cabuçu Watershed.

Near the hill slopes, there is an Agricultural Zone (ZA), with lower heights and reduced occupancy rates. Finally, in the Massif, two zones are identified: an Environmental Conservation Zone (ZCA) and a Special Zone 1 (ZE-1). The Environmental Conservation Zone allows heights up to two floors, but the subdivision can only occur between quotas of 50m and 100m, ensuring the safety of the higher elevations in the slopes.

In the AR XXVI, there are three Residential Zones: ZR-2, ZR-4 and ZR-6. The latter, which is not found in AR XVIII, can receive single-family residential use, tolerating some activities such as agriculture. Areas demarcated as ZR-6 border Special Zones 1, comprising the slopes. To the north of this AR, bordering the limit between ARs, there is an Industrial Zone classified as ZI-1, which allocates extractive industries. Downstream, there is a Special Zone 4 (ZE-4) in Guaratiba, located in a mangrove area and it is destined for leisure and recreation; and a Touristic Zone 2 (ZT-2), on the Pedra de Guaratiba coast. The ZT-2 can also receive residential use.

The mapping of the food prone areas, superimposed with these zones, reveal that there are many residential zones located in environmentally fragile portions of the watershed, especially downstream. Much of the ZR-2, located in Guaratiba (AR XXVI) is highly susceptible to floods, including the Jardim Maravilha subdivision. However, a large portion of this region is already unoccupied by urbanization, which indicates that further expansion in susceptible areas in Guaratiba should be avoided. If no actions are taken, urban expansion in flood prone areas can possibly represent an increase both in exposure and in degradation of the environment, aggravating floods in the future.

RESULTS

Scenarios

Data on land use from two temporal milestones, corresponding to the years of 2013 and 2017, were employed to analyze the expansion of the urban footprint in the city, projecting this growth for the 20-year horizon under consideration. Additionally, the increase in area occupied by lots between years 2000 and 2013 was also calculated, and this progression was projected for the designated timeframe. **Figure 4a** and **Figure 4b** schematically represents both scenarios.

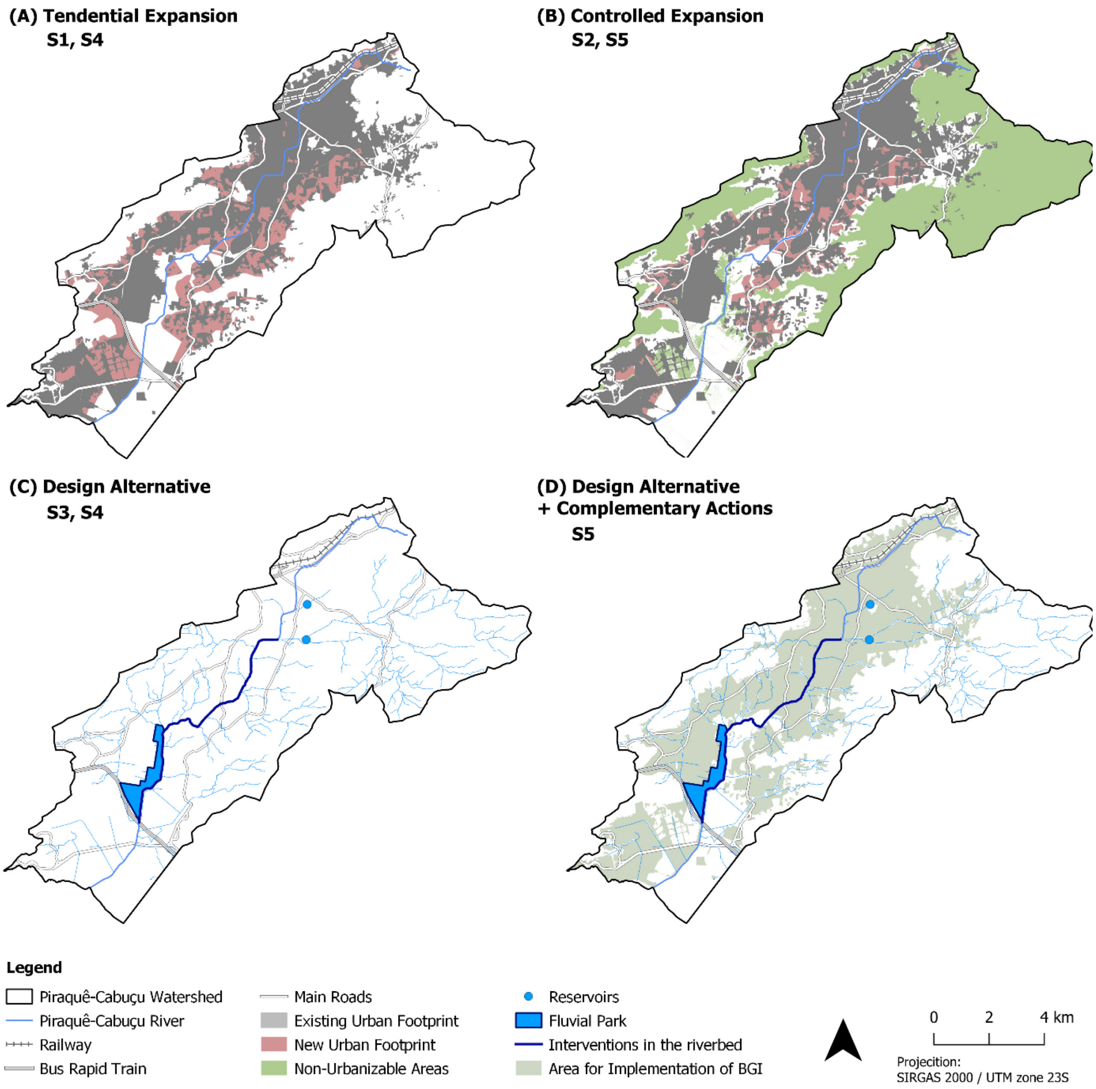

Figure 4. Diagram of the (a) Tendential and (b) Controlled Expansion Patterns, (c) Design Alternative and (d) Design Alternative with Complementary Actions.

Regarding the delineation of the new urban footprint, the Tendential Expansion Scenario (S1) envisioned urbanization growth primarily in flat areas and those occupied by fields, also considering the possibility of expansion in areas of steeper slopes. In defining this scenario, land susceptibility to floods and absolute elevations were not taken into account, meaning that the population could expand into low-elevation and environmentally vulnerable areas improperly. Conversely, for the Controlled Expansion Scenario (S2), growth was avoided in areas with elevations exceeding 60m or below 2m, which were considered non urbanizable areas, as stipulated by the PDMAP [25]. Additionally, the Riparian Buffer Strips were considered, as established by the Brazilian Forest Code [28], [29], preventing urban expansion into this area. It is worth noting that the development of both scenarios did not involve any expropriation of existing buildings and structures.

The Tendential Expansion Scenario (S1) anticipates a horizontal growth pattern, reflecting the current trend of urban sprawl. Moreover, this scenario considers the suppression of open Spaces. According to the UN-Habitat [24], in a well-functioning city streets and sidewalks should consume 30 to 35% of the urban landscape, while public open spaces should encompass between 15 and 20%. To compute the reduction of open spaces in the S1, it was assumed that roads occupy roughly 30% of the urban area, leaving lots to occupy the remaining 70%. The urban expansion, encompassing both existing areas and the addition to the current footprint) adheres to this limit, except for areas where the occupation already exceeded it, which were maintained.

For the Controlled Expansion Scenario (S2), a more modest expansion of the urban footprint was considered, aiming to minimize land degradation. Consequently, urban sprawl expanded by only 50% compared to what had been calculated as the tendency. Additionally, recognizing the vital importance of open spaces within urban areas, it was determined that approximately 15% of the urban land would be allocated to public open spaces, as stipulated by UN-Habitat, while 30% would be dedicated to streets and sidewalks. This means that the area occupied by lots would be limited to 55%. This limit was established to accommodate both densification within already urbanized areas (except where plots already exceeded 55%, in which case their occupation was maintained) and the occupation in the additional urban footprint. Furthermore, the verticalization of all new developments was also taken into account, adhering to the maximum building height limits established by zoning laws (in the zones where verticalization is permitted).

For the Official Design Alternative Scenario (S3), measures already proposed by public entities for this watershed were taken into account. The PDMAP establishes the creation of four reservoirs for this watershed. However, since this intervention was initially planned, some areas designated for the reservoirs have been urbanized, therefore only two of the four reservoirs were deemed viable. The plan also includes interventions in the riverbed of the Piraquê-Cabuçu River in certain sections, which consists on the adequacy and stabilization of the channel while preserving the existing area. Additionally, the scenario incorporated the creation of a fluvial park, as proposed by the municipal drainage company [29]. It is situated to the east of the Jardim Maravilha subdivision, on the right bank of the Piraquê-Cabuçu river, aimed at preventing urban expansion beyond the existing urban subdivision boundaries. This park is located on the right bank of the Cabuçu River, allowing river overflow into this floodplain while the urban area to the west of the river is protected by a dike and an auxiliary canal. These measures are spatially represented within the watershed in **Figure 4c**.

To enhance the effectiveness of the proposed measures, complementary actions have been added into the Official Design Alternative particularly in S5, where controlled expansion facilitates the availability of open spaces to implements these measures (**Figure 4d**). These are BGI solutions aimed at further reducing floods. It was determined that the city's open space system, including the green spaces and sidewalks will be equipped with infiltration and small-capacity storage measures, such as permeable pavement, rain gardens and detention basins, among others. If distributed throughout the watershed, these measures will facilitate stormwater infiltration, resulting in additional reductions in surface runoff and mitigating flood risk. Collectively, these complementary actions contribute to a comprehensive strategy for sustainable flood management, urban flood risk reduction, and increased flood resilience.

Simulation

The simulation was conducted using MODCEL for 25-year return period rainfall. **Figure 5** illustrates the water depths of the current situation and the differences in water depths generated from the simulations. Water depths represent the maximum flooding depths calculated in each cell during simulation, while water depths different are obtained by comparing the water depths of two different scenarios, thereby assessing the increase or decrease in flooding between a scenario and the base scenario. These water depths differences are depicted on scales of green and red, where green indicates a reduction in flooding and red indicates an increase.

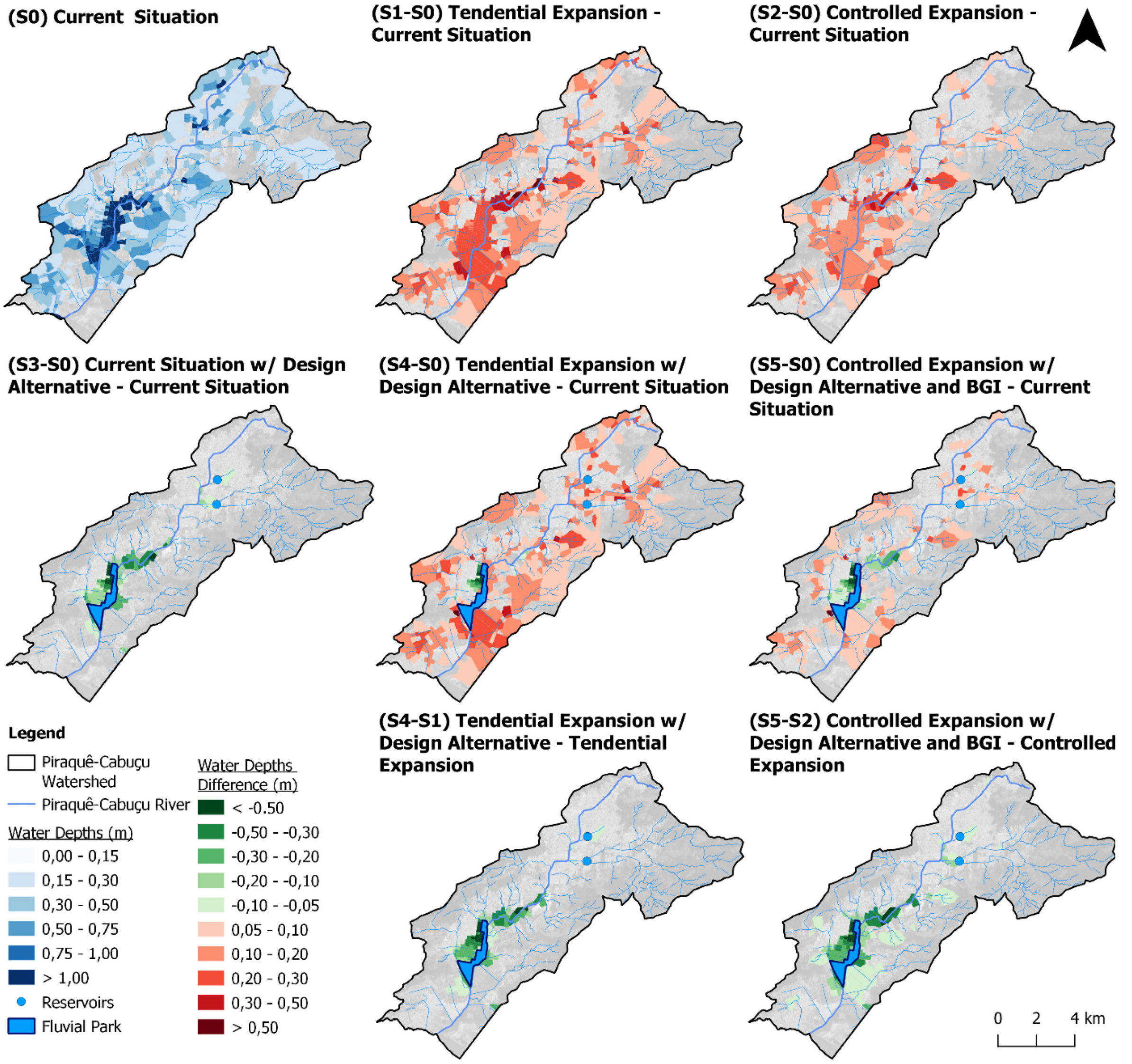

Figure 5. Water depths for the current scenario and water depths difference for all simulated scenarios.

In the Current Situation (S0), the most critical point is observed to be the region of Jardim Maravilha, characterized by low elevation and slopes, which facilitates rainwater accumulation. The result of the simulation shows that an area of approximately 8 km² experienced a maximum depth superior to 1 m, exposing the critical situation currently faced by this watershed, which tends to aggravate if measures are not taken.

In the urban expansion scenarios (S1 and S2), there was a worsening of the water depths due to increased accumulation of surface runoff generated by urban growth. A more significant deterioration is observed in the Tendential Expansion Scenario (S1) compared to the Controlled Expansion Scenario (S2). While S1 experienced an increase of 6,266,339 m³ of maximum runoff volume - the sum of the multiplication between the area of each cell and the depth difference – S2 exhibited an increase of 4,558,786 m³, equivalent to 72.8% of the volume calculated in S1. This demonstrates a higher efficiency in the urban occupation pattern adopted for the Controlled Expansion Scenario (S2) regarding stormwater management.

The water depth differences from the Official Design Alternative compared to the current situation (S3-S0) demonstrate the potential improvement in flood mitigation generated by the design intervention alone, without concern for expansion. In this scenario, there was a significant reduction in surface runoff accumulation, proving the project's effectiveness. The most significant improvement was observed in the region of Jardim Maravilha, where flooding is most pronounced in the current situation.

Observing the water depths differences between S4-S0 and S5-S0 – which consider the differences between both expansion scenarios with the design alternative and the Current Situation –the design alternative still proves effective in both expansion scenarios for improving flooding in Jardim Maravilha. However, it is noted that the improvement of the design intervention when compared to the Current Situation (S3-S0) is more significant if compared to the improvement in S4 and S5, when compared to S0. In S5-S0, the flood reduction caused by the project, even though less significant than the one observed in S1-S0, is still greater than depicted in S4-S0. Furthermore, in S5, the utilization of open spaces as BGI interventions was considered, besides the Official Design Alternative, optimizing the infiltration and storage of stormwater, which resulted in an additional gain in flood reduction.

The comparisons between S4-S1 and S5-S1 show the efficacy of the design interventions individually, considering their respective expansion scenarios as the baseline. In this case, it is observed that, although the project still proves efficient in S4, as it still generates reductions in flood depths, the design intervention incorporated in S5, with better land use utilization that permitted the implementation complementary actions in urban flood mitigation, proves to be more effective.

Focusing on the most critical area, Jardim Maravilha, it is possible to analyse the flooded area across different scenarios and assess the corresponding increases or reductions. Table 1 presents the flooded area, measured in hectares, for each scenario, along with a comparison to the current situation (S0). This allows for an evaluation of the changes in flooded area, highlighting potential decreases or increases under the various urban expansion and design alternative conditions. Flooded areas were calculated considering water depths of 30 cm which corresponds to flood levels capable of entering the houses (considering that in this type of urbanization it is common for curbs and thresholds to be only 15 cm tall).

Table1. Flooded area in Jardim Maravilha

Scenarios	Flooded Area [ha]	Change in Flooded Area [% of S0]
S0	316	-
S1	322	102%
S2	318	101%
S3	171	54%
S4	203	64%
S5	189	60%

These results demonstrate an increase in flooded area in the urban expansion scenarios (S1 and S2), with a more pronounced rise in the tendential expansion scenario (S2). This is because the urbanization pattern in the controlled expansion scenario (S2) is optimized to minimize runoff increase. Regarding the design alternative, it proved effective across all scenarios, but it was most efficient in S3, which does not include urban expansion and therefore does not alter land use. Scenarios S4 and S5 (where design alternatives are combined with urban expansion) both show less flooded area compared to S0, highlighting the long-term effectiveness of the design alternative. Notably, S5 achieves the greatest reduction in flooded area due to its combination of improved land use strategies and complementary measures to reduce runoff.

DISCUSSION

Results have shown that, despite the efficiency of the official proposal to mitigate current floods, the tendency of worsening the situation is alarming, if no measures are taken regarding land use planning. In this sense, urban growth must be conducted appropriately to prevent the sprawling over the available open spaces, which need to be qualified and appropriated by community, working as multifunctional landscapes able to offer urban and environmental services (including stormwater management).

The value of BGI and the urban open space system extend beyond flood mitigation, since they provide various vital social and ecological functions to the city. These systems contribute to improving urban quality of life, enhancing biodiversity, fostering climate adaptability, among other benefits. Even though these benefits were not fully accounted for in the study, which focused solely on flood mitigation, the multifunctionality of BGI plays a pivotal role in ensuring the vitality and sustainability of urban areas. By optimizing the use of spaces and avoiding underutilization, multifunctionality enhances the efficiency of urban land use, making the city more adaptable and dynamic. This aspect is particularly significant for promoting resilience, as it allows spaces to serve multiple purposes, including recreation, education, and ecological restoration, while also addressing flooding issues. Therefore, the multifunctional aspect of BGI should be a decisive factor in decision-making regarding urban planning.

Moreover, safeguarding open spaces is efficient on flood management even if these spaces are not used as designed BGI. This is reflected by the results of the flood depths differences comparing the Tendential Expansion Scenario (S1) with the Current Situation (S0) and the Controlled Expansion Scenario (S2) with the Current Situation (S0). Even without any design intervention, the urban expansion pattern has significant impact in floods, and the scenario that considered decent proportion of open spaces inside the urban fabric, with minimal increase in the urban footprint, has proven to be more efficient regarding floods.

Currently, improper occupation renders two of the four proposed reservoirs in PDMAP unfeasible, highlighting the urgency of safeguarding potential intervention areas. For this study, both the expansion scenarios considered that the new urban fabric would not invade the areas designated for urban interventions – the two reservoirs and the fluvial park. This choice was made to make the combination of the urban expansion scenarios and design alternative viable. However, it is important to notice that in a future scenario of continued improper expansion, the remaining intervention spaces may also face the risk of being suppressed. Therefore, effective land use management is essential to ensure the availability of open spaces needed to accommodate stormwater dynamics. Moreover, proactive planning is both more efficient and cost-effective than attempting to resolve flooding issues in improperly developed and already consolidated areas.

Limitations of the study include challenges in spatializing urban growth, due to difficulty in accurately predicting the level of transformation each portion of the territory will undergo. Urban growth can follow different trajectories, such as linear, exponential, or clustered patterns, each of which can lead to significantly different outcomes in terms of land use, runoff generation, and flood risks. Moreover, variations in the intensity, density, and distribution of urbanization directly influence the hydrological response of the area, which means the assumptions made about growth patterns can impact the reliability of the results. The lack of recent data only allowed for arithmetic projections in the urban expansion scenarios, leading to a simplification the complex dynamics of urban growth. Finally, it is important to highlight that the BGI measures were not carefully positioned in the territory, therefore the complementary actions predicted a reduction of the runoff proportional to the optimization of the open spaces with small-scale storage and infiltration infrastructure.

CONCLUSION

This work has assessed the potential aggravation of floods in a sprawling area, underscoring the critical relationship between urban open spaces and flood mitigation. Through an exploratory analysis focused on a critical case study, the research demonstrates the potential exacerbation of flood risks when open spaces are lost and not utilized effectively to accommodate stormwaters in urban development.

The construction and simulation of five different developing scenarios showed that, the urban growth pattern has significant impact in the generation of surface runoff, and the scenario which achieved greater aggravation of floods was the one where open space was suppressed.

Thus, the trend of worsening the situation is alarming, if no land use planning measures are taken. As for the design interventions, the scenario which achieved greater results in preventing flood aggravation was the one which combined efficient land use planning with the design alternative and complementary BGI measures applied in the open space system.

Thus, results show that if open spaces are supressed and not used in a multifunctional way to accommodate stormwaters in the urban developing process, urban floods will likely increase significantly. In conclusion, this study highlights the need to recognize the crucial role of open spaces in flood mitigation and to plan these spaces in advance ordering a safer future city occupation.

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NOMENCLATURE

BGI – Blue-Green Infrastructure
IBGE – Brazilian Institute of Geography and Statistics
PhySFI – Index of Physical Susceptibility to Flooding
PDMAP - Municipal Stormwater Management Master Plan
MODCEL – Flood Cell Model
AR – Administrative Region
ZR-1 – Residential Zone 1
ZR-2 – Residential Zone 2
ZR-3 – Residential Zone 3
ZR-4 – Residential Zone 4
ZR-6 – Residential Zone 6
ZCS-1 - Commercial and Service Zone 1
ZCS-2 - Commercial and Service Zone 2
ZA – Agricultural Zone
ZCA – Environmental Conservation Zone
ZE-1 – Special Zone 1
ZI-1 – Industrial Zone 1
ZE-4 – Special Zone 4
ZT-2 – Touristic Zone 2

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