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Green Infrastructure as a solution to mitigate the effects of climate change in a coastal area of social vulnerability in Fortaleza (Brazil)

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ABSTRACT

Climate change can be considered one of the main current problems of the humanity. The subject has raised concern worldwide, encouraging global leaders and experts to delve deeper into discussions and studies and propose solutions, leading to international agreements and efforts. Mitigation, adaptation, and transformation actions are required, especially in cities with higher population density, where increased demand for resources is expected in the coming years, and in coastal areas, which are more susceptible to the environmental impacts caused by climate change. The objective of this study is to analyze the feasibility of implementing Green Infrastructures (G.I.) in the district of Pirambu, an area classified as a zone of social interest in the city of Fortaleza (Brazil), and which contains a high level of vulnerability according to the municipal adaptation plan, characterized by limitations in buildings and infrastructure, high population density and low human development index. The methodology includes decision-making analysis for choosing among the different G.I. typologies and spatial analysis of data through geoprocessing software, aiming at offering ecosystem and environmental services that mitigate the impacts caused by climate change. The methodological process was based on the Fortaleza Adaptation Plan (Fortaleza, 2020b) and the Green Infrastructure Implementation Guide (IPT, 2020). Thus, four types of G.I. were proposed: multiple-use roads, rain gardens, permeable pavements, and soil bioengineering. The results show the location of each one, the environment and ecosystem services offered related to global warming, the advantages of applying them, and the Sustainable Development Goals (SDGs) that can be achieved with their implementation. At the international level, this case study should help develop decision-making methodologies and promote public policies for the performance of G.I.

1. Introduction

Successive reports of the International Panel on Climate Change (IPCC) have concluded that the global warming is evident, and that human activity has most likely been the dominant cause for the consequences observed since the mid-20th century. The last four decades have been successively warmer than any preceding decade since 1850 (IPCC, 2021). Severe and irreversible impacts on people and ecosystems are also predicted (Schipper, 2020).

COP26, held in November 2021 in Glasgow, Scotland, offered an ideal opportunity to deepen the debate on viable alternatives to slow down global warming, directly linked to the establishment of new strategies to reduce emissions associated with land use and vegetation cover (Silva Junior et al., 2021). According to Arora and Mishra (2021), four main goals were set to be achieved after the summit: global net zero carbon by mid-century; phasing out of coal use and funding of thermal power stations; reversal of deforestation; and conservation and restoration of ecosystems and development of resilient defenses, early warning systems, and infrastructure. At COP 27, which took place in the Arab Republic of Egypt and ended on November 20, 2022, the main achievement was the promise to create a climate damage compensation fund for developing countries or those directly impacted by the effects of climate change. The creation of this fund was driven by extreme weather events, such as the recent floods in countries like Pakistan and Nigeria, which highlight the importance of finding tools to minimize impacts in areas of social vulnerability. However, issues of great importance such as the energy transition aimed at reducing the use of fossil fuels were left aside at the last conference, due to the energy uncertainty created by the war between Russia and Ukraine, and pressure from countries such as Saudi Arabia and Russia itself.

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Notably, progress in fighting climate change, which is at the heart of the COP26 summit, is also a roadmap for the Sustainable Development Goals (SDGs), another important initiative in this context, formally adopted by the 2030 Agenda by the U.N. Member States. The 17 goals address the world's most severe human and environmental health issues, such as inequality, urbanization, and climate change. However, practical applications are required to interconnect the targets and improve final results (Macmillan et al., 2020). The SDGs comprise 17 goals, 169 targets, and 232 indicators, in addition to the declaration, with a shared vision, principles and commitments (Kronemberger, 2019).

Since the first IPCC report in the 1990s (IPCC, 1990), risk and vulnerability assessments have been used as essential means of gauging the impacts and hazards related to climate change, such as temperature variation, rising sea levels, and rainfall (Zanetti et al., 2016). These assessments have mainly focused on coastal regions, where climate-related stressors most significantly affect urban populations and infrastructure (Hzami et al., 2021).

According to (IPCC, 2013) predictions, sea levels in coastal areas will rise between 0.28 and 0.98m by 2100. Stronger storms are expected in the future. As a result, coastal systems will be severely affected by the destructive impacts of sea level rise, including coastal and urban flooding, resulting in loss of people and goods, displacement, damage to wetlands and mangroves, beach erosion, and seawater intrusion in groundwater and surface water. In addition, socioeconomic losses resulting from coastal flooding have increased since the last century due to the increase in affected areas (Hadipour et al., 2020).

Otto et al. (2017) provide evidence that the vulnerability of societies to climate change is equally affected by physical changes in the climate system, besides demographic, economic, institutional, and sociocultural factors. Policies traditionally associated with broader development sectors – such as social protection, public health systems, and sanitation infrastructure development – may significantly impact the ability of vulnerable communities to respond and adapt to climate change.

According to the IPCC Sixth Assessment Report (Castellanos et al., 2022), South America is very vulnerable to the impacts caused by global warming, a situation that is exacerbated by socioeconomic factors (high population growth and density, inequality, poverty, lack of adequate sanitary infrastructure, lack of investment in adaptation and prevention plans) and by high rates of deforestation, which culminate in loss of biodiversity and degradation of natural environments.

In Brazil specifically, it is possible to list several impacts already experienced or expected, such as the extreme weather events that have been occurring with greater frequency and intensity, which directly affect ecosystems and communities. The long periods of drought and unprecedented high temperatures that affect the Amazon region are also partly attributed to the effects of global warming (Castellanos et al., 2022). An increase in the number of cases of some diseases such as dengue fever, Chikungunya and Zika are also expected with the increase in temperatures in Brazilian territory, considering more favorable conditions for the reproduction of vectors (Castellanos et al., 2022).

Studies on the influence of climate change on Brazilian agricultural production show negative impacts, mainly for small producers, due to the necessary adaptations and investments, considering an increase in competition for suitable areas for agriculture and the need to improve the water resources management. Although there is projection of production growth of the main Brazilian agricultural products, areas suitable for agriculture and water deficit are the main limiting factors (Antolin et al., 2022; Da Silva et al., 2021; Martins et al., 2023; Zilli et al., 2020).

In the northeast region of Brazil, increases in temperature are expected, with greater intensity and frequency of hot extremes, a decrease in precipitation and extreme precipitation, with these factors being directly linked to the increase in droughts and extreme droughts in the region. An increase in the deficit of water availability is directly linked to these climate changes and combined with inadequate soil management practices, can increase the susceptibility of desertification, directly affecting ecosystems such as Caatinga (Castellanos et al., 2022). This scenario directly impacts agriculture and a large part of the region's productive power, which is reflected in population and social dynamics. Studies demonstrate the possibility of migration and population displacements in this region, mainly related to water and food insecurity, being directly related to climate change. (Delazeri et al., 2022; Oliveira e Pereda, 2020).

In 2020, the municipal government of Fortaleza, a coastal city in the state of Ceará, located in the Northeast region of Brazil, published its Adaptation Plan containing an index of vulnerability to climate change and the actions required to face this challenge. The document lists the following hazards posed by the significant impacts of such environmental change: rising sea levels, extreme rainfall, prolonged droughts, high temperatures, and heat waves (Fortaleza, 2020b).

The methodology used in the Adaptation Plan includes identifying current and future hotspots (by 2040). According to (Reid, 1998), the term hotspots designate areas of incredible biodiversity that are threatened by degradation and require conservation planning. Twenty-two city districts were classified as hotspots, seven with a high level of vulnerability, among which is Pirambu. In this area, analyses based on the exposure and risk maps in the document indicate a high level of climate risk for increased temperatures, extreme rainfall, and sea level rise and a medium risk for prolonged droughts (Fortaleza, 2019).

Among the adaptation measures proposed for this district, strengthening the implementation of Green Infrastructure (G.I.) stands out as a transversal public policy to mitigate impacts related to high temperatures and heat waves, prolonged droughts, and extreme rainfall (Fortaleza, 2019). However, the report does not define which types of G. I. could be used or the characteristics and technical specifications that should be considered. G.I. has drawn a lot of attention as a viable strategy to minimize the damages of climatic events and improve the provision of environmental services in developed and developing areas (Bae et al., 2021), and may contribute, directly or indirectly, to achieving the targets of the following SDG: industrialization, innovation and infrastructure (9); sustainable cities and communities (11); action against global climate change (13); life on land (15); peace, justice, and strong institutions (16); end poverty (1); zero hunger and sustainable agriculture (2); health and well-being (3); and water and sanitation (6) (Gelan & Girma, 2022; Hanna & Comín, 2021).

The European Commission defines G.I. as:

> "[…] a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services such as water purification, air quality, space for recreation, and climate mitigation and adaptation. This network of green (land) and blue (water) spaces can improve environmental conditions and, therefore, citizens' health and quality of life. It also supports a green economy, creates job opportunities, and enhances biodiversity" (European Commission, 2019).

According to Resolution 2663 of the European Parliament, dated December 12, 2013, a document that guides E.U. decision-making on integrating ecosystems and their services, planning the implementation of combined G.I (European Union, 2013). categories can provide multiple economic, ecological and social functions, improving the quality of life in the urbanized environment and providing environmental services that depend on the scale of application and their nature (European Commission, 2019). For Grădinaru and Hersperger (2019), the scales of application are local, regional, state/national, and national/international.

In Brazil, the definition of environmental and ecosystem services is given by the Federal Law 14119, dated January 13, 2021, which establishes the National Policy on Payment for Environmental Services. Ecosystem services provide relevant benefits to society through ecosystems in terms of improving, recovering, and maintaining environmental conditions. Environmental services, in turn, are collective or individual actions that provide opportunities for strengthening, healing, and supporting ecosystem services (Lei n. 14.119, 2021). However, there is no legal definition of G.I. in Brazil, as in most countries. The concept is still developing, revealing difficulties concerning identification and classification, for example.

The Green Infrastructure Implementation Guide, developed by the Institute for Technological Research (*Instituto de Pesquisas Tecnológicas* - IPT), suggests four main steps for defining the G.I. system to be implemented: learn about the possible typologies and related services; analyze the current environmental situation in the region through indicators; define priority areas; and select the typologies according to local reality (IPT, 2020). To determine locations for the expansion of environmental services, Rall, Hansen and Pauleit (2019) suggest using the Geographic Information System (GIS) as a critical supporting tool in spatial planning for G.I. implementation.

GIS can be understood as a decision-supporting system that integrates spatially referenced data in an environment of answers and problems (Cowen, 1988). Several studies address the use of geoprocessing and GIS tools in assessing G.I. viability (Bae et al., 2021; Ferreira et al., 2021; Manuel et al., 2021; Venter et al., 2020;). Zhang and Ramírez (2019), for example, evaluated and mapped ecosystem services in Barcelona, Spain, using GIS, which afforded a view of spatial distribution characteristics, providing reference points for urban green infrastructure planning and identifying priority protected areas, new construction areas, potential areas, and renovation areas.

The analysis of existing infrastructures is the focus of studies, such as Bae et al. (2021) that analyzed the conditions of green infrastructure in sixty-eight cities within Texas coastal counties, in the United States over 15 years. The research uses geospatial data and geoprocessing techniques to assess the growth,change and the connectivity of green infrastructures in these cities. The study shows that over the years, there has been a significant increase in the extent and quality of green infrastructure in the coastal cities of Texas, providing potential positive effects on flood mitigation in coastal Texas. This is attributed to various factors, such as urban planning policies focused on environmental conservation and increased awareness of the benefits of green infrastructure for climate resilience and quality of life.

Venter et al. (2020) used geospatial data and mapping techniques to examine the availability and accessibility of green spaces, parks, and other forms of green infrastructure in different neighborhoods and regions. The results highlight the existence of significant disparities in the distribution of green infrastructure, with wealthier and predominantly White neighborhoods having better access and more extensive green spaces compared to poorer and predominantly Black neighborhoods. The article argues that this unequal distribution perpetuates a form of "green apartheid," where marginalized communities are deprived of the social, environmental, and health benefits associated with green spaces. A similar approach is taken in the work developed by Pallathadka et al (2022), who related pluvial flood exposure to the green infrastructure present in Atlanta, Phoenix, and Portland, evidencing greater risks of flooding for populations of ethnic and racial minorities, of low education and median income. In Atlanta, the implementation of green infrastructure prioritized white and wealthy neighborhoods, although there are indications of equitable and appropriate management based on flood risk, mainly in the cities of Phoenix and Portland.

Other studies, in turn, evaluate urban spaces in order to develop methods or propose guidelines for the implementation of new green infrastructures, such as the work developed by Ferreira et al (2021) that proposed a multi-criteria method for designing a green infrastructure for the municipality of Setúbal. Geospatial analysis has also been used to develop methods for quantifying the supply and demand of ecosystem services, which can be a useful tool in proposing urban green infrastructure, as developed by Manuel et al (2021) for the city of Bilbao. Currently, some studies evaluate and propose the adaptation of cities (including coastal cities) by integrating green infrastructures in their urban planning processes, aiming at mitigating the impacts caused by climate change, such as the study developed by Sánchez and Govindarajulu (2023) that discusses the floods and rising sea levels caused by extreme weather events; as well as the studies proposed by Chapman and Hall (2022), Heidari et al. (2023) and Xu et al. (2023) seek to evaluate and simulate scenarios in order to develop sustainable rainwater management systems with the proposal of green infrastructures.

Based on the above, the following question is posed: What types of Green Infrastructure should be implemented, and how, in a densely populated district of Fortaleza with very low HDI and high vulnerability to climate change? The objective of this article is to analyze the feasibility of implementing G.I. in the neighborhood of Pirambu, presenting a decision-making methodology to choose types of G.I. and performing spatial analysis of data, aiming at mitigating the impacts caused by climate change.

2. Methodology

A brief description of the main methodological stages of the manuscript is presented in the flowchart, in Fig. 1.

The methodological stages consist of the following phases: Literature Review, where an examination of the existing literature on the study's topics was conducted; Definition of the Study Area, which was developed based on the literature review stage, which and allowed the determination of the specific geographical area in which the study was conducted; After defining the study area, a detailed diagnosis of the current situation in that area was performed, considering the guidelines outlined in the "Fortaleza 2040 Adaptation Plan"; Simultaneously, cartographic material of the specific study area, such as maps and spatial data, was acquired from the responsible public agencies, like the municipal government and the Brazilian Institute of Geography and Statistics; Subsequently, different typologies of GI that can be applied in the study area were analyzed, and criteria and guidelines for GI implementation were established based on the previous analyses. Geographic Information System (GIS) was used to integrate the cartographic data and the conducted analyses, providing a basis for decision-making related to GI implementation. The Implementation Proposal for GI phase involves the development of a detailed proposal for implementing GI, taking into consideration the previous results and discussions.

2.1. Study setting

Fortaleza (geodesic coordinates 3°43'06'' S and 38°32'34'' W), the capital city of the state of Ceará, located in the Northeast region of Brazil, has about 2.7 million inhabitants. It is bounded by the Atlantic Ocean to the north and has excellent regional importance in the tourism, social and cultural sectors. The city has Tropical savanna climate or tropical wet and dry climate (Aw) according to the Köppen classification (EMBRAPA, 2003), with an average annual temperature of 27°C, ranging between 22°C and 32°C. The relief consists of pre-coastal plateaus and coastal plains, with an average altitude of sixteen meters above sea level. The vegetation is predominantly *restinga* and mangrove (IPCE, 2021), with an average annual rainfall of 1,042 mm (FUNCEME, 2021).

The city's population grew from 180,185 inhabitants in 1940 to 2,452,185 in 2010 (IBGE, 2010). However, the expansion of Fortaleza was not accompanied by the necessary expansion of urban infrastructure, which is still an obstacle to the development of its master plan. (Monteiro, 2018), as attested by the Local Plan for Social Interest Housing (PLHIS-FOR), which identified 636 slum areas in Fortaleza (Fortaleza, 2010).

Pirambu is one of those districts, bounded by the Atlantic Ocean to the north, as shown in Fig. 2. According to the population estimate based on the 2010 Demographic Census, the resident population is 19,596 inhabitants (Fortaleza, 2022), with a total area of 0.57 km^2 (IPLANFOR, 2021), and a population density of 34,378.95 inhab/km^2, one of the

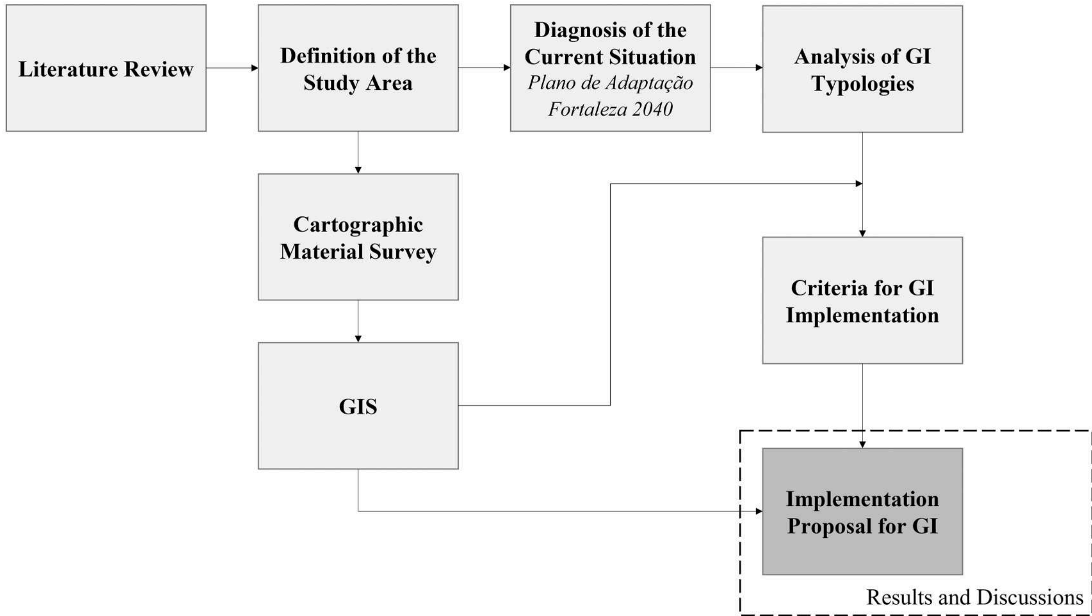

Fig. 1. Methodological stages of the study.
Source: Authors (2023).

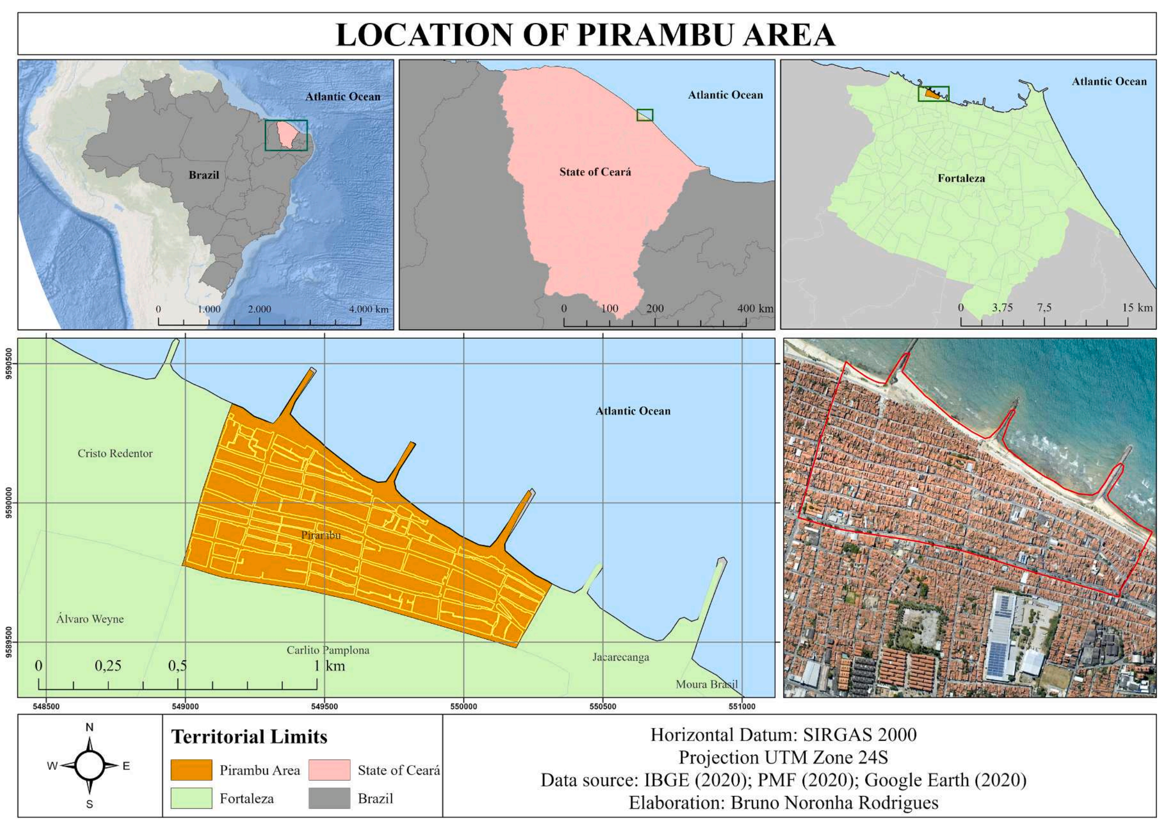

Fig. 2. Study setting.
Source: Authors (2022).

highest population density rates in the city, despite a predominantly horizontal morphology (Silva et al., 2018).

The housing typologies are small; located in narrow lots; with a maximum of three floors; without proper spacing between buildings; with facades bordering the street; with little space in backyards; and mostly self-built. Part of the district's houses is situated on dunes, hillsides, and on the beach strip, intensifying the erosion process and increasing the risk of landslides, besides dumping waste into the sea, as they are not connected to the sewage collection system. Landslides also occur due to inadequate building material, tide movement, flooding in some points caused by rainfall, and the lack of an effective drainage system (Diógenes, 2021; Silva et al., 2018).

Jerome (2021) notes that the historical roots of Pirambu relate to a fishing community dating from the 1850s. Several authors (Brasil & Cavalcanti, 2015; Monteiro, 2018; Teixeira, 2019) address historical facts that explain the emergence of the district as resulting from the social exclusion of migrants from the state interior who were fleeing the severe droughts that occurred at the beginning of the century. As the city was unable or unwilling to accommodate those people, a community was developed in physically precarious conditions, with poor urban infrastructure, dwellings built with improvised and fragile materials, and geologically irregular and inappropriate terrain.

According to the last census in Brazil in 2010, 84.29% of households in the study setting had running water; 97.15% had garbage collection; 97.86% had electricity, 76.13% had sewerage collection. 78.71% of the population were literate and had an average income of R$ 285.50 reais (approximately US$ 50.55). The total HDI was 0.2298, classified as very low (IBGE, 2010).

According to data provided by the Fortaleza Maps Platform (Fortaleza, 2021), the district has three public schools, two primary health centers, one drop-off center, and two squares. The total built-up area is 218,530.05 m^2 for residences, 33,946.92 m^2 for retail businesses, and 769.18 m^2 for service businesses. There are no registered industrial facilities. Regarding infrastructure, it is located in a Special Zone of Social Interest and in the Shoreline Project Zone, an integrated initiative that aims to address the challenges related to frail coastal ecosystems, disordered land occupation, and use, and increasing erosion and contamination processes (SEMACE, 2021). Located in the Vertente Marítima hydrographic basin, it is inserted in two sub-basins (A1 and A2) and four micro bays (A1.1, A1.2, A1.3, and A2.6), as illustrated in Fig. 3. Regarding land occupation, the soil is classified as urban.

2.2. Diagnosis of current situation

According to the Fortaleza Adaptation Plan to Climate Change, the city's climate vulnerability relates to four main hazards (Fortaleza, 2020b).

- Increased temperatures: warming trends in average and extreme temperatures that impact the population's health, especially vulnerable people. It also causes damage to biodiversity and ecosystems, as well as preserved areas and water resources.
- Prolonged droughts: changes in rainfall patterns and drought trends may cause changes in water availability and livelihoods, with consequences for the city's development, infrastructure, and population health.
- Extreme rainfall: changes in the rainfall regime also lead to excessive rain that has a direct impact on urban infrastructure, water resources, conservation units, biodiversity, and people's lives.
- Rising sea level: this mainly impacts the city's development and the infrastructure in areas close to the coast, besides biodiversity, conservation units, and mangroves.

Considering these main hazards and drawing on exposure and risk maps, the plan identified the current and future climate risk index for all districts, creating a prioritization system for implementing adaptation measures in the short, medium, and long term. This was followed by identifying hotspots, i.e., the sites in the city that are more threatened by natural hazards. The Pirambu district is classified as a high-level climate risk area both currently and in the projection for the year 2040, and measures should be applied in the short term. The district has a high level of climate risk for increased temperatures, extreme rainfall, rising sea levels, and a medium climate risk for droughts.

The 2040 Fortaleza Project outlines previously planned measures for the city, organized within 17 strategic goals, 12 highly related to climate change. Urban policy related to biodiversity is one goal that includes promoting green infrastructure as a specific action. However, the document does not detail what kind of equipment is considered G.I. nor

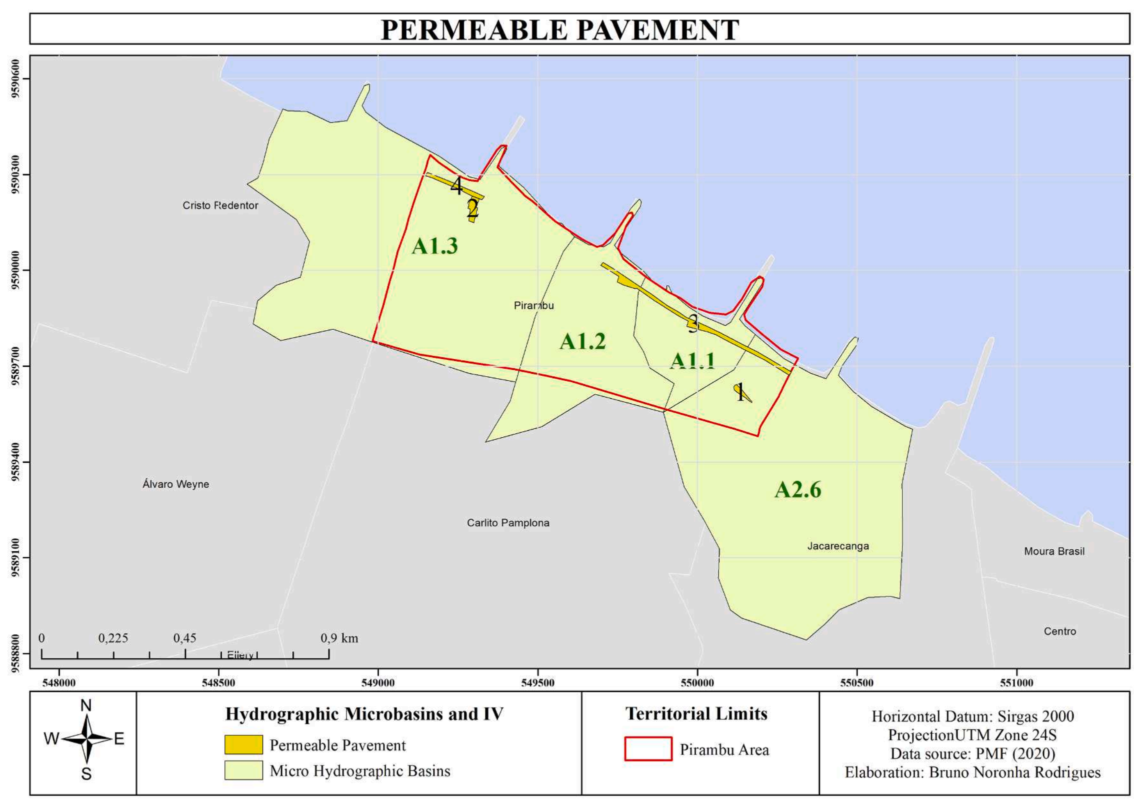

Fig. 3. Layout of permeable pavement application areas about hydrographic micro basins.
Source: Authors (2021)

create or indicate parameters for its selection. The plan links this action to mitigating three leading hazards: high temperatures and heat waves, prolonged droughts, and extreme rainfall. (Fortaleza, 2019).

2.3. Analysis of GI typologies

The selection of G.I. typologies was based on the Green Infrastructure Implementation Guide, which was designed to identify and prioritize areas with the most significant deficits in environmental functions and to provide a choice of different G.I. typologies for implementation in urban areas (IPT, 2020). The guide features a matrix that correlates the typologies, grouped according to application scales (regional, local and private), with the environmental services provided on an evaluation scale, where (-) means zero potential or not applicable; (+) means lower potential; and (++) means higher potential.

The potential scale was based on the study published by Brandão and Crespo (2016), which catalogs several G.I. typologies and then describes the benefits of each one, classifying the relation as "having assured benefit," "having potential benefit" and "indifferent to this benefit."

Based on the current and projected problems of the Pirambu district, a relation was established between the environmental services of the matrix and the hazards to be mitigated in the neighborhood. Thus, high temperatures and heat waves were related to the ecological service of reducing the effects of heat islands; prolonged droughts were related to environmental services of water flow maintenance and water quality improvement; extreme rainfall was associated with mitigating extreme water events. The local application scale was selected, which are typologies that can be implemented in streets, neighborhoods, and squares. In this group, there are 12 types of G.I. Table 1 shows the application of the matrix to the context of Pirambu.

Based on the matrix, an analysis was carried out of the feasibility of applying each of the types of G.I. in Pirambu, considering the local characteristics. It can be seen that all 12 G.I. typologies present some application potential for the provision of the environmental services required. For this work, the choice was to analyze in more detail the typologies with a minimum score of five, looking for those that could contribute more effectively to mitigating impacts related to global warming, as detailed above.

2.4. Criteria for GI implementation

The choice of applying a specific GI can be based on various criteria, taking into account environmental, social, economic, and governance factors. These criteria may vary depending on the specific context and GI objectives, but they provide a foundation for evaluating and selecting the most appropriate application. It is important to adopt a holistic approach, considering all relevant aspects and striving for a balance among different criteria.

In the development of this study, we used design criteria within the context of the study area. Considering the minimum score presented on Table 1, community gardens, stormwater planters, and road intersections were discarded. Table 2 presents a summary of the applications and limitations of each GI.

The choice of location and layout of G.I. considered the physical and infrastructure aspects of the district, such as: size and use of existing streets; place of public areas; slope; current drainage system; contribution of micro watersheds; traffic; and basic design requirements of the selected solutions.

Multiple-use roads and rain gardens have a total score of five. For the (IPT, 2020), multiple-use roads or complete streets combine urban vegetation with various other uses, such as vehicles, bike lanes, pedestrians, public transport, and spaces for bars and restaurants. They are a viable G.I. application for the study setting with no identified limitations.

Rain gardens are a solution that harnesses the biological activity of microorganisms and plants to remove pollutants from rainwater, contributing to its retention and infiltration. Generally described as shallow landscaped depressions that collect surface runoff, they are suitable for wide streets with low traffic (Yuan et al., 2017). Therefore, they are also a viable option due to the characteristics of the study setting.

Table 2
Typologies GI: applications and limitations.

Green Infrastructure	Applications	Limitations
Stormwater Ponds/ Retention Basins	Large open areas	Requirement of large areas
Constructed Wetlands	Urban environments	Not identified, depending on the specific adaptation project
Soil Bioengineering	Slopes; hillsides; degraded river environments	Requirement of specialized work; limitation in seed dormancy period; availability of species adapted to local conditions
Permeable Paving	Sidewalks; parking lots; residential yards; public leisure spaces	Low-traffic streets; risk of groundwater contamination
Green Streets	City streets	Requirement of sidewalks with adequate space for tree planting
Dry Ponds	Urban roads; rivers; linear parks; public and private gardens	Not identified, depending on the available space in the applied context
Bioswales	Urban roads near the curb; parking lots	Not recommended for densely urbanized areas
Multiple-Use Roads	City streets	Not identified, depending on the specific adaptation project
Rain Gardens	Residential areas; urban roads near the curb; gardens	Requirement of large spaces for implementation

Source: Authors (2023).

Table 1
Environmental services matrix x green infrastructure typologies.

Environmental Services Matrix X Green Infrastructure Typologies	Water flow maintenance	Mitigation of Extreme Water Events	Water Quality Improvement	Reduction of Heat Island Effects	Score
Stormwater Ponds / Retention Basins	+ +	+ +	+ +	+	7
Constructed Wetlands	+ +	+ +	+ +	+	7
Soil Bioengineering	+ +	+ +	+ +	+	7
Permeable Paving	+ +	+ +	+ +	+	7
Green Streets / Green Paths	+	+	+ +	+ +	6
Dry Ponds	+ +	+	+ +	+	6
Bioswales	+ +	+	+ +	+	6
Multiple-Use Roads / Complete Streets	+	+	+	+ +	5
Rain Gardens	+ +	+	+	+	5
Urban Agriculture / Community Gardens	+	+	+	+	4
Stormwater Planters	+	+	+	+	4
Road Intersection	+	+	+	+	4

Source: Adapted from (IPT, 2020).

Green streets, dry ponds, and bioswales have a total score of six. Green streets are tree-lined streets with integrated stormwater management with a more restricted circulation area, preferably for pedestrians and cyclists (Nawrath et al., 2019). Dry ponds, in turn, are planted depressions that collect rainwater runoff and reduce surface runoff, helping infiltration and delaying entry into the drainage system (Terêncio et al., 2020). Bioswales are channeled depressions consisting of vegetation, soil, and filtering elements that filter out rainwater pollutants and increase runoff time, carrying the waters to urban drainage systems. They are not recommended for densely urbanized areas (Spraakman et al., 2020). Considering the infrastructure characteristics of the study setting, with high urban density and streets unsuitable for application, these typologies do not represent viable alternatives.

Based on the matrix, four typologies showed more significant potential for application with a total score of seven: stormwater ponds, constructed wetlands, permeable paving, and soil bioengineering. Stormwater ponds or retention basins are flood control measures that receive surface runoff from other drainage equipment and retain water in the structure, with the limitation of requiring large areas (Zabidi et al., 2020). Constructed wetlands are similar to stormwater ponds but are also intended for domestic and industrial sewage effluents (Colares et al., 2020). The essential design requirements for properly operating these structures make it impossible to apply them to the study setting. The other two typologies present implementation possibilities.

Permeable paving, considered a type of sustainable paving, is a method of urban stormwater management that effectively reduces the peak flow of stormwater and alleviates the load on the drainage system, preventing flooding. The difference from waterproof paving is that it does not contain fine aggregates, which makes it permeable (Liu et al., 2020). The benefits associated with this type of material, compared to traditional paving, are skid resistance; noise reduction; cooling effects; and exemplary performance in water purification through the retention and absorption of runoff pollutants such as suspended solids, heavy metals, and nutrients, among others (Xie et al., 2019). According to Ogbonna and Mikailu (2018), its application is feasible in parking lots, sidewalks, residential backyards, and public leisure spaces. Special attention must be given to the risk of groundwater contamination and application in low-traffic areas.

Soil bioengineering comprises several techniques for environmental stabilization and restoration in degraded areas, such as slopes and river environments (Vergani & Graf, 2016). It usually involves low-impact measures based on using plants (or parts thereof) as building materials combined with inert materials (stone, steel, wood, among others). Costs are lower than conventional engineering structures, and the local population can become involved in the management and maintenance of the structures (Giupponi et al., 2019). Other advantages of applying these techniques are reduced need for machinery, improved soil water regime, environmental compatibility, increased stability of slopes, creation of habitats, and the possibility of execution in places of difficult access (Mello, 2013).

2.5. Geographic information system (GIS)

The maps featured in the article were designed with the ArcGIS® platform version 10.8, using as the central database the shapefiles (.shp) made available by the Fortaleza Maps Platform (Fortaleza, 2021). The coordinate system used the Universal Transverse Mercator projection – UTM Zone 24 South, SIRGAS 2000 horizontal datum. The shapefiles for Brazil and the municipalities of Ceará, used in the location map of the Pirambu district, are available in the Brazilian Institute of Geography and Statistic website (IBGE, 2020). The information on the location of the municipal drainage system was initially in .dwg format available in the digital collection of the Fortaleza city government and is part of the Municipal Basic Sanitation Plan (Fortaleza, 2014). Therefore, adjustments were required to incorporate it into the main project developed in ArcGIS®.

For the slope percentage map, designed with the Slope tool (PERCENT), data from the city's contour lines were made available by the Spatial Data Infrastructure – (IDE SEFIN, 2016), linked to the Municipal Finance Department of Fortaleza.

3. Results and discussion

Four typologies of green infrastructure are proposed based on the methodology applied: multiple-use roads, rain gardens, permeable pavement, and soil bioengineering. The following sections detail the solutions and criteria used for the proposal and present the environmental services offered and the SDGs that can be achieved with the implementation.

3.1. Multiple-use roads

This typology is ideal for avenues that combine different uses, such as pedestrians, safe bike lanes, and vehicles, a feature present in the main avenue of the study setting. Presidente Castelo Branco Avenue is approximately 8 km long and connects the boundaries of the municipalities of Caucaia and Fortaleza to the city center, with 1.2 km along the study setting. With an average width of 23m (Google Maps, 2021), it has four exclusive vehicle lanes, two for cyclists, a tree-planted median, and wide sidewalks for pedestrians.

The proposal involves regularizing and standardizing the sidewalks (width and height), incorporating accessibility for people with disabilities; improving vertical and horizontal signage to increase the safety of cyclists; providing a specific incentive area for bars and restaurants; and adjusting the median to include a more significant number of trees along the entire length, considering the Fortaleza Tree-Planting Handbook (Fortaleza, 2020a), which provides guidelines for choosing the suitable types of trees to plant along streets and sidewalks. This process must occur strategically to increase shading and intercept rainwater before it reaches the ground. Trees with dense crowns can retain significant volumes of rainfall, thus minimizing runoff (USAID, 2017). Priority should be given to native species adapted to the geographic region, with specific attributes of rusticity and less vulnerability to urban problems such as diseases and pests (Frota Júnior et al., 2018).

This typology helps in water flow maintenance and water quality improvement, services related to the issue of prolonged droughts, and mitigation of extreme water events, which are associated with the possibility of a higher incidence of heavy rainfall. It has more significant potential in reducing the effect of heat islands, helping high fight temperatures in the study setting. These services are offered because multiple-use roads use urban tree canopies in their urban design (Fluhrer et al., 2021).

The G.I. Handbook of Hartford, Connecticut, published by (The Office of Sustainability, 2018), lists several benefits that trees in harmony with avenues can bring to the city, such as: cooling the surrounding area, increasing the longevity of adjacent pavement; increasing property value; reducing the use of air conditioning and energy consumption; filtering air and water, capturing greenhouse gases, emissions and other pollutants.

The adaptation of Presidente Castelo Branco Avenue as a multiple-use road also provides other environmental services: habitat preservation, conservation of genetic diversity; reduced social vulnerability; tremendous potential to provide recreation and promote physical and mental health (Zepp et al., 2020).

The benefits of using this kind of G.I. related to the SDGs, which should be achieved by 2030, are: improve water quality by reducing pollution and substantially increasing recycling and safe reuse globally (target 6.3); substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and substantially reduce the number of people suffering from water scarcity (target 6.4); improve energy efficiency (target 7.3); reduce the adverse per capita environmental impact of cities, including by paying particular attention to air quality and municipal and other waste management (target 11.6); provide universal access to safe, inclusive, accessible, green and public spaces, in particular for women and children, older persons and persons with disabilities (target 11.7); introduce measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species (target 15.8).

Other targets that can be achieved more indirectly are: reducing exposure and vulnerability to climate-related extreme events and other economic, social, and environmental shocks and disasters (target 1.5); developing quality, reliable, sustainable, and resilient infrastructure to support economic development and human well-being, with a focus on affordable and equitable access for all (target 9.1); enhance inclusive and sustainable urbanization (target 11.3); significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to the global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations (target 11.5).

3.2. Soil bioengineering techniques

This typology corresponds to the techniques used to control erosive processes and degradation (Garcia, 2017), often not associated with G.I. typologies. The Pirambu district has an area with shoreline-type degradation and erosion (Moreira et al., 2020). Considering this context, Fig. 3 shows the proposition of soil bioengineering techniques in a total area of 37,975.85 m^2, which comprises the region of Pirambu Beach and Santa Inês Street and São Raimundo Street, along Ostras' Beach.

The main techniques used are: rolled erosion control products, hydraulically applied products, sediment retainers, cell confinement systems, geosynthetics, adhesives, catalyst additives, fixation materials, and nutrients/fertilizers (Holanda et al., 2020). The decision of which technique will be most suitable depends on an on-site investigation and specific data mining. Among the main criteria required are the history of the area, the objective and scope of the chosen solution, hydroclimatic study, soil study, detailed topographic survey, aerial photographic survey, detailing of the solution (technique, materials, and cost), and technical specifications (Maffra & Sutili, 2020).

The execution of bioengineering techniques in the coastal area of Pirambu will provide environmental services with great potential to protect water resources, combating the effects of prolonged droughts and extreme rainfall. This service occurs through the maintenance of soil banks, with the reduction of erosion on the banks of water courses and, consequently, cause a reduction in the transport of sediments and pollutants. A parameter that can be used to measure the aesthetic aspect of water quality acceptance, in this case, is turbidity, which indicates the presence of dissolved substances (USAID, 2017). Contributions to SDG targets include ensuring access to sustainable water management and sanitation for all (target 6.3) and conserving and sustainably using the oceans, seas, and marine resources for sustainable development (target 14.5), using indicator 6.3.2 – Proportion of bodies of water with good ambient water quality.

Introducing this solution can also help the environmental balance by reducing the effects of heat islands and improving air quality. According to (Boldrin et al., 2019), the stabilization provided by vegetation affords benefits such as carbon sequestration and air temperature cooling, reducing the temperature by up to 1°C in green urban areas compared to non-green sites. And improved air quality can be achieved thanks to the ability of the green regions to metabolize sulfur oxides (SO_x) and aqueous ammonia, as well as the deposition of particulate matter (PM_{10}) and heavy metals such as lead on the foliage of trees and shrubs. (Garcia, 2017). With safer access to Pirambu Beach and Ostras' Beach, provided by soil stability, it is possible to create policies to encourage tourism. It would certainly be a recreation option for the local population, providing cultural services and promoting improved well-being.

Other achievable SDG objectives are: to develop quality, reliable, sustainable and resilient infrastructure, including regional infrastructure, to support economic development and human well-being, with a focus on equitable and affordable access for all (goal 9.1) and make cities and human settlements inclusive, safe, resilient and sustainable (targets 11.3 and 11.6).

3.3. Permeable pavement

Public areas and streets with light traffic were selected in the study area to introduce permeable pavement. The choice of public leisure sites, considering a region of high population density, is a viable solution due to the possibility of simplified government intervention compared to other places such as parking lots. The proposal is to apply this type of G. I. in Patro Mor Square (800.54 m^2) and Abel Square (1,716.97 m^2), two public squares already urbanized and where the paving infrastructure would have to be replaced. Santa Inês Street and São Raimundo Street (8,889.10 m^2), and São Francisco Street (2,288.84 m^2) were also selected to receive permeable paving.

The street sections were selected based on the analysis of local traffic using the Google Maps traffic layer (Google Maps, 2021). In the absence of an on-site traffic count study, several searches were done on the Google traffic tool regarding local traffic conditions on different days and times. It was possible to determine that the most unfavorable traffic situation typically occurs on Fridays at 6:05 pm (Google Maps, 2021). Based on this analysis, the authors selected wider streets where the traffic flowed better (faster and with fewer vehicles). Another important consideration was the contributing area of runoff directed by hydrographic micro basins. With the two squares already defined for implementation (areas 1 and 2), the choice of street sections considered distribution along the other micro basins (areas 3 and 4) that did not yet have areas with permeable paving, as shown in Fig. 3.

The contributing area of micro basin A1.3, considering the public space, the paved part, and the sidewalks, measures 60,000.84 m^2. As seen in Fig. 3, areas 2 and 4, measuring respectively 1,716.97 m^2 and 2,288.84 m^2, are located in this micro basin and account for 6.68% of the impermeable area that would be replaced by permeable pavement. A stretch of area 3 (2,156.92 m^2) is inserted in micro basin A1.2, accounting for 6.30% of the total area of 34,147.23 m^2. In turn, the stretch of area 3 inserted in micro basin A1.1 measures 4,822.96 m^2, accounting for 31.52% (total micro basin area of 15,302.47 m^2). Micro basin A2.6 (13,928.75 m^2) contains a stretch of area 3 (1,848.45 m^2) and area 1 (1,584.73 m^2), accounting for 24.65%.

Another design parameter analyzed was a slope since, in agreement with (Hashemi et al., 2020), steep slopes make it impossible to use these infiltration and retention devices, which are not recommended in such cases. The Brazilian Agricultural Research Corporation (EMBRAPA, 2018) defines landform slope classes as flat (0 to 3%), gently sloping (3% to 8%), moderately sloping (8% to 20%), strongly sloping (20% to 45%), mountainous (45% to 75%) and steep (>75%). Fig. 4 shows the slope for the study setting, considering the division above. We can attest the possibility of implementing this G.I. type according to this criterion since the permeable pavement areas are primarily located on land with up to 20% slope.

Choosing the appropriate pavement type requires considering the material's performance in mitigating problems related to drainage and groundwater table level. The Construction Industry Research and Information Association (CIRIA, 2015) classifies these pavements as composed of permeable surface coatings, consisting of porous structures and composed of porous structure and devices to facilitate infiltration. The groundwater table level should be determined through an on-site study using standardized tests such as the maximum daily application rate in m^3/m^2 day (ABNT, 1997a) and land infiltration capacity in L/m^2. day (ABNT, 1997b).

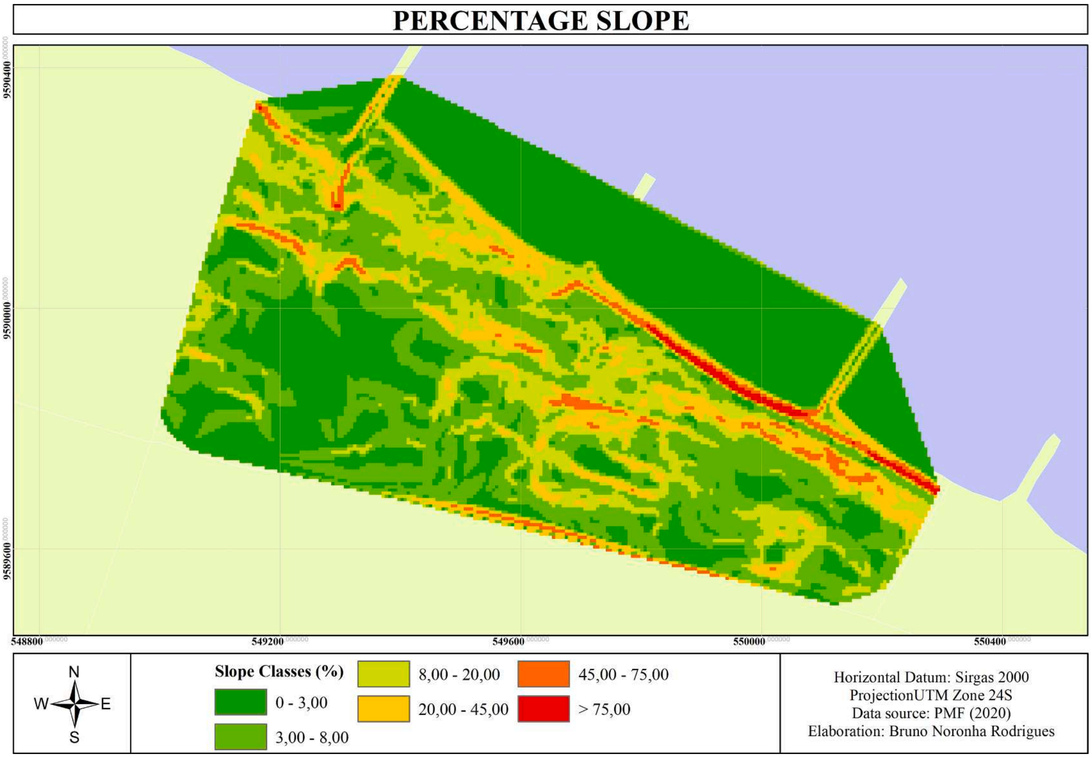

Fig. 4. Study setting slope.
Source: Authors (2021).

For this implementation, it is recommended to use porous pavements with infiltration devices of the permeable interlocking type, which are coatings composed of concrete paving pieces in which water infiltration occurs through voids and spacings between the elements (Liu & Armitage, 2020).

The initial proposal included introducing permeable paving in another public area of the district, the drop-off center. However, special attention should be given in this G.I. to the risk of groundwater table pollution and considering the difficulty of controlling the residue in the containers used for the selective collection of different kinds of waste. It was decided to exclude the area, thus preserving its waterproofing to avoid the contamination of groundwater and local soil.

An estimated total area of 13,695.45 m^2 of permeable paving applied in the district is expected to offer environmental and ecosystem services with great potential for protecting water resources, helping to maintain water flow, mitigating extreme water events, and improving the quality of water (Li et al., 2022), besides a lesser impact on reducing the effects of heat islands (Vujovic et al., 2021). This would help achieve the following SDG: no poverty (target 1.5); clean water and sanitation (targets 6.3 and 6.4); industry, innovation, and infrastructure (target 9.1); and sustainable cities and communities (target 11.3).

Rainwater may contain pollutants in particles and dissolved forms captured in the soil or atmosphere. In infiltration and drainage, water can be cleaned by natural soil purification. Water pollutants undergo adsorption, decomposition, migration, transformation, etc., in the soil environment, mainly by aerobic and anaerobic microorganisms. Thus, pollutants concentration, toxicity, or activity tends to decrease. Water can be cleaned of harmful substances before joining the underground drainage system or groundwater.

The urban microclimate can also undergo beneficial changes with this G.I. solution due to the ability of permeable pavements to reduce surface temperature by evaporative cooling. Compared to conventional concrete pavements, permeable concrete pavements have lower reflectivity, volumetric heat capacity, and thermal conductivity and tend to absorb additional heat due to higher porosity, lowering the air temperature. The higher void content and airflow levels in porous pavement structures provide faster heat dissipation than traditional pavements; therefore, their surface temperatures are lower at night (Vujovic et al., 2021).

3.4. Rain gardens

The proposal for the implementation of rain gardens considered local traffic, street width, micro basin contributing areas, land slope, and position of the existing drainage system. Several advantages can be listed in the use of this typology in urban landscapes, among them enhanced landscaping; reduced surface runoff; removal of fine sediments, nutrients, bacteria, and metals; reduced drainage system costs; and potential design flexibility (Sharma & Malaviya, 2021).

The flood mitigation function of these gardens by reducing surface runoff involves the temporary storage of stormwater to minimize peak runoff and is evaluated by peak flow delay time. For the same heavy rainfall, peak runoff is inversely proportional to peak flow delay time, and the flooding mitigation function increases with longer delay times (Zhang et al., 2020).

Rain gardens can also treat rainwater contaminated with heavy metals from everyday activities such as washing tires, burning fuel, dirt from parking areas, road asphalt, and vehicle exhaust fumes. The retention of heavy metals in the soil environment involves cation exchange (non-specific adsorption), specific adsorption, coprecipitation (with Fe and Al oxyhydroxides), and organic complexation. A high concentration of salt in rainwater causes suspended solids to form flakes that settle. These large-sized particles facilitate filtration and thus increase removal levels. The removal of heavy metals (such as Zn, Cd, Pb, Cu) occurs mainly ($\geq$90%) from the top 25 cm of the bioretention medium. Conversely, plants can only absorb a small amount (1.00 – 3.00%) of metals bound to the substrate. Metal removal is affected by substrate composition and stormwater retention time. Low hydraulic conductivity values in saturated soil (Ksat) in sand-based rain gardens reduce water loss between rainfall events but increase the efficiency of metal removal, especially copper (Malaviya et al., 2020).

The traffic study was based on the same context of the permeable paving proposal, allowing the selection of streets that were suitable for this typology. The next step involved visual analysis and using the (Google Maps, 2021) "measure distance" tool, searching for streets with adequate dimensions so that the traffic flow suffers a minimal impact. With this information, the geoprocessing software was used to identify and visualize the existing drainage system's position and induce the G.I. typology's location in the same drainage flow. Fig. 5 shows the location of the district's drainage canals and galleries and the proposed street stretches to introduce the gardens. The slope information shown in Fig. 4 was also considered.

The rain garden technical design handbook, developed in the *Solução para Cidades* Project (Solutions for Cities Project) indicates 1 ha (10,000 m^2) as the maximum contributing basin area to be controlled, i.e., the area that will have its rainwater directed to a rain garden (ABCP, 2021). Therefore, it is essential to know each micro basin's area and the gardens' position. Fig. 6 illustrates this relationship. It was defined that each rain garden would measure 5.00 meters along the sidewalk and 1.10 meters wide. It is recommended to pre-treat the application site with grass strips, for example, as it is an area with a likely high input of sediments.

The basin areas were extracted from the data of the vector files referring to them in the GIS. The A2.6 micro basin measures 487,020.69 m^2, A1.1 measures 83,510.02 m^2, A1.2 measures 189,069.05 m^2 and A1.3 measures 555,186.12 m^2, requiring at least 48, 9, 19 and 56 rain gardens, respectively. The number of parks to be implemented in each of the sections was then defined: in Section 1 – Nossa Senhora das Graças Street (between Deusimar Street and Francisco Cordeiro Street), 14 gardens; in Section 2 – Nossa Senhora das Graças Street (between Santa Rosa Street and No Denomination Street), 12 gardens; in Section 3 – Santa Inês Street (between Santa Rosa Street and No Denomination Street), 13; in Section 4 – São Raimundo Street (between Santa Rosa Street and No Denomination Street), 8; in section 5 –Álvaro de Alencar Street (between Santa Elisa Street and Street Nossa Senhora das Graças), 9; and in section 6 – Pasteur Avenue (between São Francisco Street and Felipe Camargo Street), 18 rain gardens.

With the proposed distribution, the needs of micro basins A1.1 and A1.2 would be met. Micro basin A1.3 would receive 35 rain gardens; the other 19 should be installed in the Cristo Redentor, Álvaro Weyne, and Carlito Pamplona neighborhoods that comprise the total area. A2.6, located mainly in the Jacarecanga and Carlito Pamplona neighborhoods, will only have one rain garden in Pirambu.

This G.I. typology is one of the best rainwater management practices, according to (Malaviya et al., 2019), providing environmental and ecosystem services related to the protection of water resources, with more significant potential for maintaining water flow, besides reducing the effects of heat islands, improving air quality, providing environmental balance and encouraging recreation and physical and mental health.

The SDG targets that can be achieved with the use of rain gardens are: improve water quality by reducing pollution and substantially increasing recycling and safe reuse globally (target 6.3); substantially increase water-use efficiency in all sectors and ensure sustainable withdrawals and substantially reduce the number of people suffering from water scarcity (target 6.4); develop quality, reliable, sustainable and resilient infrastructure to support economic development and human well-being, with a focus on affordable and equitable access for all (target 9.1); and enhance inclusive and sustainable urbanization (target 11.3).

The Fig. 7 shows the layout of the final proposals in the Pirambu districts.

3.5. Challenges and prospects

Implementing G.I., even at the local level, may pose significant challenges. Firstly, it is a relatively new concept. Governments, concessionaires, and the general population have difficulty grasping the

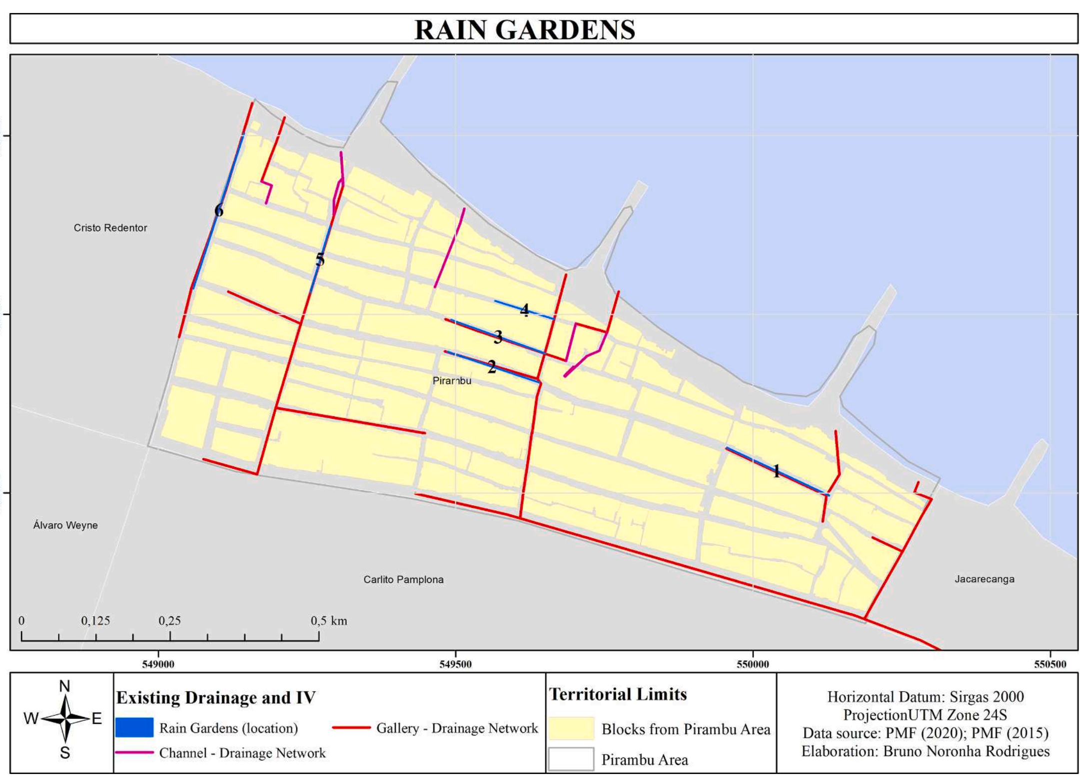

Fig. 5. Location of drainage system and proposed rain gardens.
Source: Authors (2021)

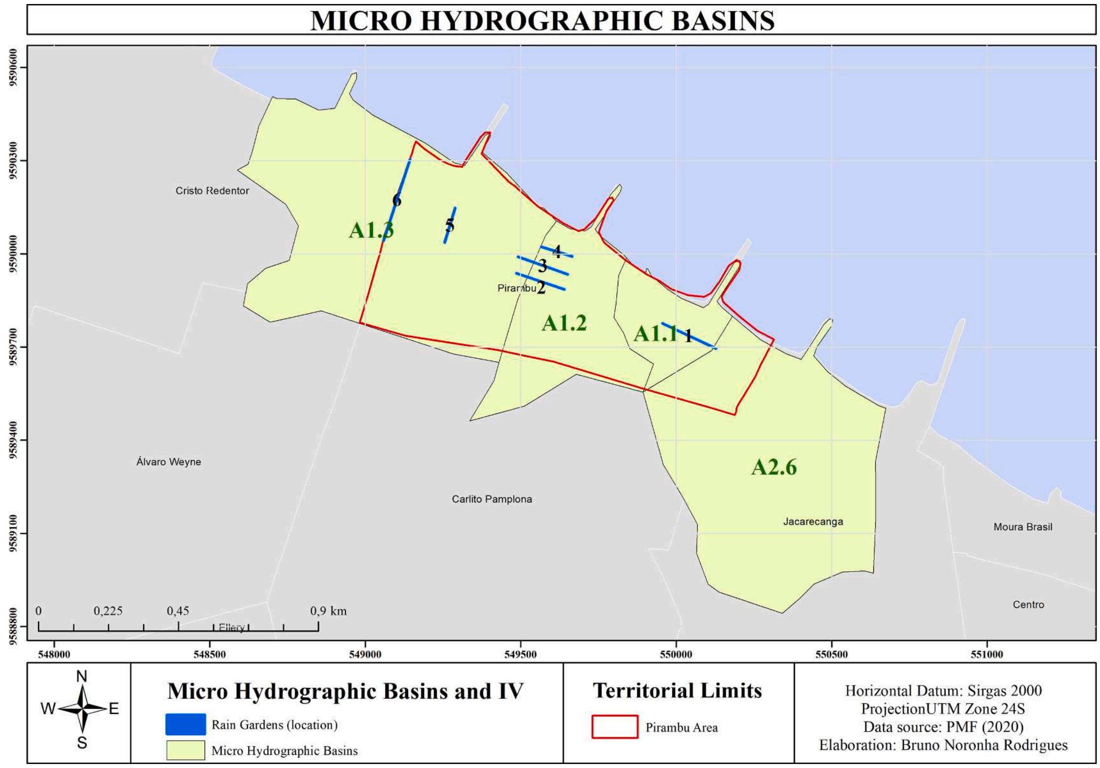

Fig. 6. Layout of rain garden application areas in relation to hydrographic micro basins.
Source: Authors (2022).

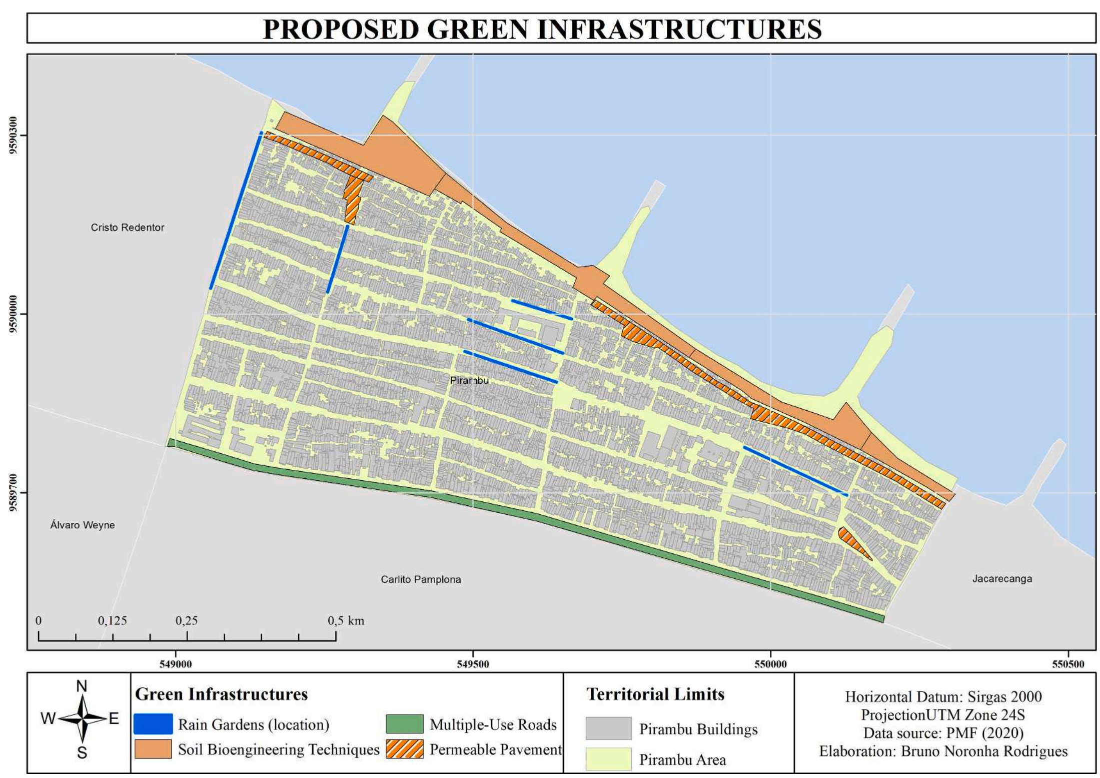

Fig. 7. Green Infrastructure Layout.
Source: Authors (2021)

nature of this type of system and the benefits that can be achieved with it, such as improved management of natural resources. The Fortaleza Adaptation Plan fails to address the concept of G.I. clearly and does not always classify green spaces and corridors as G.I. typology.

The initial investment can be pretty costly despite the long-term viability. Moreover, it may be several years before the solutions can offer a full range of improvements. The actual assessment of costs and benefits is often rooted in multiple areas and disciplines, involving different methods of calculation, and many of the benefits relate to the delivery of ecosystem services that are challenging to assess, such as promoting recreation and better quality of air. Social sciences are essential in investigating the future causal link with conflicts or degradation resulting from an infrastructure development project and relevant social issues, especially related to governance.

The economic feasibility analysis, in turn, proves to be a significant challenge due to the lack of historical data on costs and benefits, unlike gray infrastructure. As a result of such uncertainty, evaluation studies are often based on conservative assumptions, which may lead to an underestimation of the value of an investment in this type of project. At the public policy level, G.I. can play an important role in adopting broad strategies for climate change adaptation and mitigation of its effects. The sustainable management of ecosystems in the urban context provides services that help people face the challenges posed by such changes.

Regarding prospects, we can cite: the development of life cycle assessments; quantification of the social and environmental impacts of G.I.; the need to create specific tools for projects and management; creation and expansion of public policies that address the subject from national legislation to changes in local master plans; critical and comparative evaluation of practical tools used to assess benefits; and consolidation and dissemination of practical experiences, with lessons learned.

Implementing G.I. is a strategy to achieve the various goals described in the 2030 Agenda. In addition to those mentioned above, goal 13 (urgent action to combat climate change and its effects) would be directly addressed, as it describes the measures that must be urgently taken to fight climate change and its impacts.

4. Conclusions

This paper presented a methodology that makes it possible to propose the implementation of G.I. to mitigate the effects of climate change in a given study area, considering its spatial characteristics and using georeferenced data to support various analyses and solutions. In other words, they are proposals based on bibliographic references best suited to the local reality.

Based on planning for climate change adaptation in the city of Fortaleza, the Pirambu district was selected for being recognized as a critical area for the main hazards brought about by such ecosystem changes. Next, the risks were associated with the environmental services that G.I. must offer: for increased temperatures and heat waves, the service to reduce the effect of heat islands; for prolonged droughts, maintaining water flow and improving water quality; and for extreme rainfall, mitigation of extreme water events.

The (IPT, 2020) methodology for choosing G.I. typologies was applied. Following the feasibility analyses, multiple-use roads, soil bioengineering techniques, permeable paving, and rain gardens were proposed as solutions that offer essential environmental services to offset the main hazards and other benefits. And the location and quantification of each solution were demonstrated based on the study design parameters.

Geoprocessing proved to be a very effective tool in the decision-making process of implementing G.I., enabling the visualization of critical data and making it easier to conceive scenarios. Brazilian cities like Fortaleza already have databases with simplified access, where files in appropriate format can be downloaded. However, during the research, difficulty was observed in finding complete files of small towns where local public bodies do not yet invest in georeferenced data for urban planning. There is still a shortage of works of this type in the Brazilian literature, with a significant gap in G.I. applications characterized as such and in the analysis of environmental services provided.

Applying technical and scientific knowledge to urban intervention must keep in step with the development of growing environmental awareness, resulting from the sustainable perception of human intervention, to recover and plan the urban environment. Thus, G.I. stands out in enhancing natural areas and generating economic, environmental, and scenic advantages. G.I. has proven to be a strategy with great potential to help meet several SDGs, such as reducing ecological disaster risks, providing clean water, air purification, and resilience to climate change.

The research focused on the methodological path and the main criteria for inserting different types of G.I., considering as much local information as possible and using geoprocessing to build maps of solutions. It is essential in further studies to individually analyze the impact of implementing each of these typologies. Specific information such as groundwater pollution and soil analyses are necessary for a final decision by the public authorities regarding these measures.

CRediT authorship contribution statement

Bruno Noronha Rodrigues: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing. **Vitor Eduardo Molina Junior:** Conceptualization, Methodology, Writing – review & editing, Project administration, Supervision. **Felippe Benavente Canteras:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Project administration, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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