













The use of blue-green infrastructure as a multifunctional approach to watersheds with socio-environmental vulnerability

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ABSTRACT

This article investigates how to make the implementation of blue-green infrastructure (BGI) more attractive to solve urban problems in densely occupied watersheds that lack flood control and environmental quality protection infrastructure. Considering the obstacles related to implementing multifunctional solutions in developing countries, measuring its co-benefits (in addition to flood control) may influence greater public and political acceptance. Thus, the paper uses a multifunctional design approach using the urban open space system and combining the blue-green and gray infrastructure. A hydrodynamic model was used to support flood mapping. This approach also increases the land value and the environmental quality of the urban spaces. Two quantitative aspects support this evaluation. The first one represents the land value increase as a positive effect, while the second one assesses the environmental quality of the urban space using the Environmental Quality Assessment Index (EQAI). The results obtained from the urban and environmental evaluation proved that blue and green corridors could promote multiple co-benefits for consolidated urban areas. The increased environmental quality and land value were only possible due to the combined use of BGI and gray infrastructure since BGI can add benefits that the gray infrastructure is not capable of providing.

Key words: blue-green infrastructure, environmental quality assessment index, land value increase, multifunctional landscapes, socio-environmental vulnerability

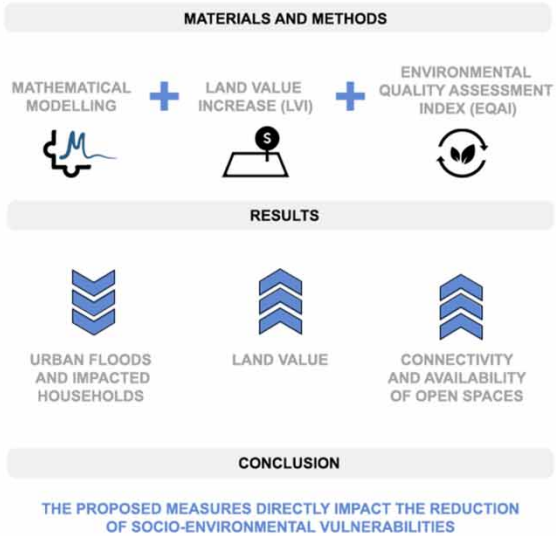
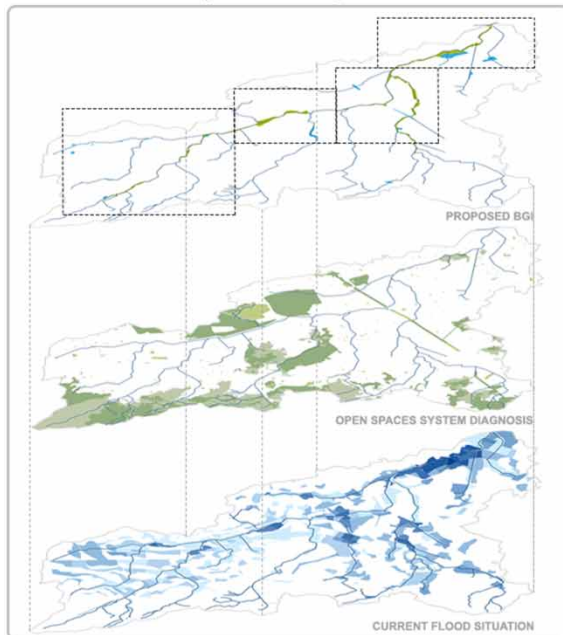
HIGHLIGHTS

- This work aims to offer a sustainable alternative to urban watersheds.
- BGI was combined with gray infrastructure in a design alternative.
- Two BGI co-benefits were assessed: land value increase and environmental quality.
- A representative area of the watershed was positively impacted by the design alternative.
- The proposed measures directly impact the reduction of socio-environmental vulnerabilities.

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GRAPHICAL ABSTRACT

ACARI RIVER WATERSHED, RIO DE JANEIRO, BRAZIL



INTRODUCTION

Accelerated urbanization, associated with inadequate land use, has aggravated socio-environmental vulnerabilities, worsened during flood events. Eventually, frequent floods reduce property values and discourage investment in the affected area, leading to its progressive impoverishment (Miguez *et al.* 2007). Considering the traditional approaches on urban drainage, usually designed for single-purpose functions and as a corrective intervention of local character (Rezende *et al.* 2019), floods also tend to be transferred downstream, severely impacting the established settlements in floodplain occupations. According to Silveira (2002), the greatest challenge in modernizing urban drainage in developing countries is to stimulate community perception of the correct management of the urban development impacts on the hydrological environment. O'Donnell *et al.* (2020) also state the need to increase awareness of citizens' needs and preferences to change their attitudes and behaviors regarding flood and water infrastructure. Therefore, benefits regarding socio-environmental circumstances need to be considered to allow flood management functions and be co-designed with other wider benefits, ensuring both achievements (Fenner 2017).

Considering the need to reduce flood risk and enhance the quality of life, a paradigm shift on urban drainage is currently under debate, reinforced by the possibility of combined use of blue-green and gray infrastructures, once these alternatives tend to complement each other and deliver a range of benefits for the urban space (Alves *et al.* 2019). The notion of blue-green infrastructure (BGI) is related to the recognition of green space and water's capacities to produce environmental benefits, such as reduction of the heat island effect, carbon sequestration, restoration or establishment of biodiversity corridors, and greater control in stormwater management (Kozak *et al.* 2020). BGI can be characterized by typologies such as rivers, natural reserves, bioswales, storage ponds, and rain gardens, which present multifunctionality as its primary strategy. Multifunctionality can be described as the possibility to perform several functions in the same land area (European Environment Agency 2011), delivering a range of benefits that meet human needs and ecosystem services towards sustainability and well-being. Therefore, it can promote the preservation of environmental attributes to readjust urban spaces towards a better interaction between local communities and the natural environment (Lourenço *et al.* 2020). Most importantly, unlike traditional approaches, the multifunctional design enables the integration of the urban drainage with the open space systems, being a feasible solution when considering the limitation and competition for available space in urban areas. Therefore, it is suggested that a multifunctional approach can improve the quality of life considering the reduction of flood risk and the uplift of social and environmental aspects.

Although several cities recognize the role of natural elements and the importance of their integration with the urban space, the implementation of BGI solutions still faces limitations and uncertainties. O'Donnell *et al.* (2017) conducted a series of semi-structured interviews with professional stakeholders of Newcastle, UK, and identified 17 types of barriers. The five most evident barriers were socio-political, reflecting a reluctance to support new approaches for water management; the lack of knowledge and awareness; funding and costs difficulties; lack of communication; and issues related to partnership works. Consequently, when considering developing countries such as Brazil, hard engineering is still disseminated as the primary strategy to flood control, aggravating social vulnerabilities. Puppim *et al.* (2020) explain that an obstacle to the widespread of BGI innovation in cities is related to political-economic factors regarding the transition between gray and green and blue infrastructure since BGI innovation can replace or weaken mature organizations in the infrastructure sector. Most infrastructure investments, if well planned, tend to impact property values positively. However, as BGI is a relatively new form of infrastructure, they still need to be investigated in-depth, seeking to analyze its economic effects and assess positive impacts in the quality of life of communities.

Past studies have discussed some assessment methods and the influence of multifunctional landscapes in delivering social, environmental, and urban benefits. Fenner (2017) reviewed some tools that can assess the multiple co-benefits of nature-based solutions, defending that although several studies mainly focused on recovering essential functions such as capturing, storing, and infiltrating stormwater, less attention is given to achieving the wider benefits associated with multifunctional projects. Kozak *et al.* (2020) explored the combined use of gray and blue-green infrastructure by analyzing two main scenarios for the Medrano Stream Basin, Argentina. The first scenario was composed of major gray infrastructure solutions combined with minor non-structural BGI, while the second scenario was composed of structurally BGI measures with reduced dependency on gray infrastructure. The findings indicated that the second alternative created more value with fewer costs. Moreover, they also showed that BGI could manage flood events, while gray infrastructure could perform as a second option, activated when BGI capacity exceeded. Alves *et al.* (2019) presented a cost-benefit analysis of flood risk mitigation measures by calculating expected annual damage, co-benefits, and costs. They combined traditional gray measures with a range of BGI typologies, such as green roofs, permeable pavements, and rainwater barrels. The results showed that when urban water management considers co-benefits, the combinations of green-gray and green-blue-gray measures appear economically viable to ensure flood risk reduction. However, the values could be enlarged if other benefits were considered, such as enhancing biodiversity, water quality, and property value.

The Center for Neighborhood Technology (CNT 2010), a reference center committed to sustainable development and livable urban communities, provides a guide to the long list of benefits – economic, social, and environmental – as a result of green infrastructure efforts. Each of these benefits has an intrinsic economic value that can go beyond the increase in the values of neighboring properties. Moreover, Burgess (2017) presents, in a report published by the Urban Land Institute, a series of real estate case studies and a series of types of stormwater policies, quantifying how water management mechanisms using green and blue infrastructure can create value for real estate projects, improving operational efficiency, as well as serving as an attractive commodity. One of the main conclusions was that natural resilience systems could increase financial viability. The study also points out that the interviewed policymakers and urban planning professionals indicated that the community's real estate sector initially hesitates with new stormwater policies. However, a body of evidence suggests a clear link between green infrastructure and rising property values. Furthermore, implementing resilient infrastructure will not only improve property values, but it will also allow private developments to continue.

From the literature review, it is understood that the combined use of BGI with gray infrastructure can increase co-benefits gains, besides being an economically viable strategy when compared to single-use purpose strategies. Considering the obstacles related to more effective implementation of multifunctional solutions in developing countries, measuring its co-benefits may influence greater public awareness of BGI, and greater political acceptance. Therefore, this research was conducted by two main questions: (1) how to combine flood risk mitigation purposes with leisure demands in socio-environmental vulnerability areas? (2) which environmental and urban benefits can be obtained from these interactions? Thus, this research aims to discuss which strategies can be applied in regions where urban growth has not been accompanied by adequate infrastructure projects and which environmental and urban benefits can be obtained when BGI is combined with conventional urban drainage systems. A hypothetical application of a multifunctional design in the Acari River Watershed, located in Rio de Janeiro, Brazil, will support the research.

METHODS

The method proposed to answer the questions raised by this research comprises three steps. Considering the capacity of natural elements to support the conventional urban drainage solutions, step 1 presents a diagnosis of the watershed's open spaces systems. This step aims to classify the open spaces according to their character – private property, public property, or Environmental Protected Areas – and check if they are floodable, defining design perspectives to these open spaces. Thus, it is possible to identify the areas that could be incorporated into the multifunctional project and the fragmented green areas that could be reconnected to the system. Based on the diagnosis, step 2 aims to present a hypothetical alternative supported by the combination of blue-green and gray infrastructure and to discuss structural and non-structural guidelines to improve urban and environmental restoration. Mathematical modeling supported the results of step 2. In this work, we used the MODCEL (Miguez *et al.* 2017), described below.

Finally, step 3 presents the results of co-benefits associated with the proposed BGI hypothetical alternative. Two quantitative aspects support this evaluation. The first one represents the land value increase as a positive effect of implementing a fluvial park, while the second one assesses the environmental quality of the urban space using the Environmental Quality Assessment Index (EQAI) (adapted from Battemarco 2020). The following sections present the detailed approach to these evaluations, while Figure 1 illustrates an overview of the methodology, outlining the three steps.

Mathematical modeling – MODCEL

The Urban Flood Cell Model – MODCEL (Miguez *et al.* 2017) is a hydrologic-hydraulic pseudo-2D-model that can simulate runoff generation, river and storm drains networks and surface flows through streets and open spaces in the city landscape. Due to its ability to represent the whole territory features, the model is helpful to understand the global impact of implementing any flood mitigation design alternative, even if the proposed measures are not directly connected with the drainage network (like off-line storage ponds in parks or on source measures like green roofs). Thus, it is possible to investigate the role of open spaces and how they can contribute to decreasing flood risks.

MODCEL is based on the concept of flow-cells (Zanobetti *et al.* 1970). The entire interest area is represented by homogeneous compartments (the flow-cells), interconnected by one-dimensional hydraulic laws to compose a two-dimensional flow network. Given a rainfall (a real event or a design rainfall reference of a pre-defined return period) and boundary conditions (upstream discharges, base flows or downstream water levels), the model provides outputs for water depths in each flow cell and discharges and velocities between each pair of cells (Miguez *et al.* 2019).

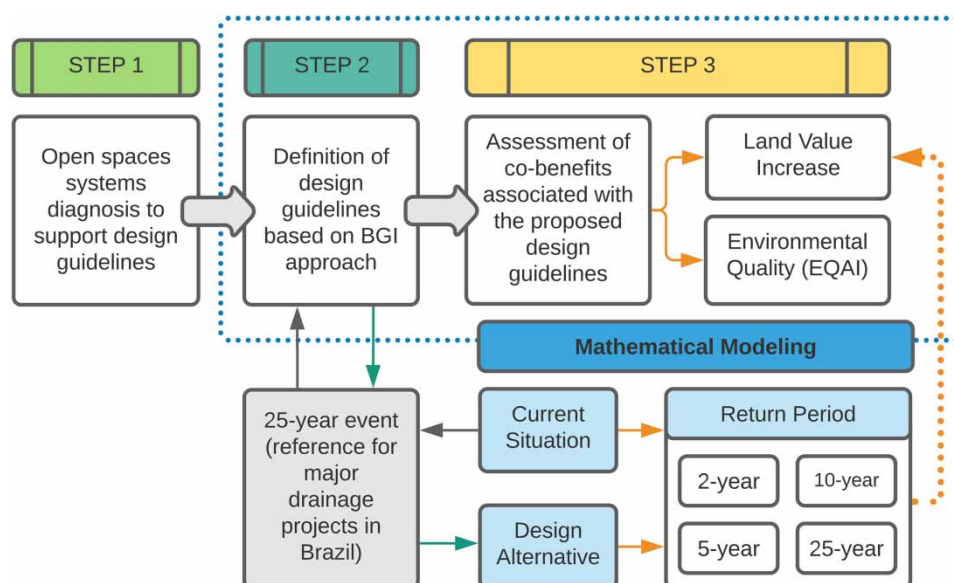


Figure 1 | Flowchart of the methodology, outlining its steps.

The simulation of four return periods is used in the case proposed in our work: 2-year, 5-year, 10-year, and 25-year. It is noteworthy that the 25-year return period is design reference for urban flood control in Brazilian practice. The simulation of the return periods is also necessary to the Land Value Increase assessment, detailed in the following item.

Land value increase (LVI)

The protection against floods and the enhancement of environmental quality in urban areas can increase the real estate value of surrounding land (Kozak *et al.* 2020). Therefore, to establish the global valorization of urban land in the watershed under analysis, we considered two components to increase land value – the first refers to the reduction of floods that affect properties, and the second, to the new natural landscapes that provide amenities to the community.

The hedonic price model is widely applied to estimate residential properties' valuation within or outside flood-plain regions (Cobián Álvarez & Resosudarmo 2019). Lengler & Mendes (2015) used this method to estimate land value increase due to flood reduction in Curitiba, Brazil. They concluded that there is an increase of 19.62% in the value of buildings where floods of the 10-year return period or more used to occur before implementing the flood mitigation design and 40.43% in areas flooded with a return period between 2 and 10 years. Thus, areas that frequently flooded before the flood mitigation design tend to be valued more than areas where flooding was more severe but occasional. These valuation percentages were used for the flood mitigation component of the land value increase, as presented in Equation (1). Data from the last Brazilian Demographic Census (IBGE 2010) were used to estimate the number of households in each valuation range.

$$I_{\text{flood}} = 0.4043 \times NH_{F1} + 0.1962 \times NH_{F2} \quad (1)$$

where:.

I_{flood} = Valorization due to flood mitigation;

NH_{F1} = number of households in areas where floods with return period between 2 and 10 years used to occur before the flood mitigation design and outside the linear park valuation zone;

NH_{F2} = number of households in areas where floods with a return period of 10-year or more used to occur before the flood mitigation design and outside the linear park valuation zone.

Besides, the implementation of BGI also improves urban environmental quality, adding more value to the land. Following Kozak *et al.* (2020), it can be expected value uplift of areas close to new linear parks with deculverting streams. These authors estimated a valorization range of 15–30% for first-line plots, 10–20% for plots up to 100 m, 5–10% for plots between 100 m and 200 m, and 2.5–5% for plots between 200 m and 300 m. Considering the lack of local references to calculate the percentages of land value increase expected due to amenities, this work considers the mean percentages for the land value increase, that is, 22.5% for first-line plots (up to 50 m), 15% for plots between 50 m and 100 m, 7.5% for plots between 100 m and 200 m, and 3.75% for plots between 200 m and 300 m. Thus, this component of the land value increase is calculated with Equation (2):

$$I_{\text{amenities}} = 0.2250 \times NH_{0-50\text{m}} + 0.150 \times NH_{50-100\text{m}} + 0.075 \times NH_{100-200\text{m}} + 0.0375 \times NH_{200-300\text{m}} \quad (2)$$

where:

$I_{\text{amenities}}$ = Valorization due to amenities provided by the linear park;

$NH_{0-50\text{m}}$ = number of households in plots up to 50 m of the linear park and outside flood area;

$NH_{50-100\text{m}}$ = number of households in plots between 50 m and 100 m of the linear park and outside flood area;

$NH_{100-200\text{m}}$ = number of households in plots between 100 m and 200 m of the linear park and outside flood area;

$NH_{200-300\text{m}}$ = number of households in plots between 200 m and 300 m of the linear park and outside flood area.

Finally, certain areas can be valued both by reducing flooding and by proximity to the linear park. In these cases, both valuation percentages are applied to estimate land value increases. Equations (3) and (4) describe

these parcels.

$$I_{\text{flood_1}\cap\text{amenities}} = 0.7203 \times NH_{F1\cap0-50\text{m}} + 0.6149 \times NH_{F1\cap50-100\text{m}} + 0.5096 \times NH_{F1\cap100-200\text{m}} + 0.4570 \times NH_{F1\cap200-300\text{m}} \quad (3)$$

$$I_{\text{flood_2}\cap\text{amenities}} = 0.4653 \times NH_{F2\cap0-50\text{m}} + 0.3756 \times NH_{F2\cap50-100\text{m}} + 0.2859 \times NH_{F2\cap100-200\text{m}} + 0.2411 \times NH_{F2\cap200-300\text{m}} \quad (4)$$

where:

$I_{\text{flood_1}\cap\text{amenities}}$ = Valorization due to flood mitigation in areas where floods of return period between 2 and 10 years used to occur and due to amenities provided by the linear park;

$I_{\text{flood_2}\cap\text{amenities}}$ = Valorization due to flood mitigation where floods of the 10-year return period or more used to occur and due to amenities provided by the linear park;

$NH_{F1\cap0-50\text{m}}$ = number of households in plots up to 50 m of the linear park and that used to flood with return period between 2 and 10 years

$NH_{F1\cap50-100\text{m}}$ = number of households in plots between 50 m and 100 m of the linear park and that used to flood with return period between 2 and 10 years;

$NH_{F1\cap100-200\text{m}}$ = number of households in plots between 100 m and 200 m of the linear park and that used to flood with return period between 2 and 10 years;

$NH_{F1\cap200-300\text{m}}$ = number of households in plots between 200 m and 300 m of the linear park and that used to flood with return period between 2 and 10 years;

$NH_{F2\cap0-50\text{m}}$ = number of households in plots up to 50 m of the linear park and that used to flood with a return period of 10-year or more;

$NH_{F2\cap50-100\text{m}}$ = number of households in plots between 50 m and 100 m of the linear park and that used to flood with a return period of 10-year or more;

$NH_{F2\cap100-200\text{m}}$ = number of households in plots between 100 m and 200 m of the linear park and that used to flood with a return period of 10-year or more;

$NH_{F2\cap200-300\text{m}}$ = the number of households in plots between 200 m and 300 m of the linear park and that used to flood with a return period of 10-year or more.

With all the components, Equation (5) summarizes the formulation adopted to the land value increase.

$$LVI = \frac{I_{\text{flood}} + I_{\text{amenities}} + I_{\text{flood_1}\cap\text{amenities}} + I_{\text{flood_2}\cap\text{amenities}}}{NH_{\text{watershed}}} \quad (5)$$

where:

LVI = Land Value Increase;

I_{flood} = Valorization due to flood mitigation;

$I_{\text{amenities}}$ = Valorization due to amenities provided by the linear park;

$I_{\text{flood_1}\cap\text{amenities}}$ = Valorization due to flood mitigation in areas where floods of return period between 2 and 10 years used to occur and due to amenities provided by the linear park;

$I_{\text{flood_2}\cap\text{amenities}}$ = Valorization due to flood mitigation where floods of the 10-year return period or more occur and due to amenities provided by the linear park;

$NH_{\text{watershed}}$ = number of households in the watershed;

Environmental quality assessment index (EQAI)

The Environmental Quality Assessment Index (EQAI) (adapted from [Battemarco 2020](#)) associates the number and the shapes of open spaces with their connectivity to assess environmental quality in the urban space. The index is composed of two parcels. The first considers the Landscape Shape Index (LSI), aiming to relate the shape of the patches with their ability to maintain the diversity of species in the habitat and be more stable and resistant to edge effects, which is favorable in regular landscape patches ([Gyenizse et al. 2014](#)). According to the formulation proposed, the index compares the shape of the patches with an equivalent square form (Equation (6)) and, the closer to 1, the better is the patch shape conformation for ecological processes and the

reduction of external disturbances.

$$LSI = \frac{4\sqrt{A}}{Per} \quad (6)$$

where:

LSI – Landscape Shape Index;
 A – Area of patches (m^2);
 Per – Perimeter of patches (m).

The second one refers to the assessment of patches connectivity, aiming to analyze the ability to maintain ecological flows (Fenner 2017). The Connectivity indicator (C) is calculated by the ratio of the number of interconnected green patches (I_p) to the total of green patches in the urban area analyzed (T_p), according to Equation (7). The interconnected green patches are defined by the contiguous green spaces identified in the spatial data.

$$C = \frac{I_p}{T_p} \quad (7)$$

where:

I_p – Number of interconnected green patches in the urban area analyzed;
 T_p – The total number of green patches in the urban area analyzed.

Therefore, the EQAI is calculated by the weighted sum of its two components (Equation (8)). In the formulation proposed, the Landscape Shape Index (LSI) is potentiated by an exponent that relates the optimum proportion for open spaces, green spaces, and public facilities in the urban environment ($\%A_{g,o}$), according to the United Nations Human Settlements Programme (UN-Habitat) (United Nations 2017), with the ratio of the total area of green and blue patches to the entire urban area analyzed ($\%A_g$).

$$EQAI = w_{LSI} \times LSI \left(\frac{\%A_{g,o}}{\%A_g} \right) + w_C \times C \quad (8)$$

where:

$EQAI$ – Environmental Quality Assessment Index;
 LSI – Landscape Shape Index;
 $\%A_{g,o}$ – Ratio of optimal area for open spaces, green spaces and public facilities in the urban environment to the entire urban area analyzed (15%, according to United Nations 2017);
 $\%A_g$ – Ratio of green area to the entire urban area analyzed;
 C – Connectivity indicator;
 w_{LSI}, w_C – Weights associated with the LSI and C indicators, assigned according to their relative importance. The sum of them should result in 1 ($w_{LSI} = w_C = 0.5$, as an initial suggestion).

CASE STUDY

The Acari River Watershed is located in the city of Rio de Janeiro, Brazil. Agricultural activities defined its original occupation until 1890 when the inauguration of Madureira's railroad encouraged the urban occupation of nearby neighborhoods. Later, the rise of local industries and the construction of essential roadways intensified the urban growth with inadequate infrastructure, leading to the occupation of lowlands and environmentally protected areas. Nowadays, the watershed covers an area of approximately 107 km^2 , and the land use is predominantly residential, with almost one million inhabitants distributed in 31 districts. Other land uses are commercial, institutional, military areas, and dispersed open spaces, including parks, squares, and electric transmission line towers.

The watershed presents a range of characteristics that potentialize its vulnerabilities related to flood events. The first one is related to its geomorphology, which naturally transfers floods to the lower regions. The second one is related to the irregular urban occupation, once the watershed has a greater concentration of slums settled near

riverbanks with no formal infrastructure. The consolidation of industrial and general services downstream encouraged the migration of low-income populations from adjacent municipalities searching for job opportunities, leading to the formation of slum areas. As a consequence of the lack of basic infrastructure, the third characteristic is related to irregular disposal of effluents into the rivers, once sanitation services are inadequate in these regions, aggravating the water quality and reducing biodiversity.

Additionally, it should be mentioned that heavy rains are responsible for severe flooding, which simultaneously affect housing, mobility, cultural heritage, economy, and community facilities systems (Oliveira *et al.* 2018). The most vulnerable areas reach more than 2 meters for a 25-year return period event (see Figure 2), which is not only related to irregular occupations but also to the lack of hydraulic capacity of rivers; lack of compatibility between the urban drainage and the mobility systems, causing flow restrictions due to existing crossings and bridges; and, finally, due to São João de Meriti River backwater.

RESULTS

Open Spaces Systems Diagnosis for the Acari River Watershed to support design guidelines

A survey of the available open areas, and the subsequent classification according to their character supported the open spaces system diagnosis in the Acari Watershed. Subsequently, the property character was cross-checked with flooding information to define design perspectives to these open spaces, as presented in Table 1 and Figure 3.

The analysis of the Acari River Watershed open spaces system indicates that urbanization generated fragmented open spaces. These fragments have some potential for contributing to urban floods mitigation. In this way, four large unoccupied patches in the watershed should be connected for environmental improvement and flood control – three of them are private areas, and the last one is a Environmental Protected Area.

It is possible to observe that the highest percentages of the open spaces are private, summing 70% of non-flooding and 16% of flooding areas. Private areas have fundamental importance, although they are more challenging to

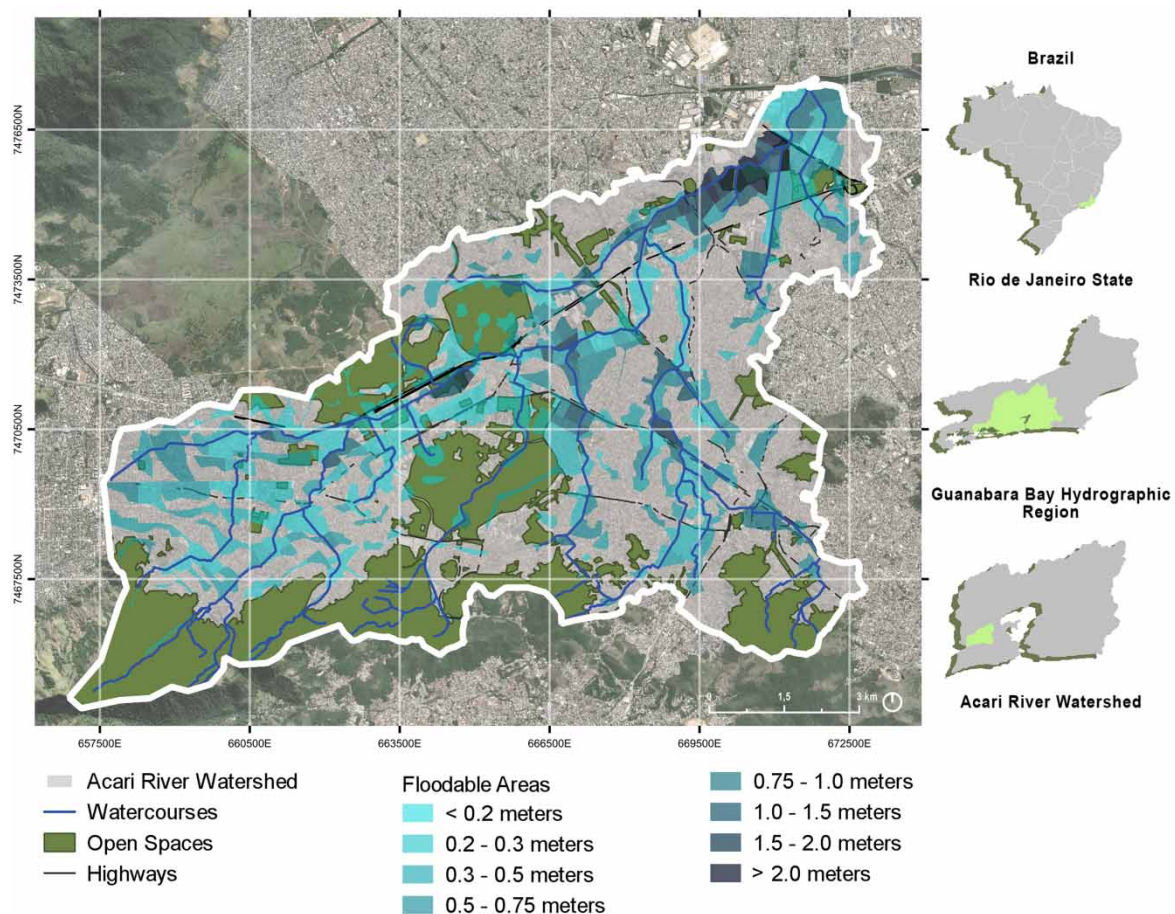
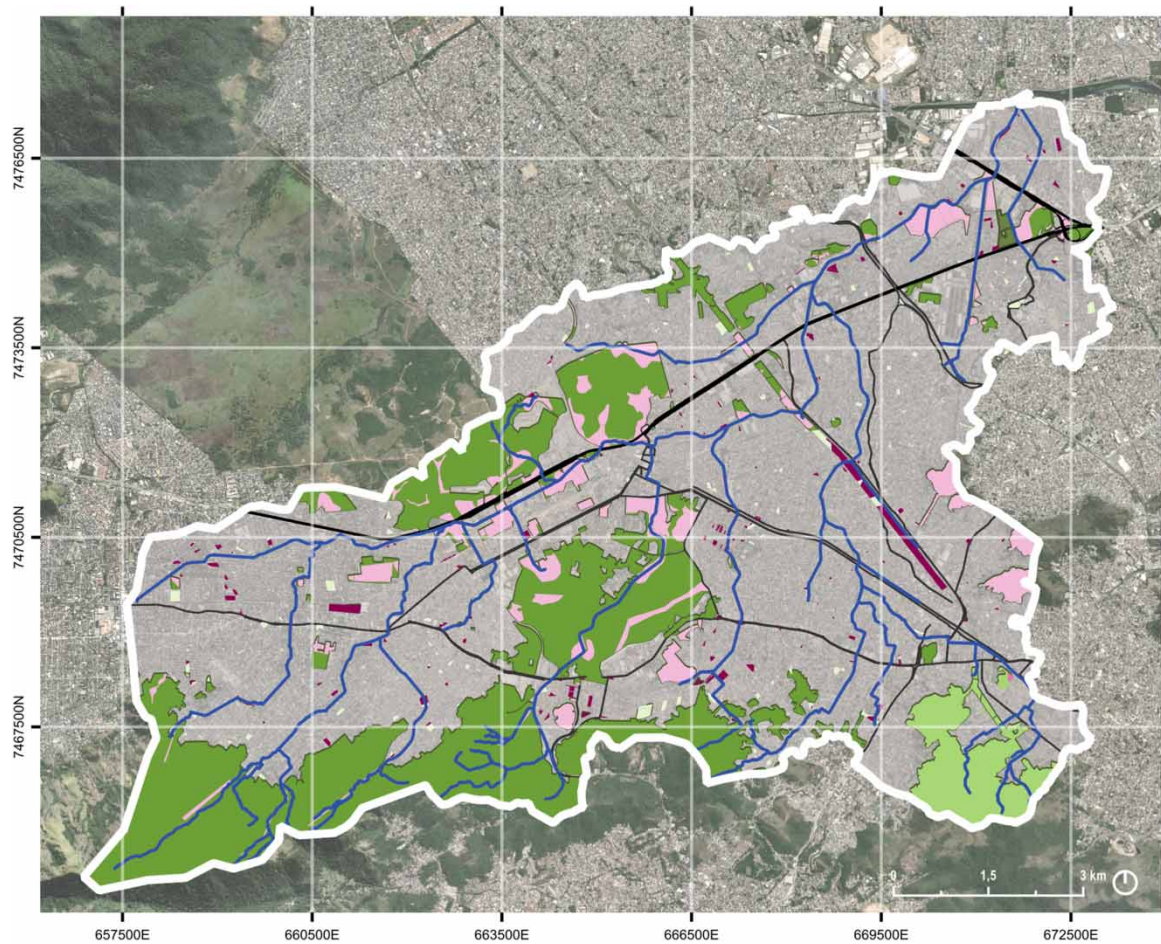


Figure 2 | Acari River Watershed's location and flooded areas.

Table 1 | Current open spaces condition and perspectives

Conditions	Property character x Flooding Information	Perspective
1	Private x non-flooding	If possible, it can be incorporated into the new open spaces system – if referring to a green area, should not be occupied or waterproofed
2	Private x flooding	COULD BE incorporated into the new open spaces system to dampen floods, if it is necessary
3	Public (Square/Urban Park) x non-flooding	SHOULD BE incorporated into the new open spaces system to dampen floods
4	Public (Square/Urban Park) x flooding	SHOULD BE incorporated into the new open spaces system to dampen floods
5	Environmental Protected Areas x non-flooding	SHOULD BE incorporated into the new open spaces system
6	Environmental Protected Areas x flooding	SHOULD BE incorporated into the new open spaces system and COULD BE used to dampen floods, if it is necessary



Open Spaces Diagnosis

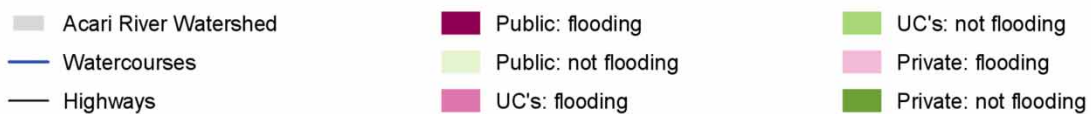


Figure 3 | Open Spaces System Diagnosis of Acari River Watershed.

incorporate into the open spaces system. The non-flooding Environmental Protected Area represents 8.7% of the entire watershed area.

The larger patches can be connected with the smaller ones (mainly composed of public spaces, such as squares and urban parks) by green corridors. To do this, an area equivalent to 5% of the total original open spaces was added to compose an integrated open space system. Another important observation, resulting from field surveys,

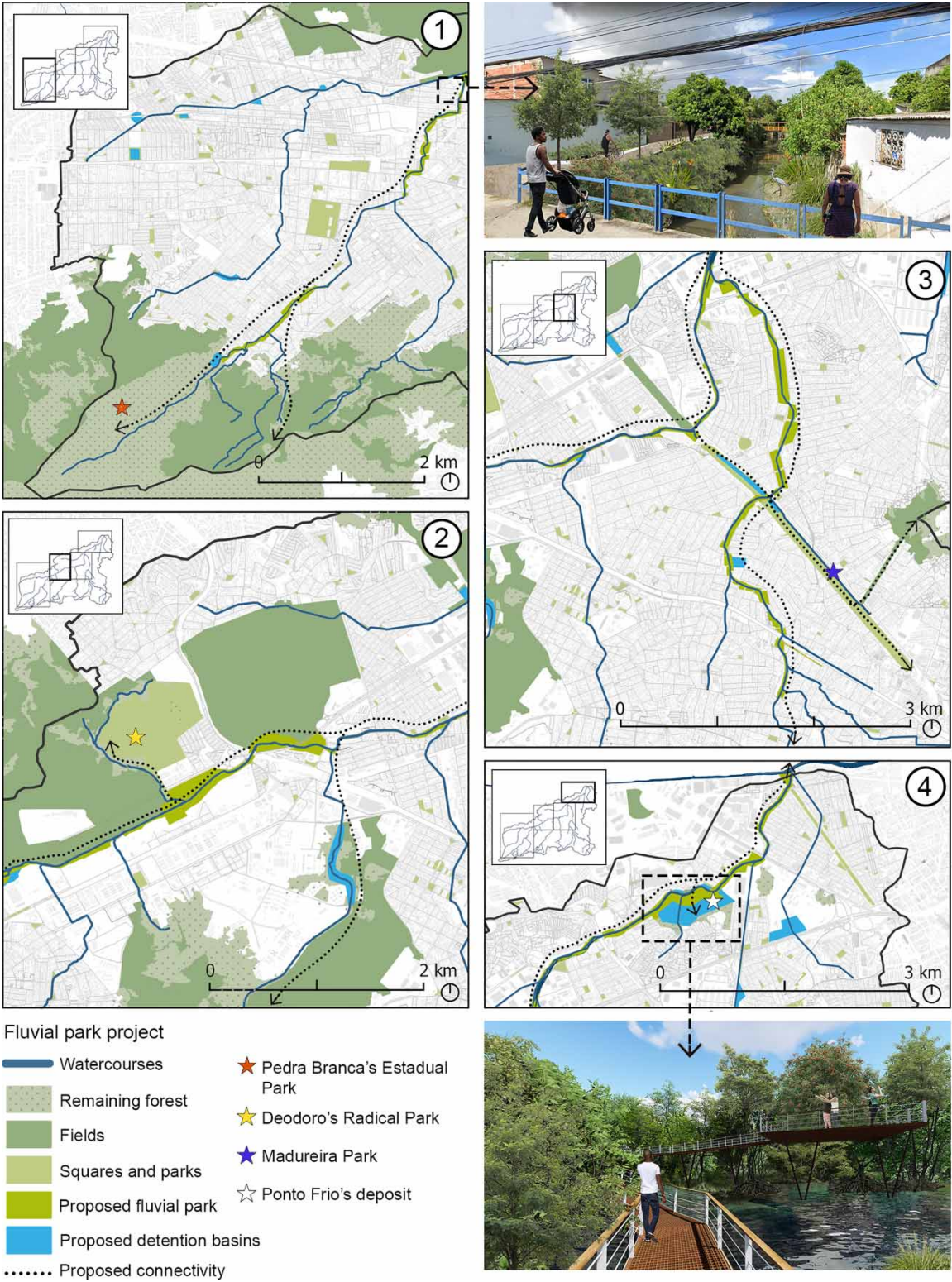


Figure 4 | Division of the watershed in four reaches and fluvial park.

refers to the irregular occupation of riverbanks and the slums that spread over riverine areas. Relocating these people to a safer place, in regular urban conditions served by proper infrastructure, could offer the possibility of implementing a long (and important, in terms of flood space allocation) green corridor along the river.

Design guidelines to Acari River Watershed

The previous diagnosis and Oliveira *et al.* (2018) research supported the creation of design guidelines for the Acari River Watershed, considering a better integration between the watercourses and the open green spaces. According to the authors, the initial design proposed structural corrections in the drainage system, cleaning, and dredging the downstream reaches to improve its hydraulic capacity, and implementing detention basins to control the excess of overflows. Besides, some open spaces were designed as floodable parks to damp floods, and two drainage pipes outlets were resized to allow better flow through critical points of the railway line. However, the authors stated that the results obtained in the hydrodynamic mathematical modeling were not wholly satisfactory, which led to the comprehension that the open spaces systems should be incorporated into the urban drainage. Therefore, the fluvial park was proposed considering that the riverbanks should be lowered to work as a secondary channel of the river, functioning as a park during periods of drought while occupied by the river waters during periods of floods. Irregular urban occupations were also suggested to be relocated from the marginal watercourses.

In this work, the analysis of spatial characteristics of the watershed, such as hydrologic conditions, land occupation patterns, and the incidence of vegetation cover led to the division of four main reaches that facilitate the elaboration of conceptual guidelines that could attend to the characteristics of each territorial situation. Figure 4 illustrates the territorial limits of the four reaches and their connections with the proposed fluvial park.

Reach 1 comprises the upstream of the Acari River Watershed, where most of its sources are in Environmental Protected Areas. Due to its higher slope and altitude, this reach is prone to low times of concentration, higher peak flows, and sediments transportation. The proportion of available green spaces contributes to the natural hydrological dynamics, reflected in low flooded areas. However, the influence of the urban grid in the modification of the natural watercourses should be noticed, once the vegetated sections located in Environmental Protected Areas become straightened and channelized when entering the urban area. Thereafter, Reach 2

Table 2 | Design guidelines to the Acari river watershed

Reach	Key characteristics and current issues	Design Guidelines
1	Residential zone with regular and irregular occupations. Few flooded areas due to its topography. Natural and clean waterways located at Protection Areas. Pedra Branca's Estadual Park (PBEP) as its main public recreational space.	Connection of the fluvial park with the PBEP to guarantee the water quality and enhance biodiversity. Restoration of riparian vegetation along the green corridor. Squares used as multifunctional detention basins. Restoration of bridges for the river contemplation; insertion of bicycle paths to improve local mobility and leisure.
2	Institutional and military zone. Few flooded areas due to the proportion of available green spaces. Diffuse pollution of waterways. Deodoro's Radical Park is the main public space.	Blue-green corridor along the riverbanks, and phytoremediation plants to control pollutant loads. Interconnect leisure opportunities and attract a larger contingent of visitors to Deodoro's Radical Park through its connection with the proposed fluvial park.
3	Residential zone with regular and irregular occupations. Affected by floods that exceed 1 meter. Pollution caused by irregular sewage disposal. Madureira Park is the main open space.	Integration of the Madureira Park with the fluvial park, improving its storage opportunities. Rehabilitation of vegetation. Definition of multiple activities on the secondary channel. Local squares as detention basins. Encourage workshops and environmental education classes.
4	Residential and industrial zone, mostly composed of irregular occupations. Constantly affected by floods that exceed 2 meters. High level of pollution caused by the irregular sewage discharge. Local squares and Ponto Frio's deposit is the main open space.	Provide recreational spaces in the secondary channel. Use of existing squares to accommodate stormwater. Rehabilitation of the marginal vegetation along the green corridor. Ponto Frio's deposit as a floodable park. Educational signs to inform about the ecosystem services.

starts from the confluence between the Rivers Piraquara and Marinho, becoming the Marangá River. These watercourses have mostly a natural conformation, preserving its riparian vegetation. Considering the local topography and the influence of the water bodies of the previous reach, the water volume in the channel increases, although this region is less affected by urban floods. After, Reach 3 starts from the confluence between the Rivers Sapopemba and Tingui, encompassing the most significant numbers of districts located in the watershed. Its land occupation is primarily residential, presenting the Madureira Park as the most relevant local park serving six districts. According to the open spaces system diagnosis, this park is also a significant public floodable space available for damp floods. Along reach 3, the watercourses are mostly straightened and channelized, reducing infiltration opportunities due to the lack of vegetated and permeable surfaces. The current situation is highly aggravated when considering the more significant number of residences settled near the riverbanks, contributing to water pollution and hiding the river from the landscape. Finally, Reach 4 comprises the downstream area of the Acari River Watershed, and it is considered the most critical of the four reaches. Its main weaknesses rely on the vulnerability of the residents, once floodable areas reach more than 2 meters, resulting in economic losses and health hazards.

The key characteristics and current issues of the four reaches are presented in Table 2, followed by the design guidelines proposed for each situation. Finally, Figure 5 illustrates the reduction in the flood depth with the

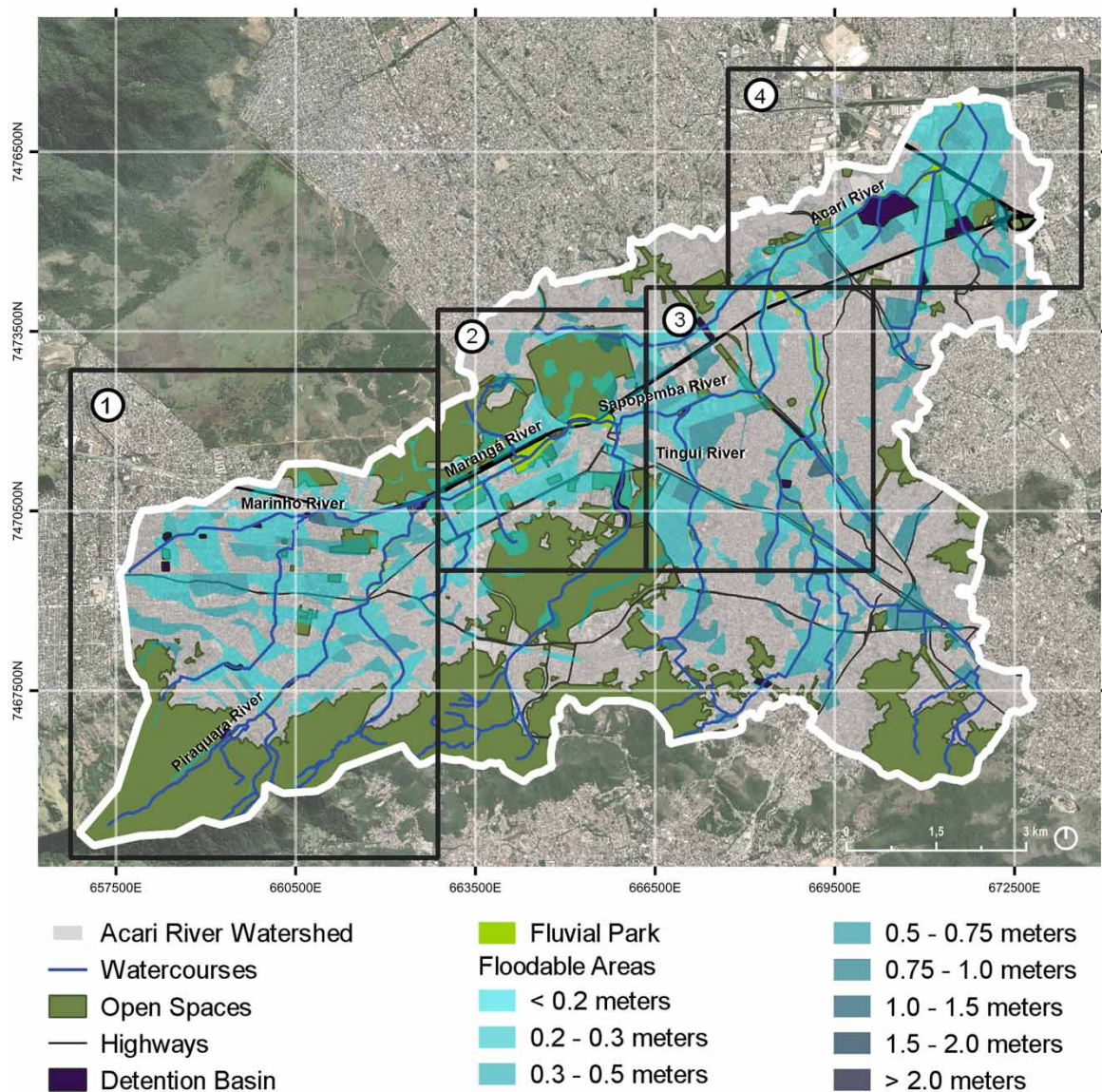


Figure 5 | Division in four reaches and reduction of the flooded areas.

implementation of the proposed measures in the hypothetical alternative. The flooded area decreased from 8.065.397 m² in the current situation to 4.687.739 m² in the design alternative.

Land value increase (LVI)

The proposed alternative adds value to the urban territory considering that it incorporates green areas and reduces flood impacts. The result indicates a total LVI of approximately 4.2%, an average for the whole Acari Watershed, even knowing that not all areas are valued.

Besides this global result, it is also possible to spatialize the LVI, as shown in Figure 6. The area that is effectively impacted by LVI corresponds to 18% of the watershed.

Finally, the proposed method was also applied separately for each of the four reaches previously presented. The expected LVI for reaches 1, 2, 3 and 4 are 2.23%, 2.44%, 5.79% and 10.29%, respectively. The main difference is related to the flood protection introduced by BGI in reaches 3 and 4, where frequent floods occur in the current situation.

Environmental quality assessment index (EQAI)

For the calculation of the EQAI, only open spaces with a representative dimension in the watershed scale, that is, with areas greater than 5 km², were considered to perform a macro analysis. In terms of representativeness, in the

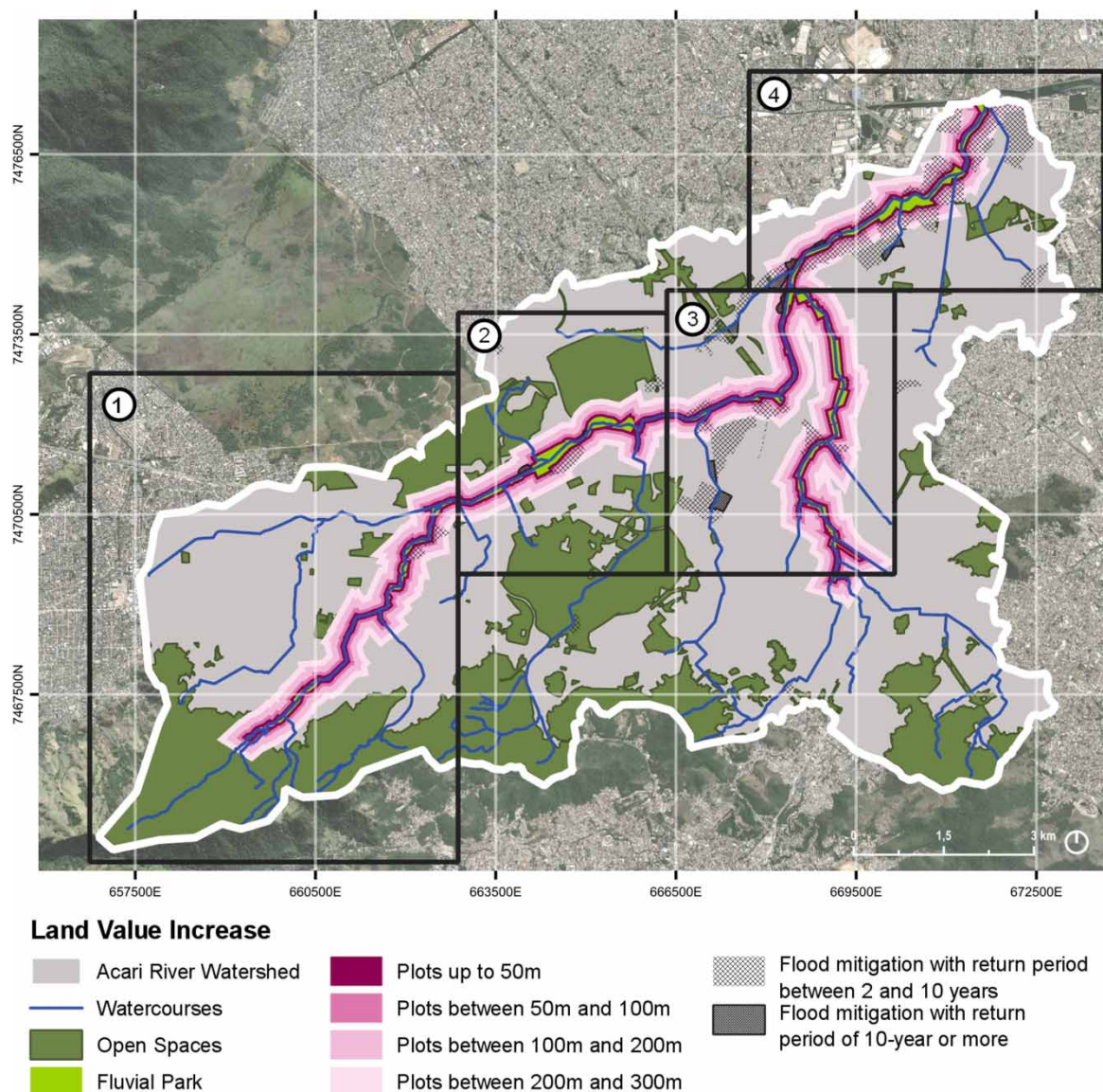


Figure 6 | Land Value Increase per reaches.

current situation, the open spaces are 26% of the entire watershed area, while, in the design alternative, this value increases to 28%.

The Landscape Shape Index calculation indicates a slightly higher value in the current situation (0.12) when compared to the design alternative (0.09). These results are explained by the introduction of linear parks in the design alternative, which are elongated, thus being more susceptible to edge disturbances. However, this difference is compensated by the ratio of open spaces to the watershed area.

Concerning the connectivity of the open spaces, in the current situation, there are only three interconnected green patches of a total of 17 patches, resulting in an indicator value of 0.18. With the implementation of the proposed fluvial park, 10 other patches were connected to the original 3 connected patches. Thus, including the fluvial park patch, 14 patches are interconnected of a total of 18 patches, increasing the indicator to 0.78.

Finally, the results of the EQAI indicate a significant improvement in terms of environmental quality in the design alternative. The EQAI increases from 0.24 to 0.53. Therefore, although linear and more susceptible to edge effects, the proposed fluvial park introduces significant benefits in terms of connectivity.

DISCUSSION

The Open Spaces Systems Diagnosis showed the relevance of mapping the areas that can be integrated with urban drainage and used for recreational purposes as an alternative for consolidated watersheds with high population density and low space availability. In this sense, the open spaces system was presented as a key element responsible for connecting fragmented areas and increasing amenities through urban greening. The fluvial park proposed by Oliveira *et al.* (2018) was divided and complemented with design guidelines, so the particularities of the four reaches could be evaluated in detail.

As presented in the Introduction section, BGI can be composed of many natural or man-made typologies, such as bioswales and rain gardens. Considering the proposed fluvial park, the design alternative focused mainly on the natural elements, such as rivers, urban vegetation, and natural forests; and man-made typologies included using a fluvial park and detention basins. However, it did not exclude gray elements due to their effectiveness for flood mitigation.

The whole flooded area decreased by 50% in the design alternative. This flood mitigation directly impacts the reduction of the social vulnerability in the watershed since the floods cause damage to households and their contents, contributing to the impoverishment of the population. In this context, the proposed measures, including relocating the population from risk areas, generate a positive impact on affected households, reducing them by 28%.

Therefore, the combined use of BGI and gray infrastructure showed an increase of 4.2% related to the land value which can be reflected in public collection through urban territory taxes. In this way, the increased tax collection can be used to fund, at least in part, the proposed BGI measures. Besides, when evaluating the reaches separately, it can be noticed that the land value increase is more significant in reaches 3 and 4, where floods are more severe. If the proposed measures were more distributed in the watershed considering other water-courses besides the main river, it would be possible to obtain an even more significant increase in land value. Table 3 summarizes the results obtained in the evaluations.

In terms of environmental quality, applying the BGI approach in the Acari River Watershed showed that it is possible to enhance ecological benefits in urban areas. In highly urbanized watersheds, it is hard to establish open spaces with regular shape, mainly when the recovery of floodplains is fundamental to minimizing flood

Table 3 | Summary of the results

General Information Results	Current situation	Multifunctional design
Watershed area	107 km ²	
Open spaces area	26%	28%
Flood-affected area	8.065.397 m ²	4.687.739 m ²
EQAI	0.24	0.53
Area of the measures proposed	–	1.694.210, 4 m ²
Land valued area	–	18%
Total land value increase (LVI)	–	4.2%

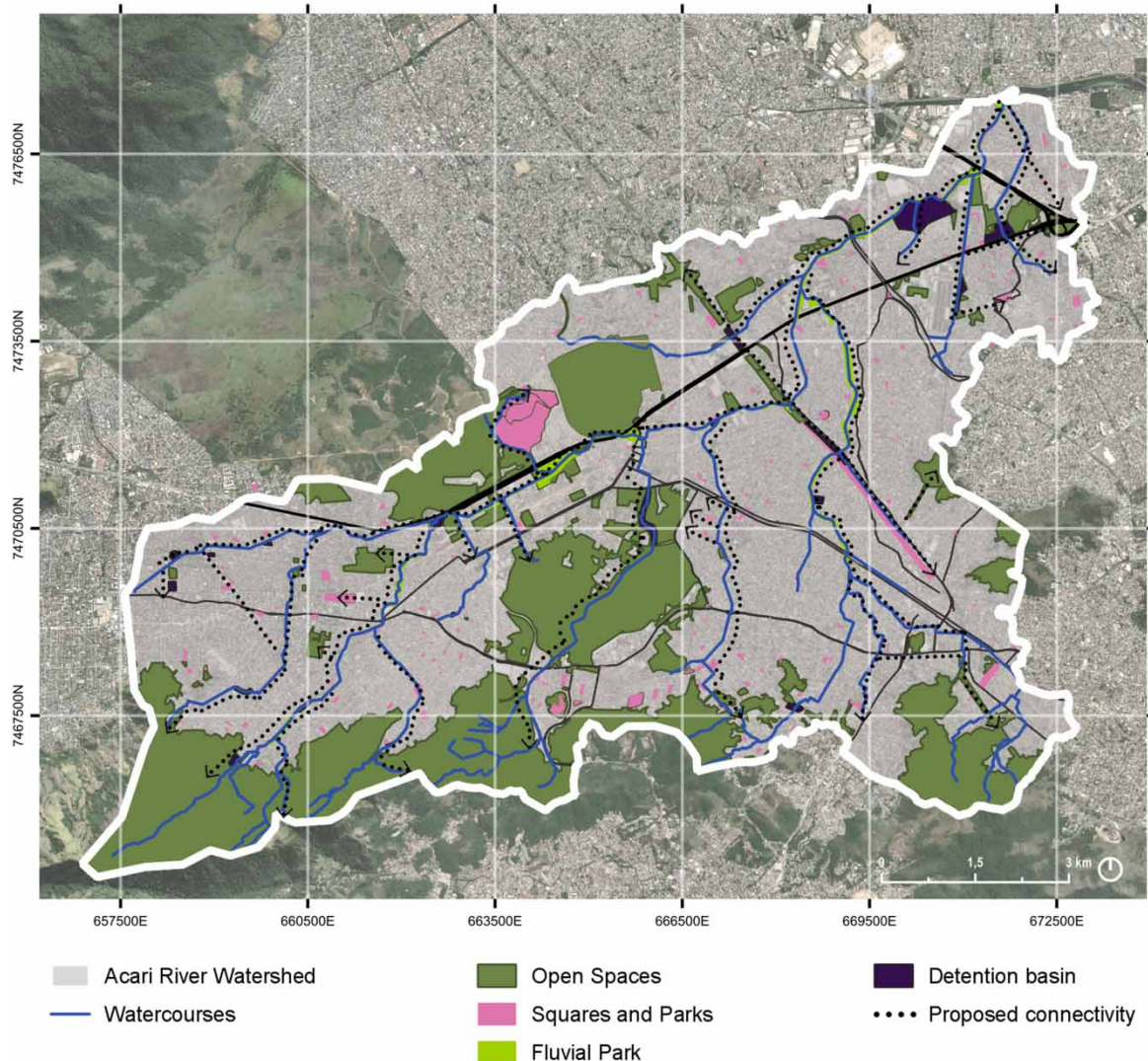


Figure 7 | Potential areas and their connections with the open spaces system.

impacts. However, the connectivity of the open spaces is possible even in those conditions and can represent the main benefit, as in the case study. Moreover, significant results could be expected if other areas that still have the potential for a BGI application were integrated with the open spaces system, which could expand the results beyond the fluvial park, as shown in Figure 7. The evaluation by reaches could facilitate future processes.

CONCLUSIONS

The rapid expansion of urban areas has aggravated socio-environmental vulnerabilities and created new challenges for city managers, emphasizing the need to discuss urban watersheds management. In this context, this paper proposed a hypothetical multifunctional alternative for flood management, nature preservation, and leisure opportunities in the Acari River Watershed, Rio de Janeiro, Brazil. The mathematical modeling indicated that the most critical areas reach more than 2 meters of water depths, responsible for a range of economic and urban losses.

The proposed fluvial park aimed to address improvements considering the characteristics of each area. The urban and environmental evaluation results proved that blue and green corridors could promote multiple co-benefits for consolidated urban areas. The increased environmental quality and land value were only possible due to the combined use of BGI and gray infrastructure since BGI can add benefits that the gray infrastructure is not capable of providing. Therefore, the relevance of the fluvial park is recognized not only for its relationship

with flood management but also in terms of amenity, biodiversity, local economy, and the creation of community awareness.

Despite the urban and environmental enhancement promoted by BGI, its political and public acceptance is still a challenge, especially in developing countries. There is a lack of sustainable solutions, reflecting the lack of constructed examples that can be used as local references. Consequently, there is a significant consensus that gray infrastructure is the only alternative to flood risk management.

Finally, future work will be conducted in two biases: in the first one, the objective is to create BGI design guidelines that can be applied in urban watersheds. The guidelines will be composed of several typologies of BGI and will have the participation of residents from the Acari River Watershed during its conception. In the second bias, more comprehensive evaluations should be proposed considering a wide range of BGI co-benefits. In this way, it is intended to assist managers in justifying the adoption of more sustainable measures.

ACKNOWLEDGEMENTS

This work was supported by the *Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro* (FAPERJ) [E-26/200.417/2021; E-26/201.404/2021(26079)]; by the *Conselho Nacional de Desenvolvimento Científico e Tecnológico – Brasil* (CNPq) [142284/2018-1; 303862/2020-3]; by the *Coordenação de Aperfeiçoamento de Pessoal de Nível Superior- Brasil* (CAPES) [Finance Code 001; 88887.495814/2020-00; 88887.485239/2020-00; 1526717]; and by the *Programa Institucional de Bolsa de Iniciação Científica* from the Federal University of Rio de Janeiro (PIBIC-UFRJ) [Edital n° 169 CEG/CEPG 2020]. We also acknowledge the UNESCO Chair for Urban Drainage in Regions of Coastal Lowlands from the Federal University of Rio de Janeiro, to which this research is linked.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 24 October 2021; accepted in revised form 29 November 2021. Available online 6 December 2021