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Original Research Article

Territorial Ordering Through Hydrological Interest Areas and Functional Spatial Arches

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ABSTRACT

This study proposes guiding principles for flood risk mitigation by integrating Nature-based Solutions with the concept of Hydrological Interest Areas as a background for urban interventions. The methodological framework provides a matrix of joint urban and environmental planning recommendations, considering both physiographic characteristics and urban settlement patterns, along with a final program of necessities. Using the Bambu River Watershed in Maricá, Rio de Janeiro, Brazil, as a case study, the research evaluates three urban planning scenarios against the current situation. The Uchronic Scenario represents an idealized flood-free urban development, whereas the Current Situation reveals that nearly 21% of properties are in flood-prone areas. The Desirable Scenario involves extensive relocations,

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while the Realistic Scenario applies feasible open-space interventions, protecting 2,243 lots during a 25-year event. The findings confirm that integrating Hydrological Interest Areas and Nature-based Solutions is an effective strategy to enhance flood resilience while addressing social and environmental challenges.

KEYWORDS

Open Space System, Flood Mitigation, Multifunctional Landscapes, Hydrological Interest Area.

INTRODUCTION

The adverse impacts of rapid and misplanned urbanization, characterized by the reduction of open green spaces and the increase in both constructed and impervious areas, have become increasingly evident in the form of hydrological disturbances. Globally, floods are among the most critical consequences of these imbalances, capable of disrupting essential infrastructure systems in cities and causing significant financial damage to vulnerable and inadequately prepared areas [1]. In developing countries, the uncontrolled urban expansion driven by social pressures often occurs in floodplains and hillslope landslide risk areas, posing significant challenges to drainage systems and exacerbating the population's vulnerability to fatalities [2], [3]. Consequently, inadequate housing conditions and the progressive occupation of irregular areas are key factors limiting the ability to address urban flood challenges in these regions. The lack of comprehensive land use planning and the unrestricted appropriation of public spaces within the territory impede effective decision-making and urban interventions [3], limiting efforts to implement multifunctional drainage systems to safely manage flooding and improve the quality of urban areas. Rather than relying on traditional monofunctional drainage solutions that improve flow conveyance (and frequently transfer floods downstream), a more effective strategy should focus on maximizing the multifunctional potential of landscape design, incorporating flood control strategies while integrating urban-scale planning to revitalize the built environment [4].

Nature-based Solutions (NbS) are increasingly being adopted in urban areas to address the challenges posed by rapid urbanization and the growing impacts of climate change, including urban flooding. The concept is commonly defined as a multidisciplinary and integrated approach aimed at protecting, managing, and restoring natural or modified ecosystems, while simultaneously promoting human wellbeing and biodiversity gains [5]–[7]. NbS are a practical and promising tool to compose multifunctional landscapes to offer environmental services, including flooding mitigation When green and blue spaces are integrated with gray infrastructure in a hybrid approach, new opportunities arise to recognize the complementarity between built and natural environments [7]. This approach provides a viable means of restoring the hydraulic and ecological functions of a watershed, aiming to re-establish, as much as possible, its natural characteristics prior to urbanization. In reference to this, Lourenço et al. [8] developed a hypothetical alternative historic growth scenario applied to the Mangue Channel watershed in Rio de Janeiro, Brazil. This uchronic scenario, simulated from the early nineteenth century, assumed that urbanization followed a structured land-use plan, with the drainage network interacting with urban open spaces as a central element. The results indicated that the alternative scenario could have led to a nearly flood-free situation in the present. Similarly, Oliveira et al. [9] developed and simulated an uchronic scenario for the Acari River Watershed, another vulnerable region in Rio de Janeiro, to assess the capacity of natural drainage systems in managing urban floods. Their results confirmed that sustainable urban development would significantly reduce the consequences of flooding and enhance resilience to climate change.

Additionally, promoting NbS in expanding cities can deliver a wide range of ecosystem services while enhancing environmental quality [10]. These interventions can be applied across multiple scales, from local settings to broader watershed extents [6], [11], [12]. Most importantly, NbS can be integrated with ecological management zoning and territorial planning, taking into account the impacts of human activities on ecological functions [13]. However, mapping demand and identifying priority areas for implementing NbS as a watershed management alternative remains a gap in the literature, as discussed by a limited number of authors, including Longato et al. [10], Alves et al. [14], Pan et al. [15], and Dagenais, Thomas and Paquette [16]. Addressing the urban drainage challenges in cities requires identifying and defining the types of NbS interventions suitable for implementation at the watershed scale, considering its physiographic characteristics and specific requirements. In this regard, it is important to emphasize that in natural settings, topography plays a crucial role in runoff patterns and significantly influence the hydrological response of a watershed, whereas in urban environments, the influence is shaped by the height, form, and type of urban elements, including buildings, street patterns, and pavement types [3], [17]. Therefore, in urban areas, preserving natural spaces is critical for providing multifunctional areas that integrate recreational spaces with stormwater retention [1], [18], [19]. NbS interventions should be incorporated into the remaining open space system of the watershed, with guidelines that consider both formal and informal settlements in the surrounding areas.

In light of this, Miguez et al. [20] propose a functional interpretation of watershed areas based on a spatial analysis of the territory, which will also be applied in this work. This approach identifies three distinct segments in watersheds, termed "spatial arches", each of them exhibiting unique behaviors and interactions with the built environment. These arches typically align with the upstream, midstream, and downstream stretches of a river system. The river and its tributaries serve as a unifying element, integrating the segments and establishing a cohesive longitudinal connection across the watershed. For each functional arch, a summarizing concept was proposed. The upstream arch is associated with the principle of conservation, as it is often comprised of Environmental Conservation Units or urban green spaces. These zones play a critical role in sustaining the water cycle and minimizing the impacts of flow generation on downstream areas. The middle arch is characterized by the concept of integration between the natural environment and urban developments, representing a transition between these two landscapes. These zones require strategies that preserve permeable space, create opportunities for water storage, and interact with social functions. Finally, the downstream arch – the usually most urbanized watershed segment – requires careful consideration of natural systems, respecting the waterbodies' spaces. These areas must ensure the discharge capacity of the drainage system to prevent flooding, and guarantee water quality before it reaches subsequent water bodies, but without transferring floods downstream. Moreover, Miguez et al. [20] argue that a water-oriented urban planning must incorporate the delimitation of a Hydrological Interest Area (HIA) [20], [21], a zoning category designed to integrate the natural behaviour of watersheds into the urban planning process. This zoning seeks to preserve critical areas from flooding and improve quality of life. In this context, the HIA delimitation primarily consists of green and flood-prone open spaces in mild slope areas.

In this sense, the objective of this study is to validate the hypothesis that Hydrological Interest Areas (HIA) can act as a strategic framework for setting up the spatial arches concept and defining urban restructuring principles to mitigate flood risks, enhance ecological functions and improve urban spatial quality. To assess this hypothesis, the contribution of this research lies in exploring innovative planning approaches that incorporate NbS within hydrologically sensitive areas, particularly through the distinctive identification of functional spatial arches that exhibit unique urban-environmental interactions throughout the watershed. The Bambu River Watershed, located in Maricá, Rio de Janeiro, Brazil, serves as a case study, where hypothetical urban planning scenarios, including an uchronic one, are developed to assess the effectiveness of various spatial planning strategies incorporating NbS. Through this process, this study establishes a correlation matrix, termed Guidelines for Territorial Reorganization, to simultaneously analyse physiographic characteristics and urban occupation patterns coexisting within the same watershed, based on the spatial arches concept [20]. Methodologically, this approach addresses a critical gap in the literature by identifying priority areas for NbS implementation in urban watersheds while accounting for urban development pressures. Furthermore, it not only facilitates a balance between urban expansion and flood risk mitigation but also underscores the socio-environmental value of urban parks within an integrated planning framework. By demonstrating how the functional interpretation of spatial arches and the HIA framework can inform sustainable territorial reorganization, this study presents a decision-support tool for policymakers and urban planners, offering a transferable model for urban watersheds facing similar hydrological challenges.

MATERIALS AND METHODS

The methodological framework proposed in this work provides a matrix of joint urban and environmental planning recommendations, integrating the original physiographic characteristics and the urban settlement patterns of the interest area. The method follows a structured step-by-step approach, beginning with the creation of a uchronic scenario in which the urban growth process occurred recognizing and giving space to the urban water dynamics, demonstrating the effectiveness of this procedure in mitigating urban flooding. Building on insights from the uchronic simulation, along with an analysis of available open spaces and the watershed's functional dynamics, a correlation matrix is developed to simultaneously assess physiographic attributes and urban occupation patterns. This matrix serves as a basis for future planning guidelines. Following this analysis, two distinct design alternatives are formulated: a realistic scenario and a desirable scenario. Both aim to promote more sustainable land use, incorporating land use management strategies and flood mitigation projects, but they differ in their levels of control and feasibility. The realistic scenario acknowledges existing spatial and practical constraints, whereas the desirable scenario envisions an optimal yet aspirational approach - one that remains feasible but represents a more ambitious vision for urban development and flood resilience.

The next step involves identifying the Hydrological Interest Area (HIA), which serves as the foundation for future planning proposals. The criteria for delineating the HIA, as detailed in Miguez et al. [20], are: (i) legally protected areas (that already exists), (ii) coastal lowlands, (iii) mild to almost flat open spaces and (iv) riverine flood-prone regions. The HIA ignoring occupied conditions serves as a base for the uchronic scenario, resulting in a broader area, as it assumes the entire watershed is composed of open spaces (in the starting point of its development), including all flat areas. In contrast, the current HIA, based on the existing urban occupation, only considers the flat open spaces that remain in their natural state under present conditions. The uchronic HIA represents the HIA that could have been defined prior to the initial urban development, preserving all areas critical to the water cycle and those prone to flooding.

Based on the unoccupied HIA, an Uchronic Scenario is developed to explore a hypothetical past to present development of the watershed, providing a baseline to analyze how different historical decisions might have shaped its current state. A mathematical hydrodynamic model is then employed to map flood patterns associated to this scenario and to the current conditions of the watershed. The Urban Flood Cell Model-MODCEL [22] was selected for this application, although other models could have also been used – the model choice is a user decision. The results of the two simulations are expected to reveal a more favorable outcome for the Uchronic Scenario when compared to the current flooding patterns, likely demonstrating reduced flood risks. This comparison underscores the potential benefits of integrating hydrological preservation into urban planning strategies.

The Uchronic Scenario reveals lost opportunities, highlighting the need to address the challenges of the current urban setup. By considering the lessons learned from the uchronic results, the current HIA –although reduced when compared to the uchronic HIA – remains feasible to guide proper future urban planning, serving as a foundation for implementing blue and green actions aligned with proper land use management.

Through the lessons learned from simulation of the Uchronic Scenario and the subsequent comprehension of the Current Situation, it is possible to propose a Desirable Scenario and a Realistic Scenario. In both cases, the preservation of remaining open green spaces is prioritized. However, the Realistic Scenario acknowledges the spatial constraints of the watershed, offering more practical and probably more feasible guidelines for urban development, even if not completely solving alone all the flooding problems, while the Desirable Scenario aims to get the closest possible to the Uchronic Scenario, probably loosing part of its feasibility.

The core idea in both scenarios is to use the urban open space system to structure a hybrid blue-green-grey multifunctional infrastructure system, guided by the HIA concept and individualized to each stretch of the watershed, according to its natural functions, but integrating them with the urban needs. Therefore, at the same time the proposed measures should target flood mitigation, they would also create opportunities to enhance urbanity by integrating greenways, squares, local parks, fluvial parks and environmental conservation units. This approach establishes environmental capillarity within the urban fabric, providing both environmental and urban services. The extent of this conceptual application varies between the Desirable to the Realistic Scenarios.

To support this discussion, another conceptual approach is introduced: the watershed spatial arches. This concept emphasizes that different sections of a watershed demand distinct hydraulic and urban solutions due to their varying topographic configurations and usual levels of urbanization (differing in service demands). The approach divides the watershed into three sections: the upper arch, the middle arch and the downstream arch.

The guidelines for designing realistic and desirable scenarios are established through a matrix of joint urban and environmental planning recommendations. This matrix intends to provide intervention guidelines for the open space system using the HIA as background, in each portion of the watershed – that is, in each of the three spatial arches that individualizes the watershed functions interacting with the urban features.

The upper reaches of the river, with the highest slopes in the watershed, are tied to the upper spatial arch of the watershed, where the focus is on environmental preservation, especially regarding the quality and extent of the green cover. However, since downstream areas are usually occupied and suffering from urban-environmental imbalances, it is important to use this upper arch as a natural buffer to improve water retention, to compensate for downstream urbanization. This effect can be obtained by generating storage opportunities on the way to the foothills, where the transition to the mid-reaches of the river occurs. The mid watershed is where the concept of integration becomes more important, recognizing that urban and environmental needs have to be jointly considered. Urban open spaces can be modified to shelter multifunctional purposes, also including the hydraulic function to temporarily store floods and dampen flood peaks. However, urban services must continue to be offered, for example, with leisure facilities. In the downstream reaches, the respect concept applies, unfolded in two main lines of action: the watershed capacity discharge has to be guaranteed, to avoid backwater effects and flooding, but it cannot affect downstream neighborhoods by transferring floods downstream.

Therefore, the guidelines matrix combines physical traits and land use patterns to offer specific recommendations crossing the watershed arches as defined in the previous lines. This matrix is structured around two primary axes: the physiographic characteristics of the watershed, linked to the concept of Hydrological Interest Areas (HIA), and the urban settlement characteristics, categorized from upstream to downstream. The physiographic characteristics of the watershed were defined by features that influence drainage patterns and directly respond to precipitation events. These features included geological formations with varying elevations, slopes and reliefs, such as hilltops, mountain slopes, foothills, riverine flood-prone areas, flat areas, and coastal lowlands. These topographical features are intricately associated with the characteristics that constitute the spatial arches.

Subsequently, the physiographic characteristics of the watershed were correlated with urban occupation patterns, specifically the level of territorial density, which directly impacts natural hydrological processes that contribute to water retention and soil permeability. This study considered five density categories: non-occupation, rural areas, low-density occupation, medium-density occupation, and high-density occupation. The Guidelines for Territorial Reorganization were developed to support the implementation of both the Desirable and Realistic Scenarios. In the Desirable Scenario, interventions outlined in the matrix are intended to be applied across the entire HIA, regardless of their current land use. In contrast, the Realistic Scenario focuses strictly on utilizing available open spaces within the HIA Then, two matrices were developed: one for the realistic scenario and one for the desirable scenario. Table 1 shows the Guidelines for Territorial Reorganization for the Desirable Scenario and its relationship with the spatial arches, while Table 2 shows the Guidelines for Territorial Reorganization for the Desirable Scenario and its relationship with the spatial arches.

Table 1. Guidelines for Territorial Reorganization for the Desirable Scenario.

DESIRABLE SCENARIO						
Spatial Arch	**Physical aspects**	**Land and Use Occupation**				
		Non-occupation	**Rural zones**	**Low-density occupation**	**Medium-density occupation**	**High-density occupation**
1st arch	**Hilltops**	If vegetated, preserve; if not vegetated, reforest.	Remove and reforest.			
	Mountain slopes					
2nd arch	**Foothill**	If vegetated, preserve; if not vegetated, reforest; create flood buffer zones.			Relocate, reforest, and create flood attenuation areas.	
	Riverine Flood-Prone Region	If vegetated, preserve; if not vegetated, reforest.	Remove built-up areas and replace them with rural parks.	Relocate and create a multifunctional park to prevent occupation.		
	Flat areas	Flood attenuation areas and/or areas to encourage urban expansion with sustainable management.	Rural park and/or areas to encourage urban expansion with sustainable management.	Multifunctional park and/or areas to encourage urban expansion with sustainable management.	Multifunctional park, allowing the maintenance of existing occupations, provided that the available free area is sufficient to protect these occupations.	

3rd arch	**Coastal Lowlands**	Maintain as vegetated open space and/or areas to encourage urban expansion with sustainable management.		Coastal park and/or areas to encourage urban expansion with sustainable management.	Coastal park and/or areas to promote urban expansion with sustainable management.	

Table 2. Guidelines for Territorial Reorganization for the Realistic Scenario.

REALISTIC SCENARIO						
Spatial Arch	**Physical aspects**	**Land and Use Occupation**				
		Non-occupation	**Rural zones**	**Low-density occupation**	**Medium-density occupation**	**High-density occupation**
1st arch	**Hilltops** **Mountain slopes**	If vegetated, preserve; if not vegetated, reforest.	If the settlements are formal: assess the risk. If the settlements are informal: relocation and revegetation of the area.			
2nd arch	**Foothill**	If vegetated, preserve; if not vegetated, revegetate and create flood buffer zones.				
	Riverine Flood-Prone Region	If vegetated, preserve; if not vegetated, reforest.		If the settlements are formal: create multifunctional park in the available open spaces. If the settlements are informal: relocate and incorporate the area into the multifunctional linear park.		
	Flat areas	Flood buffer areas and/or areas promoting urban expansion with sustainable management.	Rural park and/or areas promoting urban expansion with sustainable management.	Multifunctional buffer park and/or areas promoting urban expansion with sustainable management.	Multifunctional buffer park, allowing for the maintenance and even expansion of settlements with sustainable management, as long as the available open space is sufficient to protect these settlements.	
3rd arch	**Coastal Lowlands**	Maintain as a vegetated open area and/or areas promoting urban expansion with sustainable management.		Coastal park and/or areas promoting urban expansion with sustainable management.	Coastal park, allowing for the maintenance and even expansion of settlements with sustainable management, as long as the available open space is sufficient to protect these settlements.	

Figure 1 presents the logical flowchart showing the articulation of the general procedures composing the proposed method.

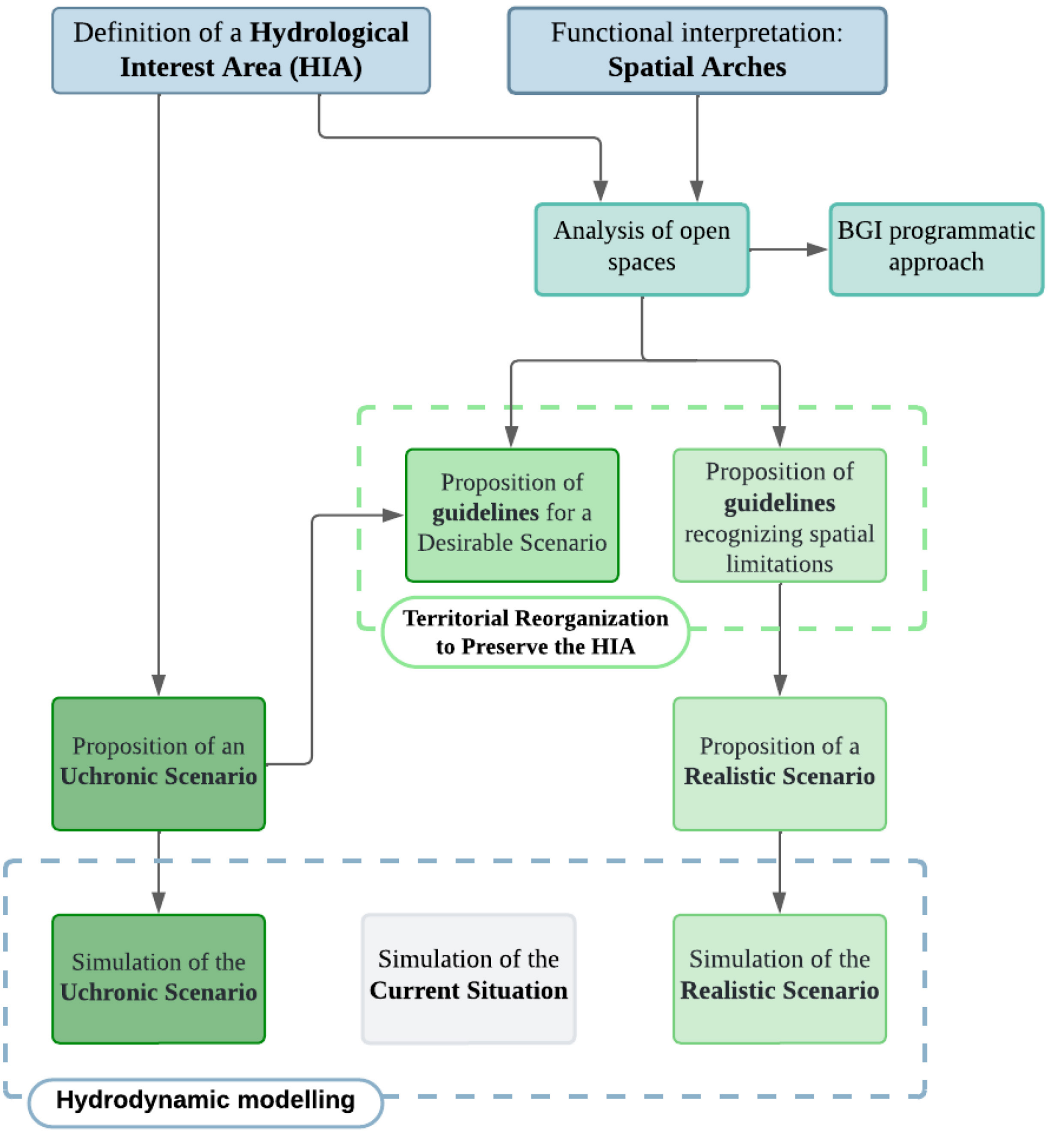

Figure 1. Flowchart of the main stages of the research.

Data collection and manipulation

The data collection process integrates hydrological, environmental, and urban parameters based on official datasets [23], including topographic and hydrological maps, land use classifications, and census data. Additionally, the hydrodynamic modelling accounts for historical flood records and rainfall data to calibrate and validate flood risk dynamics in the study area. Geographic Information System (GIS) tools were then employed to analyze the data collected.

Analysis Techniques

Hydrological Interest Area (HIA)

This is a novel and formal type of land use class that recognizes that an urban system based on Nature-based Solutions is essential for fostering sustainable development and improving flood resilience in cities. This study adopts the concept of HIA – introduced by Miguez et al. [20] - as background for planning and design of combined urban flood control and urban landscape measures. It serves environmental preservation purposes and supports design propositions by identifying floodable areas and open green spaces. These are potential areas for accommodating design solutions that maintain a harmonious balance between environmental preservation and urban expansion, while preventing future occupation of flood prone areas. Moreover, these areas should be under strict land use management to guarantee available space for water dynamics. The delimitation of a HIA is based on the intersection of four criteria, as previously described in Miguez et al. [20]: legally protected areas, coastal lowlands, predominantly flat open spaces, and riverine flood-prone regions.

Three categories of land use zoning emerged from the original HIA application: (1) Environmental Full Protected Areas, which already exist and were identified by the first criterion; (2) Environmental Areas subject to Sustainable Land Use Management, which also already exist and were defined by the first criterion; and (3) Environmental Areas subject to Sustainable Land Use Management to be created, based on the remaining three criteria used in the HIA's construction. The “Environmental Areas subject to Sustainable Land Use Management” permits urbanization, but only under preventive regulations and specific construction standards defined in Environmental Management Plans. The resulting HIA network can shelter a blue-green infrastructure approach, including extensive green conservation areas, downstream lowlands, flat open spaces, and connecting floodplains and fluvial corridors.

<u>Programmatic Approach to Designing Blue-Green Parks in each Arch</u>

The general guidelines for territorial reorganization can be enhanced by incorporating a detailed "program of necessities" that outlines park implementation strategies. This approach aims to optimize potential interventions across the different areas of the watershed, taking into account the physiographic characteristics of the spatial arches. In this context, the social emphasis of the strategies is highlighted, demonstrating how Nature-based Solutions can cope with the quality of life improvement for the local population. The program of necessities is organized into six main categories, which are further subdivided into additional categories. These include: Sustainable Urban Drainage; Sustainable Mobility; Sports and Leisure; Education, Culture, Entertainment and Art; Environmental Preservation; and Other Infrastructure and Services.

The "Sustainable Urban Drainage" section aims to highlight the water management actions that can be incorporated into the park typologies. These include the creation of multifunctional areas for water storage, which help mitigate peak flood levels and flooding extents, while also providing recreational spaces for the public. The incorporation of artificial lagoons and wetlands is also proposed, offering both aesthetic value and contributing to water quality treatment, while also alleviating flooding in the surrounding areas. Additionally, the implementation of permeable pavements in open public spaces, such as parking lots with low to medium traffic, is recommended to reduce surface runoff.

The "Sustainable Mobility" category emphasizes the development of interconnected bicycle routes across the watershed, alongside pedestrian pathways that preserve soil permeability; therefore, it tackles the opportunities for active mobility. In regions within the downstream arch, sustainable mobility strategies may also involve the creation of inland waterway terminals, potentially integrated with local transportation systems or tourism initiatives, if the fluvial system is connected to navigable lagoons or other large waters bodies.

The "Sports and Leisure" category encompasses various elements designed to serve local populations and enhance quality of life by promoting outdoor physical activities and other leisure opportunities. These elements may include, for example, sports courts for a range of activities; fitness areas; tracks for athletics; equestrian routes linked to stables or facilities for housing horses; playgrounds; and infrastructures that support water sports, such as rental stations for boards, canoes, and other equipment. Additionally, observation areas should be strategically placed at the territory to offer views of significant landscape features, including natural elements or cultural landmarks. This element plays a crucial role in connecting the population with its natural landscape.

The "Education, Culture, Entertainment, and Art" category proposes general institutional facilities associated with the spatial arches. In this regard, amphitheatres could serve as a venue for hosting a wide range of events and performances for the community, as well as outdoor movie projection areas, that should be placed in large open spaces and accommodate diverse uses. Additionally, spaces for cultural and recreational events, as well as venues for art exhibitions, are suggested. These areas, designed to host a variety of cultural activities, should be in accessible locations. Furthermore, the creation of spaces dedicated to landscape art or site-specific installations is also recommended, supporting the placement of art installations or sculptures within the landscape, thus establishing new landmarks.

In the category of “Environmental Preservation”, since the conservation of natural areas maintains the hydrological infiltration functions. These areas are also dedicated to the conservation of local flora and fauna acting as environmental anchors in the built environment. Another important use refers to land designated for agroforestry systems, as it enables the integration of agricultural cultivation with trees or shrubs, promoting community involvement. The restoration of riparian vegetation is another key focus; especially in regions that have undergone significant urbanization. This measure is essential for the environmental rehabilitation of watercourses, safeguarding these areas, and enhancing wildlife activity. Finally, the creation of ecological islands, when the fluvial system connects with lagoons, wetlands or great ponds, is proposed to support aquatic plant species that contribute to improved water quality and provide rehabilitated habitats.

In the "Other Infrastructure and Services" category, several facilities can be proposed to enhance user experience and encourage greater engagement with the parks and project areas. These include coffee shops and kiosks offering food options for park visitors; shading structures that encourage visitors to spend time in the areas; parking lots with permeable surfaces, incorporating permeable pavements to increase water infiltration and reduce surface runoff. Efficient and informative signage is also proposed, not only to outline the multifunctional roles of the parks but also to serve as educational tools, fostering a greater public connection to environmental resources.

Considering the possible contents of the program of necessities, it becomes clear that most parks located in the Upper Arch feature fewer leisure support facilities and assume a role of more natural elements. This is because the construction of large-scale structures could attract a higher population density to the area, potentially compromising regions of significant hydrological importance. In this context, considering that the Upper Arches serve the dual purpose of reserving and preserving existing open spaces, the design strategies for these areas are focused on conservation, enabling contemplative activities with minimal environmental impact. In contrast, the park typologies located in the Middle and Downstream Arches can offer greater integration with the public, as they are situated closer to urban zones. Table 3 illustrates the program of necessities related to the proposed spatial arches interpretation.

Table 3. Program of necessities associated with the spatial arches.

PROGRAM OF NECESSITIES		SPATIAL ARCHES				
		1st ARCH		2nd ARCH		3rd ARCH
CATEGORY	SUBCATEGORY	Storage Parks	Conservation and Reforestation areas	Rural Parks	Multifunctional Parks	Coastal Park
Sustainable Urban	Multifunctional floodable area	✓		✓	✓	

Drainage	Artificial lagoons or wetland					✓
	Permeable pavements			✓	✓	✓
Sustainable Mobility	Cycle paths	✓		✓	✓	✓
	Walking trails	✓		✓	✓	✓
	Bicycle parking			✓	✓	✓
	Hydroviary station					✓
Sports and Leisure	Sport courts			✓	✓	✓
	Athletics running tracks				✓	
	Horseback riding trails	✓		✓		
	Observation area	✓		✓	✓	✓
	Fitness area				✓	✓
	Playground			✓	✓	✓
	Support for lake sports					✓
Education, Culture, Entertainment and Art	Amphitheater for events and performances				✓	✓
	Outdoor movie screening area				✓	
	Spaces for cultural and educational events				✓	✓
	Space for art exhibitions				✓	
	Landscape art or site specific	✓	✓	✓		
Environmental Preservation	Zones to the preservation of local fauna and flora	✓	✓	✓	✓	✓
	Areas for agroforestry	✓	✓	✓	✓	✓
	Riparian vegetation restoration			✓	✓	✓
	Lagoon recover					✓
	Ecological islands					✓
Other Infrastructure and Services	Benches and shaded areas for relaxation	✓		✓	✓	✓
	Coffee shops and kiosks				✓	✓
	Shade structures			✓	✓	✓
	Parking lot with permeable surfaces and green areas				✓	✓
	Efficient and informative signage	✓	✓	✓	✓	✓

Modelling and Simulations

To simulate urban flooding dynamics and assess the impact of different planning strategies, this study used the Urban Flow Cell Model (MODCEL) [22], a hydrological-hydrodynamic tool that represents surface runoff produced during flood events in urban spaces, as well as its interaction with storm drains and open channels, which are also represented in an integrated computational system. Furthermore, this model has been used in several previous works [1], [24]–[26] also including watersheds in the Municipality of Maricá [20], [27], which will be used in the case study application, demonstrating its reliability for this analysis. However, the proposed method does not depend on this choice – any other convenient hydrodynamic model, providing flood simulation features, could be used by the modeler.

For comparison purposes, all simulations of urban occupation scenarios were performed for a 25-year return period event, as this represents the standard criterion typically adopted for major drainage projects in Brazil. Simulation results were processed using GIS tools, generating flood hazard maps to compare scenario effectiveness. The Desirable Scenario was not simulated with MODCEL since it represents an aspirational target that combines significant population relocations and comprehensive environmental interventions. These characteristics make it less suitable for practical purposes, as it assumes conditions that targets the uchronic scenario results (that will be simulated) and it is not immediately implementable without extensive socio-political and infrastructural changes. Instead, its primary purpose is to guide strategic planning and inform the development of feasible scenarios, such as the Realistic Scenario, which incorporates practical already existing constraints.

Scenario Development

This study analyses four distinct scenarios to explore guiding principles for the development of sustainable and resilient cities. The Bambu Watershed, located in the Municipality of Maricá, Rio de Janeiro, Brazil, was selected as case study to evaluate these scenarios and validate the proposed approach. The scenarios include: (1) Uchronic Scenario, as an hypothetical alternative development path where the HIA is identified before urbanization and fully preserved; (2) Current Scenario, depicting the existing land use patterns, their impacts on flooding, and current flood mitigation strategies already in place; (3) Desirable Scenario, seeking to mimic the natural dynamics observed in the Uchronic Scenario while addressing the relocation of residents from the most vulnerable areas identified in the Current Situation; (4) Realistic Scenario, representing a feasible compromise between urban expansion and maintaining natural dynamics, acknowledging the necessity of protecting some already consolidated settlements. Details of the analyzed scenarios are described below.

<u>Uchronic Scenario.</u> This scenario envisions a hypothetical development path and plans an alternative urban growth, imagining a situation where time could be turned back, and development occurs with full respect for the HIA boundaries. It represents the most favorable condition for urban development, prioritizing the protection of ecological zones and natural flood-prone areas, thereby preventing population exposure to floods. Unlike approaches that rely on mitigation strategies to address the consequences of unplanned urbanization, it emphasizes proactive planning. As a result, there is no need for constructing reservoirs or implementing multifunctional water storage strategies.

Additionally, this scenario assumes that the city under analysis could reach the same current population size but distributed in areas that exert less pressure on natural dynamics. A significant adjustment in HIA calculations for this scenario involves fully incorporating flat areas with slopes of less than 0.5%, which are often occupied in the current situation.

Modeling this scenario used the HIA framework as the basis for planning. In this hypothetical case, the HIA retained its vegetation, while urban development was directed to areas outside the HIA. From a modelling perspective, in addition to modifying runoff coefficients to reflect changes in land use, it was assumed that the original hydraulic capacities of watercourses were preserved, with no obstructions or artificial constraints on flow paths.

<u>Current Situation</u>. The analysis of the Current Situation highlights existing occupation patterns in the watershed, serving as a benchmark for comparison with the most favourable urban development proposed in the Uchronic Scenario. More importantly, it facilitates identifying the constraints needed to formulate future scenarios that reorganize urban spaces while ballancing urban and environmental needs.

The Current Situation was modelled using MODCEL, incorporating data on topography, hydrography, land use, and occupation. The model was calibrated and validated by comparing flood extents from simulations with historical flood records and observed water depths. The results serve as a reference for assessing the effectiveness of the proposed interventions.

Desirable Scenario. Building on the concept of the Uchronic Scenario, the Desirable Scenario envisions restoring and preserving the HIA from the outset of the city's development within a framework of low-risk urban occupation. Its focus lies in recovering the hydrological and environmental functions of an already-occupied watershed by relocating residents currently residing within the HIA to (nearly) replicate the conditions outlined in the Uchronic Scenario. While this scenario is aspirational and not directly simulated in this work, it serves as a guide for identifying optimal intervention strategies, but represents high socio and economic costs. The proposed interventions include:

- Storage Parks: Located upstream of the watershed, these parks can incorporate reservoirs to store significant water volumes using dams, which can also be integrated with recreational amenities. Storage parks can also be constructed through excavation, in areas of natural depressions, lower elevations, or river confluences. Dams are recommended to contain large water volumes and protect surrounding urban developments, but they have to be carefully planned, to avoid other types of environmental degradation or operartional risks. Additionally, open spaces with dense vegetation, particularly in less urbanized areas, should be preserved or restored if already degraded.
- Conservation and Reforestation areas: This strategy focuses on preserving the original physical characteristics of specific watershed sections, enhancing stormwater retention, filtration, natural infiltration, and aquifer recharge. Conservation and reforestation also help control urban sprawl, prevent excessive soil impermeabilization, and promote local biodiversity by maintaining or restoring green spaces.
- Rural Parks: Situated preferably upstream, in areas with low population density, rural parks preserve natural ecosystems, rehabilitate water resources, and restore degraded landscapes. These parks also support reforestation efforts, especially in deforested areas vulnerable to urban expansion, and offer opportunities for sustainable agriculture to ensure food security. Additionally, they promote interaction with nature, education, and community-based practices through plant and animal life engagement.
- Multifunctional Parks: Located in areas with higher population density, these parks should be implemented along water bodies to support the drainage network storage demands and provide public open spaces for recreational use, fostering stronger connections between the population and natural resources. Ideally, multifunctional parks should be situated in urbanized areas with medium to high population density, allowing their facilities and infrastructure to address a variety of social local needs. Such interventions may include urban reservoirs or smaller detention basins to improve their capacity for capturing and storing rainwater.
- Coastal Parks: At the end of the drainage system, if the fluvial system drains to sea, coastal parks offer spaces for community gathering and recreation while accommodating social-use facilities and improving connectivity. These parks can enhance hydrological dynamics by facilitating channel dredging or restoring water bodies, enabling direct interaction with coastal lagoon systems and other aquatic environments. When the ultimately destination of the interest watershed is the sea, improving the conveyance of the final river reaches can offer better upstream conditions facilitating reservoir discharges

The proposed interventions represent the potential for implementing transformative projects in the watershed, assuming that all necessary relocations could be realized.

Realistic Scenario. Recognizing the unfeasibility of widespread relocations, as proposed in the Desirable Scenario, the Realistic Scenario focuses on implementing the minimum necessary actions to restore degraded environmental and hydrological functions using similar individual actions, as presented in the previous scenarios, but with greater parcimony. This approach prioritizes urban reorganization through interventions in open or irregularly occupied spaces that can be reversed (mainly because high risks demand people relocation). While it aspires to move toward the Desirable Scenario, the Realistic Scenario acknowledges spatial constraints present in the Current Situation.

The Realistic Scenario was simulated using MODCEL, incorporating a set of interventions in open spaces aimed at mitigating flooding. In this case, storage parks, reforestation, rural parks, and multifunctional parks were integrated into the modelling of the Current Situation. These strategies contributed to enhancing infiltration and reorganizing runoff through increased storage capacity.

CASE STUDY

A case study in a rapidly developing and environmentally fragile area is used to illustrate the application of the scenarios. This case corresponds to the Bambu River watershed, in the city of Maricá, at the Metropolitan Region of Rio de Janeiro, Brazil. Maricá is a coastal city that covers an area of 361.572 km² and has been undergoing a phase of accelerated urban expansion, largely attributed to the implementation of several social programs that have progressively contributed to its socio-economic development. It also has a prosperous economy, mainly resulting from petroleum royalties. According to the latest demographic census [23], the population has increased by 54.87% over the past twelve years, rising from 127,461 to 197,277 inhabitants. Maricá is also recognized for its significant wealth of heritage assets, encompassing historical, cultural, and environmental value, such as one of the largest lagoon complexes in the state, named Maricá-Guarapina. The local topography is characterized by a distinct natural "amphitheatre" formation [20], where the mountainous terrain features steep slopes over short distances followed by coastal plains. This geomorphological structure facilitates the rapid runoff of rainwater and riverine contributions toward the floodplain areas. In these regions, the influence of the sea on the lagoon system creates a restriction to fluvial discharges at the river mouths, exacerbating the incidence of urban flooding. Currently, only 19.85% of the municipality is classified as urban area, with medium-density occupation along the highways and the coastline. In light of the potential risks associated with future urban expansion, particularly the encroachment on riverine floodplain areas, the preservation of open green spaces has emerged as a critical priority. This is especially urgent given that flooding is already a recurring issue in several neighbourhoods, including the city center.

More specifically, the Bambu River Watershed, the interest area of this case study, has an area of approximately 109 km², and 18.7 km of extension along the main river. The local altimetry shows a variation from 0 to 870 meters, where most of the urban areas are located in coastal lowlands, at elevations lower than 50 meters. In this sense, the upstream areas of the watershed are composed of higher slopes, characterized as “mountainous”, “scarped” or “corrugated” areas, where average slopes can vary from 50% to over 75%; while the downstream areas are comprised of “plain” and “soft-corrugated” areas, where average slopes are close to 0% and argisol are the predominant type of soil. Due to the level variation from upstream to downstream, which is characterized by short stretches in high gradients and long stretches in plain areas, rainwater is rapidly concentrated in the urban areas, leading to urban flooding. The Bambu River flows to the Maricá Lagoon. The average annual precipitation is nearly 1150 mm and the rainy season occurs in summer.

The current land use shows that 37.80% of the territory is occupied by urban areas, characterized by residential and commercial sectors. On the other hand, green open spaces (field/pasture or vegetation) comprise 60.37% of area, blue spaces (wetlands, areas of fluvial/lagoon dynamics) represent 1.13% of the watershed, and 0,7% represent other elements (sand, rocks, etc.). In general, the selected area has a consolidated urban fabric near the lagoon borderlines, and a dispersed occupation near the urban northern limit. Most of the open spaces correspond to areas of environmental interest, such as conservation units; vulnerable areas subjected to flooding; rougher terrains, generating difficulties for occupation; and rural areas, where the occupation is incipient and urban development is not allowed by the city master plan. Figure 2 shows the delimitation of the Bambu River Watershed.

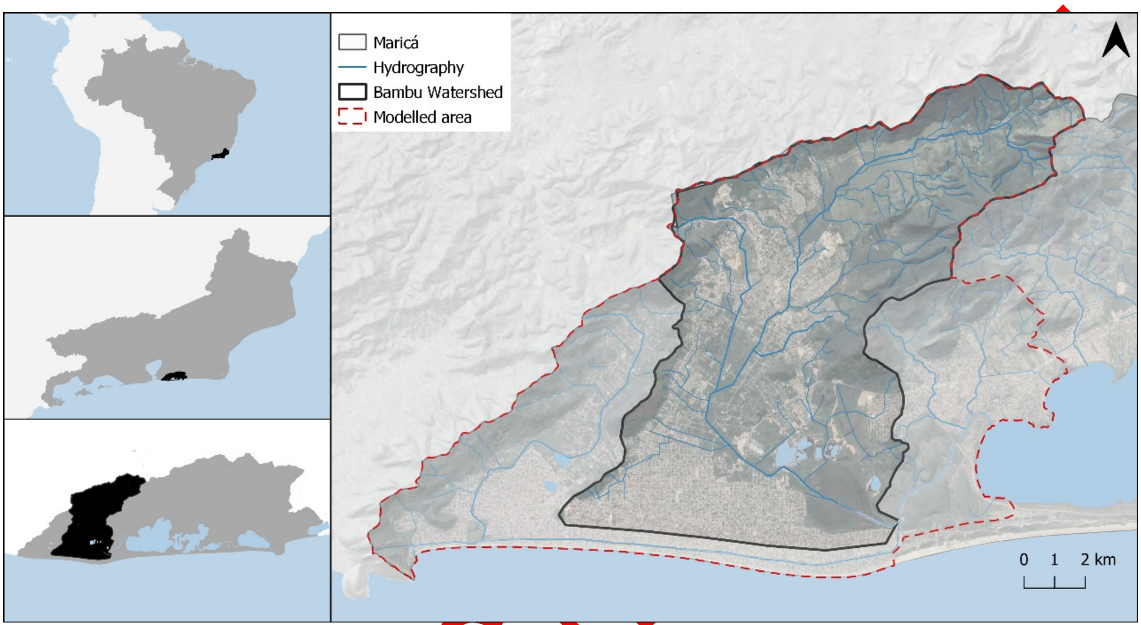

Figure 2. Location of the Bambu River Watershed in Maricá Municipality.

RESULTS

The following subsections organize the results by scenario. The Uchronic Scenario outlines the delineation of the uchronic HIA and the simulated water depths. The Current Scenario presents the water depths as observed under present-day conditions. The Desirable Scenario presents the proposed matrix with guidelines for an ideal, although currently unfeasible, situation without hydrodynamic simulation outcomes. In contrast, the Realistic Scenario includes the results from a practical design alternative developed in accordance with the guidelines of the realistic matrix.

Uchronic Scenario

To achieve the setup of this scenario, the boundary of the original HIA was superimposed onto existing lots, leading to excluding buildings located within the interest area. To accommodate the current population in the remaining areas, the excess population was redistributed across vacant lots in less environmentally vulnerable regions. Furthermore, the hydrodynamic simulation model considered that, under a development planning that prioritizes ecological preservation and natural floodplain dynamics, rivers would follow their natural courses without obstructions such as low bridges, rectifications, constrictions, or other elements that increase flow velocity or reduce the flow cross-sections.

Figure 4 illustrates the results of the Uchronic Scenario. Under ideal urban planning conditions that respect water dynamics, the majority of the Bambu River Watershed would be included in the HIA, with the most extensive urbanization occurring in the downstream regions, where the largest portion of the municipality's population is currently concentrated. By prioritizing the preservation of water spaces, this scenario enhances ecological benefits for the region, with green corridors strengthening connections to natural parks and the lagoon system. In this scenario, 65% of the territory is allocated as HIA, while only 35% is designated for urban areas. Despite the reduced percentage of land outside the HIA, it remains sufficient to accommodate the entire current population, with additional capacity still available. Furthermore, by restoring the system original discharge capacity, flooding is limited to a maximum depth of 30 cm during a 25-year return period in most areas. In this watershed, water depths of up to 30 cm do not affect buildings due to the elevation of the house sills. With sufficient space for population distribution outside the HIA, the Uchronic Scenario ensures that 100% of the local inhabitants could be housed in non-impacted areas in this hypothetical situation. Thus, urban planning incorporating the HIA concept from the outset enables a city to develop with reduced flood risks without additional protective measures and consequent costs.

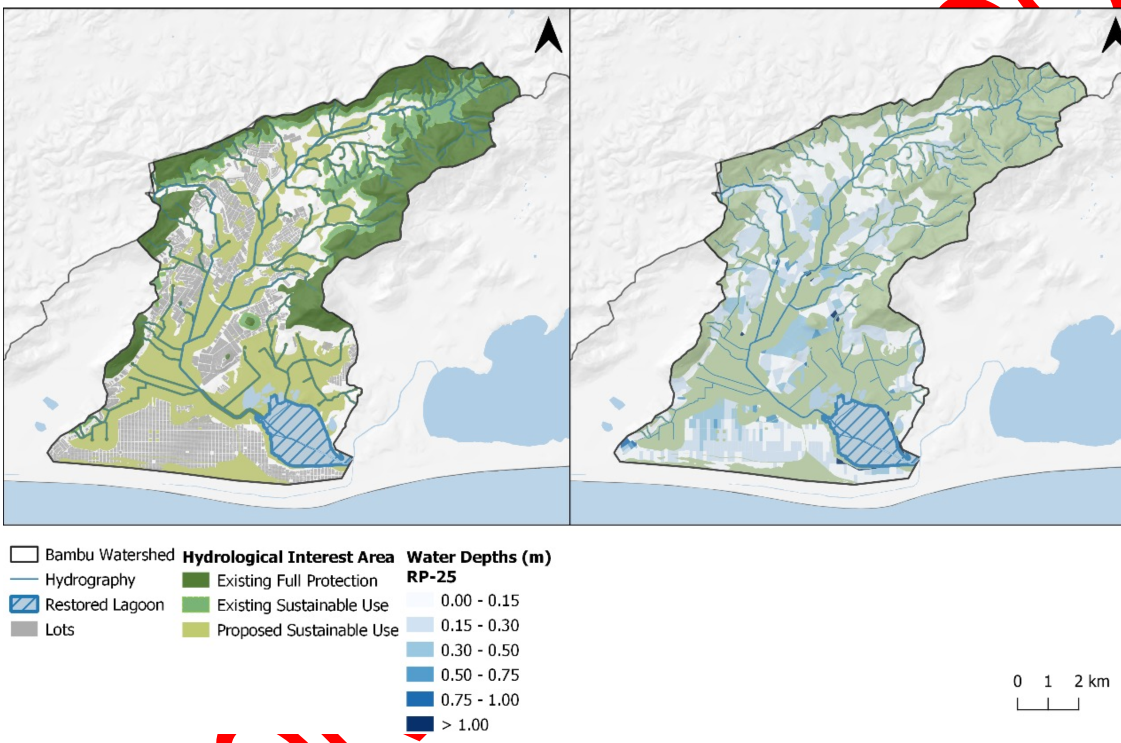

Figure 3. Uchronic Scenario: (a) HIA boundary and available spaces for lot allocation; (b) Simulated flood depths for a 25-year return period event.

Current Situation

In the Current Situation, presented in Figure 4, the land use pattern is characterized by a consolidated urban fabric, with higher population density near the coastline and sparser occupation within the administrative boundaries of the watershed. This configuration is primarily influenced by the region’s land parceling and land use characteristics, which predominantly feature smaller single-family residential lots in the downstream areas, and larger rural lots in the upstream zones. Additionally, areas adjacent to Environmental Conservation Units show an urban fabric in the process of consolidation, while the remaining open green spaces within the watershed correspond to environmentally sensitive areas at risk of flooding. Notably, there is a significant encroachment in the riverine areas, which should ideally be protected to allow the natural river overflows.

The mathematical simulations for a 25-year return period event reveal that urban areas with higher population density are also the most prone to flooding. More specifically, on the left bank of the Bambu River, a distinctive feature of the region results in a concentration of drained volumes in the watershed area surrounding a low-income housing development, the Carlos Marighella Residential Condominium. The drainage challenges in these floodplains create a zone with significant flooding, where water depths exceed 1.0 m. Overall, nearly 21% of the existing lots are located in areas with water depths greater than 0.30 m, and 7% are affected by floods exceeding 0.50 m. The water accumulation area has very low ground elevations, ranging between 2.0 and 3.0 m, with the only outlet being a channel that flows directly into the Vigário River.

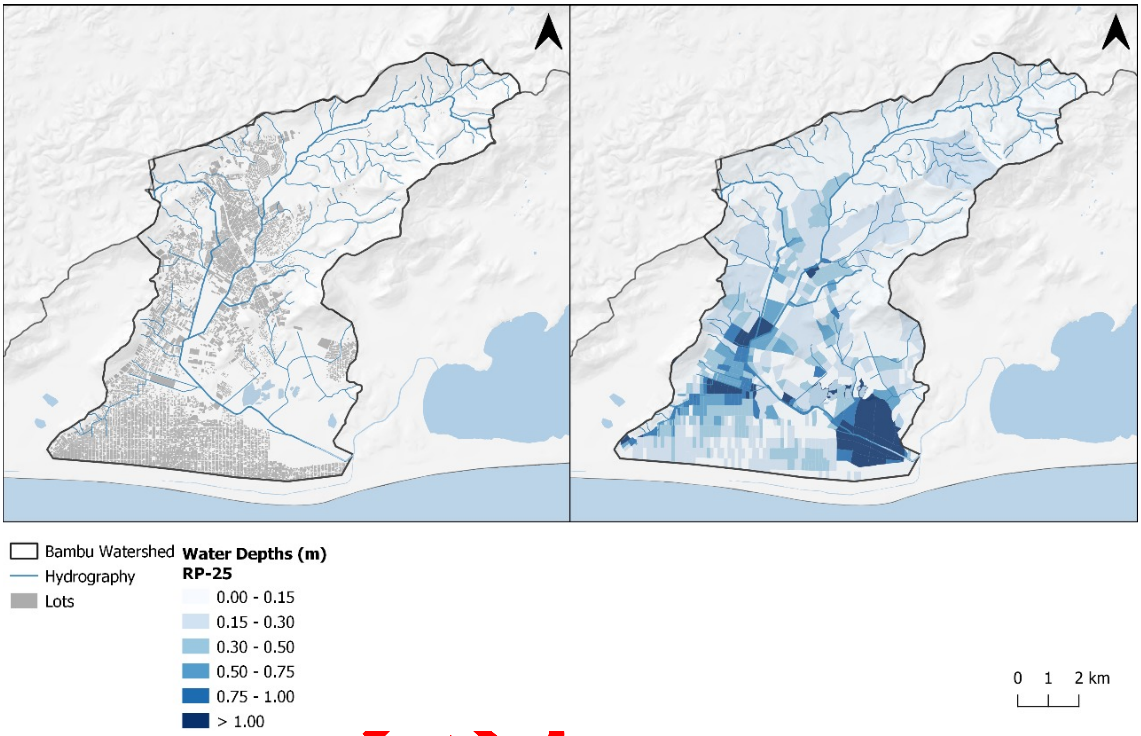

Figure 4. Current Situation: (a) Existing lots within the watershed; (b) Simulated flood depths for a 25-year return period event.

Desirable Scenario

The Desirable Scenario builds upon the Uchronic Scenario reference but focuses on reorganizing the territory to integrate the HIA framework, rather than assuming its prior development in full compliance with the HIA. Therefore, the goal of the Desirable Scenario is to identify the necessary measures to bring Current Situation as close as possible to the ideal conditions outlined in the Uchronic Scenario. In addition to preserving the HIA, this scenario also incorporates the functional interpretation of the spatial arches to structurally guide the local design of blue-green system components.

In the Desirable Scenario, where natural dynamics coexist harmoniously with urban development, the guidelines for hilltops and mountain slopes are identical. In areas designated for non-occupation, the recommendation is to conserve the existing vegetation or reforest degraded areas. Conversely, in regions ranging from rural zones to high-density occupation on hilltops or mountain slopes, existing buildings should be vacated to allow for reforestation. In foothill areas, where water flow rates can be higher, land use (ranging from non-occupation to low-density development) should prioritize conserving existing vegetated areas or reforesting bare zones, while also establishing flood-buffer zones. In riverine flood-prone regions, which are most vulnerable to flooding, non-occupied areas must be preserved with their natural vegetation or reforested.

In rural areas, existing structures should be removed to establish rural parks. Low to high-density zones, should be vacated to facilitate the development of multifunctional linear parks. This strategy is designed not only to mitigate flooding but also to prevent the emergence of informal settlements along riverbanks. Flat areas, often prone to drainage challenges, should be designated as flood-buffer zones or for urban expansion with sustainable management practices. In low-density areas, the creation of multifunctional parks or zones for sustainable urban growth is recommended, ensuring that these open spaces are integrated with necessary urban infrastructure. In medium or high-density areas, multifunctional parks are also advisable, if the available open space is adequate to maintain existing developments and protect these settlements.

Finally, in coastal lowlands, both non-occupation areas and rural zones should remain as vegetated open spaces or be designated for sustainable urban expansion. Open spaces in low-density occupation areas should be converted into waterfront parks or areas for urban expansion with sustainable management, while open spaces located in medium and high-density occupation areas should be transformed into waterfront parks.

Although the Desirable Scenario offers a conceptually sound proposal for territorial reorganization while preserving the HIA, its practical feasibility is limited. An analysis of the Current Situation reveals that approximately 9,480 lots would need to be relocated to achieve this scenario, making it unlikely to gain acceptance from the community or decision-makers. Considering the average household occupation, this would lead to moving more than 20,000 people (which represents more than 10% of the total municipal population). Additionally, the Desirable Scenario would entail substantial costs associated with compensating the relocated population. Given these constraints, the focus shifted toward more feasible proposals for territorial reorganization that are limited to available open or irregularly occupied spaces in risky areas within the watershed, ensuring a more feasible and realistic approach.

Realistic Scenario

The Realistic Scenario is an adaptation of the Desirable Scenario, considering not only the delimitation of the HIA and the functional interpretation of the spatial arches, but also prioritizing measures focused on available open spaces or reversing irregularly occupied spaces within the watershed.

The guidelines for the Realistic Scenario emphasize environmental preservation and sustainable development across various land use types. In hilltops and mountain slopes with no settlements, vegetation should be preserved, and re-vegetation efforts should be undertaken in its absence. In rural zones and areas with varying occupation densities, formal settlements should undergo risk assessments, while informal settlements may require relocation and re-vegetation to mitigate environmental and social risks. In foothill areas, if not occupied, vegetation should be preserved or re-established, accompanied by the creation of flood-buffer zones. Multifunctional parks are recommended in open spaces across rural zones, from low to high-density occupation, with specific risk mitigation measures for formal settlements and relocation strategies for informal ones.

Similarly, in riverine flood-prone zones, non-occupied areas should be re-vegetated or preserved, including the establishment of flood-buffer zones. Multifunctional parks are recommended for both low and high-density occupied zones. In flat areas, flood-buffer zones and sustainable urban expansion should be prioritized in non-occupied areas. In low-density occupation areas, multifunctional parks and sustainable urban expansion areas should be explored, while medium-density areas could benefit from multifunctional parks. High-density areas, in turn, would require multifunctional parks to contain further urban sprawl. In coastal lowlands, the focus should be on preserving vegetated open spaces and promoting sustainable expansion in non-occupied and rural areas, while in low-density coastal zones, waterfront parks should be proposed to support sustainable settlement growth. High-density coastal areas would also require waterfront parks to manage urban development effectively. This comprehensive approach ensures a balance between environmental conservation, risk mitigation, and sustainable urban development.

The general goal is to preserve and restore critical areas to mitigate flooding while minimizing large-scale relocations. To this end, four major interventions are proposed in the simulation, aligning with the spatial arches functions and the program of necessities formulated for these areas.

In practical terms, a "Storage Park" is proposed in the upper arch, consisting of two integrated reservoirs situated in a predominantly rural area. This park preserves the natural characteristics of the site while providing space for equestrian activities, agroforestry, and other compatible uses. In the mid-watershed arc, two "Multifunctional Parks" are designated to simultaneously mitigate urban flooding that affects the surrounding households and provide leisure and recreational spaces. Finally, in the downstream arch, a "Coastal Park" is proposed for the Brava Lagoon – a formal water body currently degraded and almost lost to siltation and urban pressures. This intervention aims to restore this water body, recovering its natural structure, while providing leisure spaces, ecological islands to support biodiversity, and enhancing sustainable urban mobility through fluvial inland transportation. In this scenario, relocations are considered complementary measures, contingent on the availability and quality of the remaining open spaces for intervention.

Figure 5 presents the proposed Realistic Scenario along with its modelling results. In this scenario, there is a significant reduction in flood depths and, consequently, in the number of affected lots. Overall, there was an 82% decrease in the number of lots affected by floods exceeding 1 m, a 68% reduction in lots impacted by floods over 0.5 m and 43% reduction in lots impacted by floods over 0.3 m. This means that 2,234 lots previously vulnerable to floods over 0.3 m are no longer at risk during a 25-year return period event. It is important to highlight that the proposed measures do not account for relocations – they were not needed, because the proposed measures could fit in the available open spaces. This choice limits the available spaces for interventions. The results of the Realistic Scenario could be further improved by incorporating key HIA spaces through relocations, thus progressing toward the Desirable Scenario and achieving outcomes closer to those of the Uchronic Scenario.

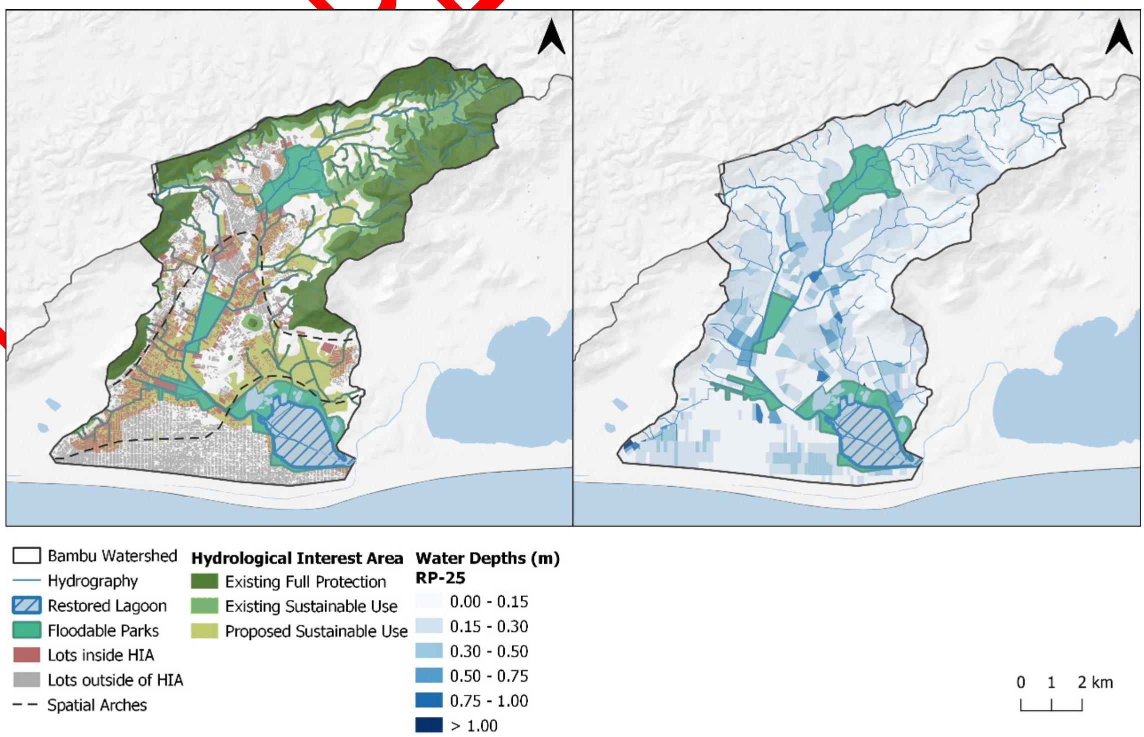

Figure 5. Realistic Scenario: (a) HIA boundary, spatial arches, existing lots, and proposed interventions; (b) Simulated flood depths for a 25-year return period event.

Territorial planning and reorganization strategies based on the HIA concept are adaptable to other watersheds. For areas that are not yet urbanized, the Uchronic Scenario, as a conceptually ideal framework for planning, can serve as a model for guiding development, reducing the need for additional protective measures after urbanization. In densely populated areas, the Guidelines for Territorial Reorganization of the Realistic Scenario offers principles and guidelines that can assist decision-makers in implementing interventions with the potential to mitigate risks while simultaneously delivering environmental and social benefits to surrounding communities.

The Desirable Scenario is constrained by the challenges of relocation and its associated costs. Therefore, when moving from the realistic to the desirable scenario, it is crucial to assess the additional benefits of incorporating relocation spaces into the project and a cost-benefit analysis is required.

CONCLUSION

The negative consequences of rapid and unplanned urbanization are becoming increasingly evident in cities, particularly through the heightened frequency and severity of urban floods. However, strategically implementing NbS in remaining urban green spaces offers multiple benefits. In this context, this study proposed a framework for establishing guiding principles for urban restructuring aimed at reducing flood risks using the concept of Hydrological Interest Areas and the functional arches interpretation, to incorporate the watershed behavior and the interactions between natural and urban demands in the planning process. To assess this proposal, hypothetical urban planning scenarios were developed for the Bambu River Watershed in Maricá, Rio de Janeiro, Brazil, simulating various strategies that integrate natural elements across the watershed with different constraints. This process resulted in the development of a correlation matrix, referred to as the Guidelines for Territorial Reorganization, which simultaneously examines physiographic features and urban development patterns from upstream to downstream, linking them to the spatial arches concept, where the upper arch refers to preservation, the middle arch fosters environment and urban integration and the downstream arch seek to respect watershed limits and discharge capacity to downstream.

The first scenario proposes a positive reference situation, where a what-if condition is developed. This uchronic scenario assess how the watershed could respond to flood challenges if it had been developed according to environmental awareness, preserving the whole original Hydrological interest area. The analysis reveals that the Uchronic Scenario ensures no residents are located in flood-prone areas, whereas the simulation of Current Situation indicates that nearly 21% of properties are in zones with water depths exceeding 0.30 m, and 7% are exposed to floods greater than 0.50 m. The Desirable Scenario, which would require extensive and non-practical lot relocations, led to the development of the desirable Guidelines for Territorial Reorganization. In contrast, the Realistic Scenario incorporated an adaptation of these Guidelines, proposing four key interventions within still available green open spaces, resulting in significant reductions in flood exposure. Under this scenario, 12% of lots remain vulnerable to floods exceeding 0.30 m, and 2% to floods over 0.50 m, but 2,243 lots are protected from flooding associated with a 25-year return period event.

These results confirmed that integrating Hydrological Interest Areas (HIA) and Nature-based Solutions (NbS) can balance urban planning needs with flood risk mitigation, enhancing both environmental resilience and social equity. Moreover, the study explored the social value of parks within a program of necessities, complementing the matrix of integrated urban and environmental planning recommendations. The functional interpretation of spatial arches in urban planning, combined with the HIA framework, provides a methodological basis for effectively defining a stage of action for incorporating Nature-based Solutions, ensuring a synergy between social and environmental demands while aligning with flood risk mitigation strategies. Therefore, the findings of this study have important implications for urban planning and flood risk management, as they provide territorial organization strategies to effectively reduce flood risks while maintaining socio-environmental balance. Notably, the Realistic Scenario demonstrated substantial improvements without requiring relocations, highlighting its practicability and feasibility. By preserving ecological zones and restoring the natural discharge capacities of watercourses, the proposed measures effectively reduced flood impacts while fostering safer and more resilient urban spaces.

In general, the strengths of this study lie in its novel integration of HIA and NbS within urban planning, offering a valuable framework for "reading" the territory, interpreting its functionalities and mitigating flood risks. The Guidelines for Territorial Reorganization provide a structured decision-support tool, while the different scenarios demonstrate the feasibility of implementing NbS. However, the main limitation of this work refers to the need of available open spaces. Although conceptually sound, the Uchronic scenario is recognized as a desirable image, but if the current situation is too degraded and available open spaces are not significant, reorganizing the urban watershed according to the proposed Guidelines for Territorial Reorganization can be very difficult and economically unfeasible.

The proposed methodological framework can be applied to other urban watersheds facing similar hydrological challenges and the next steps of this research intend to test this proposal in watersheds facing different stages of urbanization. The combination of spatial analysis, hydrodynamic modelling, and urban reorganization guidelines provides a flexible and adaptable approach to different geographical, environmental, and socio-economic contexts. By refining the Hydrological Interest Areas framework and expanding the application of NbS, this method can serve as a decision-support tool for policymakers, urban planners, and environmental agencies, fostering sustainable urban development strategies in flood-prone areas. Future research should also further explore the long-term hydrological performance of the proposed solutions, incorporating climate change projections to assess the resilience of NbS under future rainfall and sea-level rise scenarios. Additionally, socio-economic analyses, including a benefit-costs assessment, should be conducted to evaluate the feasibility of population relocations to expand the proposed interventions, maximizing benefits to vulnerable population still residing in flood-prone zones.

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NOMENCLATURE

Abbreviations

GIS	Geographic Information System
HIA	Hydrological Interest Areas
MODCEL	Urban Flow-Cell Model
NbS	Nature-based Solutions

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