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Assessing Drainage Infrastructure in Coastal Lowlands: Challenges, Design Choices, and Environmental and Urban Impacts

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Abstract: Urban flooding is a growing concern, particularly in coastal lowland cities where climate change exacerbates hazards through rising sea levels and intense rainfall. Traditional flood defenses like fluvial polders often exacerbate urban fragmentation and maintenance costs if poorly integrated into planning. This study proposes a multifunctional assessment design framework to evaluate polder design effectiveness considering both the hydraulic and social–environmental dimensions, emphasizing blue–green infrastructure (BGI) for flood control, leisure, and landscape integration. Three design scenarios for Rio de Janeiro's Jardim Maravilha neighborhood were modeled hydrodynamically: S1 (dike near urban areas, pump-dependent) and S2/S3 (dikes along the riverbank, gravity-driven). Results show S2/S3 outperformed S1 in storage capacity (2.7× larger volume), freeboard resilience (0.42–0.43 m vs. 0.25 m), and urban integration (floodable parks accessible to communities), though S1 had faster reservoir emptying. Under climate change, all scenarios sustained functionality, but S1's freeboard reduced by 86%, nearing its limit. The framework's standardized scoring system balanced quantitative and qualitative criteria, revealing trade-offs between hydraulic efficiency and urban adaptability. The optimized S3 design, incorporating external storage and dredging, achieved the best compromise. This approach aids decision-making by systematically evaluating resilience, operational feasibility, and long-term climate adaptation, supporting sustainable flood infrastructure in coastal cities.

Keywords: urban resilience to floods; coastal lowlands; drainage infrastructure; fluvial polder system; climate change; hydrodynamic modeling

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1. Introduction

Urban flooding is a socio-natural disaster that causes significant damage to cities and their inhabitants, and its frequency and severity are increasing globally [1,2]. Primary factors contributing to this process include environmental degradation, uncoordinated land-use planning, fast urban population growth, and climate change [3]. The latter can be particularly significant in coastal lowland cities, where global warming combines effects such as mean sea level rising and more intense rainfall, significantly exacerbating flood

hazards [4]. Coastal dynamics often limit the discharge capacity of rivers and drainage systems, making these areas especially vulnerable to extreme weather events and prolonged inundation [5]. Consequently, there is an increasing need for adaptative solutions, such as providing flood storage areas, giving room to the rivers and using localized flood defenses, like dikes and polders, to manage stormwater and mitigate flooding impacts.

However, these conventional flood defenses pose their own set of challenges. If not integrated into urban planning, the construction of these hard engineering structures can lead to the occupation of environmentally sensitive areas under a false sense of security, overlooking the fact that there are always residual risks associated with such artificial solutions [6]. Moreover, they can act as physical and visual barriers, fragmenting urban spaces, reducing urban and environmental quality, and disrupting the natural functions of riverine ecosystems [7]. Their dependence on continuous operation and maintenance, often combined with costly pumping systems and a lack of adaptability, further highlights the need for a paradigm shift in how flood defenses are designed and integrated into urban landscapes [8].

This transition seeks to harmonize urban and natural demands by moving away from solely using traditional conveyance-focused measures and prioritizing the restoration of flow patterns closer to pre-urbanization conditions whenever possible [9]. Such efforts face significant challenges in areas that were once swamps or mangroves and are now established urban neighborhoods, especially if they still lack complete infrastructure [10]. This approach not only aims to reduce flood depths but also mitigates flood risks by addressing the vulnerability of the socioeconomic system, while simultaneously enhancing the ecological and social value of urban spaces [11].

In response to these challenges, the concept of resilience in the context of urban flooding has gained prominence [3]. Key milestones in this matter include the Hyogo Framework for Action 2005–2015 [12] and the Sendai Framework for Disaster Risk Reduction 2015–2030 [13], which underscored the importance of resilience as a global commitment in disaster risk reduction [14]. When applied to flood management, resilience focuses on mitigating the adverse impacts of extreme weather events, which can have devastating consequences for communities and lead to large-scale disasters [15].

Urban flood resilience refers to a city's capacity to prevent and withstand floods, recover from physical damage and socioeconomic losses, preserve its core characteristics, and adapt to future flood-related challenges [16]. Especially in coastal lowlands, a resilient approach involves incorporating flood mitigation measures into the urban fabric. This ensures that such measures contribute to both city functionality and environmental sustainability. If these measures are not integrated into the urban landscape, they may lack social support and become unsustainable over time, thus failing to be truly resilient. Urban planning must incorporate watershed management strategies to promote urban and environmental quality, fostering a balance between urban development and ecological preservation [17].

A key aspect of this shift to integrate social and environmental actions refers to the principle of multifunctionality, which can integrate ecological, social, and economic functions into urban infrastructure [18]. Multifunctional designs ensure that flood defenses serve multiple purposes beyond flood control, optimizing the usual limited urban open spaces while enhancing the city's vitality. For example, integrating ecological functions and landscaping into flood defenses can enhance biodiversity, improve aesthetics, and create spaces that foster human–nature interaction [19], while adding leisure options and active mobility alternatives can offer urban services. Such designs not only reduce operational costs but also promote long-term resilience by addressing both immediate flood risks and broader urban challenges.

There are numerous terminologies that describe design strategies within the resilient approach, many of which are being adopted by governments worldwide. One prominent example is blue and green infrastructure (BGI), which refers to a network of natural and semi-natural systems designed to manage water, support biodiversity, and deliver social and ecological benefits [20]. Unlike traditional gray infrastructure, BGI emphasizes nature-based solutions such as urban wetlands, fluvial parks, green roofs, rain gardens, and permeable pavements, ranging from the watershed scale to the local scale, but integrating the set of actions into a functional infrastructure system. These systems mimic natural hydrological processes, enhancing water retention, infiltration, and evapotranspiration while reducing runoff and, consequently, flood risks. Additionally, BGI contributes to urban cooling, air quality improvement, and carbon sequestration, making it a critical component of climate adaptation strategies [21] and offering wider benefits. Importantly, BGI can be combined with gray infrastructure to create hybrid systems that leverage the strengths of both approaches, combining blue–green systems' sustainability with gray systems' reliability [22]. Several studies point to the hybrid infrastructure approach as the most feasible and efficient [23–25], since this integration not only enhances urban flood resilience but also promotes ecological restoration, social well-being, and economic vitality [26], while building upon existing infrastructure systems.

There are several available tools to evaluate the performance of urban infrastructure or urban projects, such as the Envision Framework, which covers multiple categories of urban benefits and can establish goals for project optimization [27]. In the context of sustainable buildings, various rating systems are available, including BREEAM (UK), DGNB (Germany), ITACA (Italy), LiderA (Portugal), and HQE (France) [28]. This study, however, proposes a more streamlined evaluation approach, using an objective, non-exhaustive set of criteria specifically designed for polder assessment. This study, however, proposes a more targeted evaluation approach for specifically assessing polder projects, using an objective and non-exhaustive set of criteria developed to go beyond the technical hydraulic characteristics of such projects. In fact, in addition to the more obvious parameters—such as dike height, internal storage volumes, and discharge devices—the proposed evaluation also considers variables associated with the project's resilience, such as flap gates closure and opening times and the internal reservoir freeboard. It also includes the assessment of water quality aspects (due to storm water and waste water interactions), flow transfer to downstream, and urban integration—an often-neglected aspect in infrastructure assessments—emphasizing the essential role of multifunctionality in sustainable development.

In this context, this research assesses urban resilience to floods in coastal lowlands, focusing on the effective and resilient incorporation of polders into the urban landscape. Polders, as potential components of design alternatives in stressed situations, like in flat riverine areas occupied by urban settlements or fluvial plains near coastal lowland, must meet the city's demands while minimizing impacts on environmental and urban quality. If a polder is not integrated with other urban functions, the space may remain underutilized during dry periods or even face irregular urban encroachment. This poses risks to the population and reduces the effective and necessary water storage capacity. A notable example can be seen in the Iguaçu Project [29], in the Metropolitan Region of Rio de Janeiro, Brazil, where some areas originally designated for water retention were irregularly occupied by urban expansion [30]. In the same project, it was also registered that newer upstream polders have increased the risk of overtopping to downstream older polder structures, due to increased transferred discharges [29].

Designing effective polders in terms of social, environmental, and functional aspects involves several challenges. For instance, providing more space for the river by placing the dike closer to urban areas reduces the space available for urban expansion and limits the

capacity to accommodate flood volumes within the polder. On one hand, this results in lower river flooding levels, as more natural areas remain available for flood management. On the other hand, increasing space in the river floodplains results in flood damping and longer flooding periods. The balance between these effects can either facilitate or complicate flap gate operations, as the gates may remain closed for extended periods.

Conversely, constructing the dike closer to the riverbanks increases the available open space and storage capacity within the polder but may degrade fluvial ecological functions. In terms of flap gate operation, reducing the space allocated to the river accelerates the flow but leads to higher water levels. As a result, predicting flap gate operations is not simple or direct. This assessment requires a detailed evaluation of local urban, environmental, and topographic conditions. Additionally, in both scenarios, the use of pumps may become necessary, introducing an additional dependency on power supply, which reduces system resilience. Furthermore, dike construction can contribute to urban segregation. These factors should be carefully evaluated from a systemic perspective.

Tackling these challenges requires aligning sustainable stormwater management with global sustainability goals. This proposal is consistent with the United Nations' Sustainable Development Goals (SDGs) 9, 11, and 13, which emphasize resilient infrastructure, sustainable cities and communities, and actions to combat the effects of climate change [31]. By addressing these goals, this research contributes to the global effort to create cities that are not only flood-resilient but also socially inclusive and environmentally sustainable.

The practical objective of this study is to propose an evaluation framework for designing polders in coastal lowlands using a multifunctional urban design approach for flood mitigation, while also considering the integration of urban services such as leisure, mobility, sanitation, and landscaping, through the application of blue–green infrastructure concepts. This framework will also target practical design parameters related with polder operation in a resilient perspective, specifically addressing dike positioning, required storage volumes, and flap gate design and operation, preferably avoiding pumping solutions.

2. Materials and Methods

The proposed framework involves the development and application of a method for evaluating the design effectiveness of alternative multifunctional urban polders aimed at flood mitigation, as well as their social–environmental results.

The design of a fluvial polder is primarily defined by three main parameters:

- The height of the protective levee, which determines the maximum water level the system can withstand;
- The internal storage volume of the retention reservoir (or buffer storage), which dictates the system's ability to temporarily retain floodwaters associated with the runoff produced in the protected area;
- The diameter of the flap gates, which controls the outflow discharge capacity of the polder.

However, although these parameters are necessary for designing a polder, they do not allow a comprehensive assessment of the operation of this structure and its interaction with the urban environment, nor do they allow for evaluating the long-term resilience of the polder.

To address these issues, other dimensions must be considered for an effective design assessment. For instance, to ensure long-term resilience, additional parameters must be carefully evaluated, as follows:

- Available internal freeboard of the reservoir (related to the additional storage volume available to face stressed/unpredicted conditions): the greater the available storage capacity, the more resilient the system becomes, as it can accommodate unexpected increases in internal flooding volumes or unexpected delays in the flap gates opening.

- Flap gate closure timing: the faster the gates can open and start to drain the internal reservoir, the more effectively the system can adapt to extreme, successive, or prolonged flood events, thereby enhancing resilience.
- Avoidance of increased downstream discharge: a poorly designed levee can accelerate peak discharges, reducing natural flow attenuation by eliminating storage along riparian areas. If the project transfers higher discharge volumes, it may compromise overall flood resilience by increasing flood risks downstream.
- Dependence on pumping systems: A high reliance on pumps reduces resilience, as pumping failures (due to maintenance issues, power outages, or mechanical malfunctions) can prevent the proper expected drainage functions. However, if pumps are incorporated as a redundancy measure—meaning they are not essential for standard operation but provide additional capacity to handle extreme events—the overall resilience of the system can increase.
- Urban interaction: Dikes can be formidable barriers to urban continuity, creating urban edges. In this sense, the design of multifunctional spaces occupying the dike vicinity and offering urban services is important
- Water quality: the use of temporary reservoirs (with possible long emptying times) containing polluted waters can be critical if the population is in direct contact with these waters.

Therefore, besides the hydraulic parameters and the operational behavior, it is also important to consider that polders will create reservoirs closer to urban settlements, and these reservoirs will have an interaction with the city and its population. So, it is important to incorporate additional urban functions into these reservoirs to favor its integration with the city demands which will support its long-term sustainability. In this sense, if the city's inhabitants are able to interact with the polder reservoirs, the quality of the water should be considered, as these reservoirs will work receiving urban drainage discharges that can be combined with sewage disposal.

By integrating all these factors into the design assessment, a fluvial polder can provide effective flood protection while ensuring sustainable and adaptive resilience against extreme hydrological conditions.

To apply the proposed method, various prospecting scenarios considering different design alternatives were created to allow the development of an exploratory discussion about the design possibilities and their effects, fostering the necessary discussion around this subject. This process aims to establish a set of general guidelines that can assist in the design process across different cases, ensuring that the complete overall rationale can be consistently replicated. This exploratory evaluation method relies on the support of simulation tools, as explained in detail in the sequence of the text. In this sense, this section is subdivided into five parts: "Section 2.1. General Procedures", "Section 2.2. Resilience Criteria", "Section 2.3. Scenario Construction", "Section 2.4. Evaluation Framework", and "Section 2.5. Modelling and Simulation Tools".

2.1. General Procedures

The position of the dike in a lowland protective polder system represents a design choice leading to diverse consequences. The dike effects over the main river flow, the inner storage volumes and the structures controlling discharge exchanges between the protected land and main rivers are the core variables to be considered in this type of project. However, reducing flood risks and increasing resilience, both for current conditions and future stressed scenarios, depend on other critical aspects that must also be considered.

The first methodological step of the proposed framework defines a set of indicators to compose the resilience criteria supporting design assessment. Departing from this

general picture, a multicriteria evaluation matrix is defined, taking into consideration five dimensions: the hydraulic characteristics of the polder, its flood mitigation performance, its operational feasibility, its interaction with other urban functions, and water quality.

Intending to test the practical use, the representativeness, and the completeness of the matrix defined in this framework, two different design alternatives are initially built: the first one gives more space to the river implementing the dike near the urban area; the second poses the dike near the riverbank. These two alternatives were then compared between each other according to the matrix of resilient criteria. The evaluation of the results can lead to a third improved alternative to be tested, intending to bench mark the resilient indicators. Then, all the alternatives are also tested in future conditions, marked by stressed climate change conditions. These stressful situations can provide additional lessons to guideline the project design. In the end, these guidelines will be systematized as design references for polder projects.

2.2. Resilience Criteria

A set of criteria was created for each one of these five dimensions. Some of them are numerical/quantitative and some are non-numerical/qualitative. However, the latter are converted into numerical scores to ensure they can be standardized, operated, and compared within the final assessment matrix. The value of each criterion was determined for each scenario, and then they were normalized according to the TOPSIS logic, a technique for order preference by similarity to an ideal solution. This method is a widely used tool in multicriteria methodologies that has been successfully applied in many sectors [32].

The criteria adopted for each dimension are presented in Table 1 and further described below.

Table 1. Dimensions and criteria.

Dimensions	Criteria
Hydraulic characteristics	Polder reservoir free board (m) Storage volume (m^3) Coordination along the watershed (m^3/s)
Flood mitigation	Reduction in flooded areas over 30 cm (%) Reduction in flooded areas over 50 cm (%) Reduction in flooded areas over 100 cm (%)
Operational feasibility	Dependence on pumps Flap gate closed duration (h)
Interaction between hydraulic structures and urban functions	Multifunctional spaces Urban continuity
Water quality	Reduction in BOD (%) Emptying time of the reservoir (h)

2.2.1. Hydraulic Characteristics

Three criteria are adopted to assess the hydraulic characteristics dimension: storage volume; polder reservoir free board; and the coordination of actions along the watershed.

The reservoir free board refers to the vertical distance between the maximum water level in the polder reservoir and the elevation of the urbanized area that is protected by the polder. This buffer zone provides additional storage capacity during extreme events, preventing potential failure of the system in cases of greater demands (in a stressful situation). A larger free board enhances the system's resilience by accommodating fluctuations in water levels.

The storage volume refers to the storage capacity needed to support the project aim, while the available free board of the internal reservoir is related to an additional available

storage volume, before failing. Larger volumes indicate greater resilience. A higher potential capacity enhances the system's ability to withstand extreme events, without reaching the protected occupied areas. This is particularly important in the face of future challenges posed by climate change. If the internal reservoir uses almost all the available volume, it has no elasticity to face unforeseen events.

On the other hand, the coordination of actions across the watershed is related to the proper functioning of the polder when considering the whole basin. This is essential to prevent the unintended transfer of increased flow rates downstream. For instance, a levee can accelerate river flows and reduce natural discharges attenuation by eliminating storage capacity along riverine floodplains. If a project ultimately increases discharge volumes downstream, it may undermine resilience, potentially causing flooding in adjacent areas rather than mitigating the problem as a whole. This criterion is measured by the relative difference in discharges of each scenario in comparison to the current situation.

On the contrary, combining the levee with flow attenuation measures can help to dampen flood peaks, protecting downstream areas and increasing dike structural safety but eventually delaying the opening of the levee flap gates. This would possibly lead greater internal storage capacity requirement in the polder system or even a complementary pumping solution. Therefore, ensuring strategic coordination of all watershed interventions is essential for long-term flood resilience.

2.2.2. Flood Mitigation

Flood mitigation was assessed using the Urban Flow Cell Model, MODCEL, a hydrological–hydrodynamic modeling tool, as detailed in Section 2.5. This model was used to calculate water depths over the studied area, considering different scenarios of flood mitigation alternatives for a design rainfall event. For each scenario, flooded areas over 30 cm, 50 cm, and 1 m were determined as reference thresholds for comparison, covering three different aspects that compose the flood mitigation dimension.

These limits were determined based on the following considerations: 30 cm represents the water level that impacts mobility and begins to reach houses, taking into account the construction patterns of the study area. At 50 cm, the house contents and structure begin to experience significant damage, while 1 m is regarded as the critical level, associated with substantial content loss within the house.

2.2.3. Operational Feasibility

Operational feasibility involves assessing the functional performance of the polder infrastructure and its operational demands over time. A resilient project should strike a balance between high efficiency and low operational and maintenance efforts [33]. This balance helps prevent potential system failures and reduces the possibility of losing efficiency over time, which can occur due to inadequate maintenance and management. So, the adopted criteria for this dimension were the dependence on pumps and the flap gate closed duration.

Regarding the flap gate closed duration, the faster the gates can open and start to drain the internal reservoir, the more effectively the system can adapt to extreme, successive, or prolonged flood events, thereby enhancing resilience. According to this criterion, when both pumps and flap gates are present, the beginning of the operation is defined as the moment when either the flap gate or the pumps commence operation—whichever occurs first. This definition is because both mechanisms have the function of returning water to the river.

Regarding the dependence on pumping systems, it is seen that a high reliance on pumps reduces resilience, as a pump failure (due to maintenance issues, power outages, or

mechanical malfunctions) can prevent the proper expected drainage functions. However, if pumps are incorporated as a redundancy measure—meaning they are not essential for standard operation but provide additional capacity to handle extreme events—the overall resilience of the system can increase.

2.2.4. Interaction Between Hydraulic Structures and Urban Functions

The interaction between hydraulic structures and urban functions should align with the principles of multifunctional design. A project must be efficient not only during extreme rainfall events but also must be useful in dry periods. To achieve this, it should incorporate additional urban functions, avoid the underutilization of spaces, and create favorable conditions that allow society to adopt this solution, supporting its long-term sustainability [34]. This approach enhances the city's vitality and aesthetic appeal [35]. Whenever possible, flood mitigation projects should foster a connection between the population and water, promoting environmental education and maintaining ecological functions. This prevents water from being concealed in the urban environment by using barriers or underground systems.

This dimension is defined by two complementary criteria: the presence of multifunctional spaces within the hydraulic solution and their effective access integration, here referred to as urban continuity. In other words, the accessibility of an urban facility in this case reflects its integration into the urban fabric. A multifunctional space, while capable of providing diverse functions, may remain underutilized if it is poorly connected—visually or physically—to the city and isolated from its surroundings.

2.2.5. Water Quality

Water quality is a major concern, especially when sanitation systems fail or do not cover the whole urban area, discharging sewage into local drainage channels and ponds. To prevent health risks and maintain clean reservoirs for visitors, it is crucial to include sanitation measures in the project. All scenarios feature a dry-weather flow collector along the internal channel and reservoirs in the polder, preventing sewage disposal in dry weather, though diluted overflows may happen during rainfall events.

Water quality was evaluated using the QUAL-UFMG model, as detailed in Section 2.5, to analyze pollutant dispersion and overall system performance in the context of sanitation challenges. This aspect is particularly important to the inner reservoirs of the polder—if adequate preventive measures are not implemented, a contaminated reservoir may be located near the urban settlement. In this way, the main sources of sewer discharges were identified, and an analysis of the biochemical oxygen demand (BOD) concentration was carried out to evaluate how it can interfere in the water quality of the proposed reservoirs and how it can be mitigated.

There are many water quality parameters in the specialized literature. However, BOD is one of the most important indicators to evaluate the total quantity of biodegradable organic pollutants in water, being highly used for monitoring water quality in the wastewater treatment process. Besides that, the interaction between storm sewers and waste waters is one of the most significant issues in the city's sanitary context. In this sense, this parameter can be used as a simple approach to evaluate the sewage contamination in a water body.

However, considering that all projects should prevent water quality degradation, and also considering that, during wet weather, diluted sewers will reach the reservoirs, an important design parameter, in this case, refers to the emptying time of the reservoir, reducing the opportunities of contact of the polluted waters with the local community. It is noted that the reservoir emptying time, although used here as a parameter for water

quality, can also serve as a measure of resilience in terms of flood mitigation. Shorter times indicate that the area can store new volumes of water in case of successive rainfall events.

In this sense, the adopted criteria for water quality were the reservoir concentration of BOD and the emptying time of the reservoirs.

2.3. Scenario Construction

The rationale of this approach seeks to compare the effectiveness of different design alternatives with the current situation of the study area, exploring the simulations to offer a general view of the design choices process and offering general guidelines to improve polder design responses, including resilience issues.

The design alternatives initially consider two possible dike positions for a polder protecting an urbanized area from river flooding:

- A dike that is close to the river allows greater urban expansion but may constrict the river channel, impacting fluvial ecology and raising flood levels, which could hinder flap gate operation and increase the risk of overtopping. This choice may require compensatory measures on the opposite riverbank, such as new storage areas and/or enhanced channel conveyance.
- A dike that is farther from the river partially preserves the floodplain functions but limits urban development and reduces internal storage capacity, potentially requiring pumps to manage water levels.

Each option involves trade-offs between urban expansion, flood risk, and ecological impact, requiring careful evaluation.

Therefore, the proposed design alternatives for this framework evaluation are (S1) a dike close to the urban area, (S2) a dike close to the river, and (S3) a dike close to the river with complementary actions to enhance the project's effectiveness. It is anticipated that S3, having learned from the experiences of S1 and S2, will achieve higher scores in the framework assessment. The purpose of these alternatives is to develop practical and effective projects by considering two distinct dike placement options. This approach enables a comprehensive evaluation of the various aspects of each option, facilitating the development of informed design guidelines. We recognize that different solutions can be the most feasible to different urban and hydrographic setups; therefore—and we do not intend to find a single optimal choice—the final result is an assessment framework that can be replicated in different places to find their own local optimum choices.

The scenarios will also be evaluated in current and in stressed climatic conditions, incorporating increased precipitation and mean sea level rise due to climate change to incorporate resilient adaptation aspects in the design assessment. The evaluation of urban resilience to floods must include a timespan assessment, considering the tendency of unpredictable drivers stressing the design standards. For this purpose, a moderate climate change scenario for the year 2100 was considered, predicting a mean sea level rise of 0.5 m and an increase of 20% in precipitation, in alignment with projected values from the IPCC [36]. The purpose is to test how the proposed assessment framework responds to changes in project conditions, rather than to make an exact prediction.

This proposal results in the following scenarios and their variants:

- S0a—current situation;
- S0b—current situation + climate change;
- S1a—dike close to the urban area;
- S1b—dike close to the urban area + climate change;
- S2a—dike close to the river;
- S2b—dike close to the river + climate change;
- S3a—dike close to the river with complementary measures;

- S3b—dike close to the river with complementary measures + climate change.

It should be noted that introducing climate change can bring important uncertainties to the assessment process. In this work, intending to show and validate the method, we defined a single climate change scenario. However, to support a practical decision, different climate change scenarios could have been proposed, in order to build a range of possible quantitative prognosis, as outputs of the method, but using the same assessment framework.

2.4. Evaluation Framework

The resilience criteria defined in Section 2.2 were normalized to simplify comparison through different scenarios. However, some indicators are numerical, while others are non-numerical. This is important because the normalization function for each criterion classification will be different.

The normalization of numerical indicators will be given by a linear relation defined according to the maximum and minimum values obtained for the different scenarios. The maximum values will receive the normalized value of 1, while the minimum will be equal to 0. Intermediate values will occupy the scale ranging from 0 to 1. On the other hand, the non-numerical criteria will be translated by discrete values in which 1 means it "fully meets the criterion", 0.5 means it "partially meets the criterion", and 0 means it "does not meet the criterion". This approach adopted for non-numerical criteria seeks to translate a qualitative characteristic into a numerical value to facilitate comparisons between scenarios while keeping the same scale used for numerical criteria. In short, this choice offers a middle point, a positive and a negative evaluation.

By following this normalization process, the intervention scenario that possesses the highest value in the sum of all criteria is considered to meet the optimum solution. Table 2 shows the adopted criteria, its classifications, and the normalized function.

Table 2. Normalization function of each criterion.

Criteria Classification	Criteria	Maximum Normalized Value = 1	Intermediate Normalized Value = x	Minimum Normalized Value = 0
Numerical	Polder reservoir free board (m) Storage volume (m^3) Coordination of action along the watershed (m^3/s) Reduction in flooded areas over 30 cm (%) Reduction in flooded areas over 50 cm (%) Reduction in flooded areas over 100 cm (%) Reduction in BOD (%) Flap Gate Closed Duration (h) Emptying time of the reservoir (h)	Maximum criteria value of all scenarios	Value given by a linear relation defined according to the maximum and minimum values obtained among all the scenarios	Minimum criteria value of all scenarios

Table 2. *Cont.*

		Maximum Normalized Value = 1	Intermediate Normalized Value = 0.5	Minimum Normalized Value = 0
Non-numerical	Dependence on pumps	There is no dependence on pumping to the correct functioning of the polder, but pumps are considered to improve the resilience of the system during critical events	There is no dependence on pumping to the correct functioning of the polder	There is a dependence on pumping to the correct functioning of the polder
	Multifunctional spaces	The project incorporates additional urban functions to favor its integration with the city demands which supports its long-term sustainability	The project has some urban functions, other than those for flood mitigation, but there is a poor integration with the city's demands	The project does not incorporate any urban functions other than those for flood mitigation
	Urban continuity	The location of the dike favors the integration of the urban area with the park	The location of the dike separates the urban area from the park, fragmenting the territory and hindering its integration with the city	There is no connection between the urban areas and the parks

2.5. Modeling and Simulation Tools

2.5.1. MODCEL

The flood simulation is evaluated with the support of MODCEL, a hydrologic–hydrodynamic model tailored to map floods in urban areas [37]. It is based on the concept of flow cells, where the watershed is systematically represented through integrated small compartments, simulating urban and natural landscapes. It models surface flows, rivers, and underground storm drains using a pseudo-three-dimensional method, linking the two horizontal flow planes vertically.

The flow cells provide storage areas for mass balance while composing a looped flow network. They are based on predefined types (channels, storm drains, urban plains, reservoirs, and natural plains, among others). They are interconnected by diverse hydraulic links that perform hydrodynamic functions, among which we find open channel flows, storm drains, weirs, orifice, inlets, pumps, and flap gates, among others. Depending on the type of cells and connections, different coefficients and physical information are set in the model configuration.

The simulation results yield detailed insights, including the water depth at each individual cell, as well as discharge rates and flow velocities between adjacent cells, providing a comprehensive understanding of the hydrodynamic behavior of the system.

It is important to point out that it is the responsibility of the modeler to interpret terrain features to provide synthetic geometrical information characterizing each cell and each connection between cells to the model. This means that MODCEL cannot function by a blind, automatic application of geomatics tools requiring a comprehensive understanding of the system behavior [37]. There is a preliminary conceptual and interpretative phase that is nearly connected to an adequate model representation. It is also important to highlight that the model choice can vary according to the modelers' preferences or case characteristics. A different choice does not invalidate the proposed framework.

The rainfall events used in the hydrodynamic simulations were calculated for a 25-year return period, which is the design standard for major drainage projects in Brazil. Additionally, the model domain receives a downstream boundary condition representing tidal variations—in this case, a spring tide condition was used to define a critical condition.

2.5.2. QUAL-UFMG

Water quality simulations were conducted using the QUAL-UFMG model, developed by Von Sperling [38] based on adaptations of the QUAL2E model, created by the U.S. Environmental Protection Agency (USEPA) [39]. The main simplifications of QUAL-UFMG compared to QUAL2E are the exclusion of algae modeling and all its interactions with other constituents, the omission of longitudinal dispersion, and the use of numerical integration via the Euler method.

The model consists of four spreadsheets: (1) a sheet containing the formulas and typical coefficients of the equations used in the model; (2) a sheet that allows the user to detail the unifilar diagram of the modeled river stretch; (3) a sheet dedicated to modeling the main river, performing calculations, and presenting results; and (4) a sheet used for modeling tributaries of the main river, with results transferred to the previous spreadsheet. Multiple spreadsheets can be created to model different tributaries.

QUAL-UFMG simulates several water quality constituents, assuming that they are fully mixed in the flow. During the simulation, it is possible to include discharge points (industrial and domestic loads), withdrawals, tributary inflows, and incremental flows. The modeled constituents include BOD, dissolved oxygen (DO), total nitrogen and its fractions (organic, ammoniacal, nitrite, and nitrate), total phosphorus and its fractions (organic and inorganic), and thermotolerant coliforms. The results obtained are concentration profile graphs of these constituents along the watercourse, enabling the analysis of self-purification and comparison with current environmental standards.

The main limitations of this model refer to its inability to represent algae interactions with other constituents, which may be important for the simulation of lentic environments; the non-representation of longitudinal dispersion; and the necessity of short integration steps to proceed with all calculations.

As said previously, the water quality modeling was made considering only BOD, taken as representative of the sewer pollution. However, other parameters, and even other simulation models can be used to support this assessment. The general framework is not tied to a specific modeling choice.

3. Study Area

The study area is located in the Piraquê-Cabuçu River Watershed, specifically in its lower reaches, within the Jardim Maravilha neighborhood in Rio de Janeiro's western zone, in Brazil. The Piraquê-Cabuçu River originates from the Pedra Branca Massif in its upstream areas, flowing through 12 km with a draining catchment of 108 km^2 before outflowing into the Sepetiba Bay.

Historically, the western portion of Rio de Janeiro, including this watershed, served as an agricultural and industrial hub from the 15th to the 18th centuries. However, the second half of the 20th century saw significant urbanization in this region, spurred by improved road access and real estate speculation. More recently, in the 21st century, major government initiatives aimed at preparing for international events, such as the 2014 FIFA World Cup and the 2016 Olympic Games, led to substantial transportation investments and further accelerated the region's development. Despite this growth, public investment in basic urban infrastructure has remained insufficient, leaving many residents—who face low socio-economic conditions—without essential services.

Jardim Maravilha is an urban subdivision located in the district of Guaratiba, within this watershed, with a population of over 32,000 inhabitants. This site was selected due to its pronounced vulnerability to urban flooding, driven by factors such as low terrain elevations and mild slopes, high levels of social vulnerability, and extensive urban sprawling. These conditions underscore the escalating risks faced by the local population and the increasing challenges posed by soil sealing and future climate changes. Figure 1 shows the location of the Piraquê-Cabuçu Watershed in Rio de Janeiro/Brazil and highlights Jardim Maravilha.

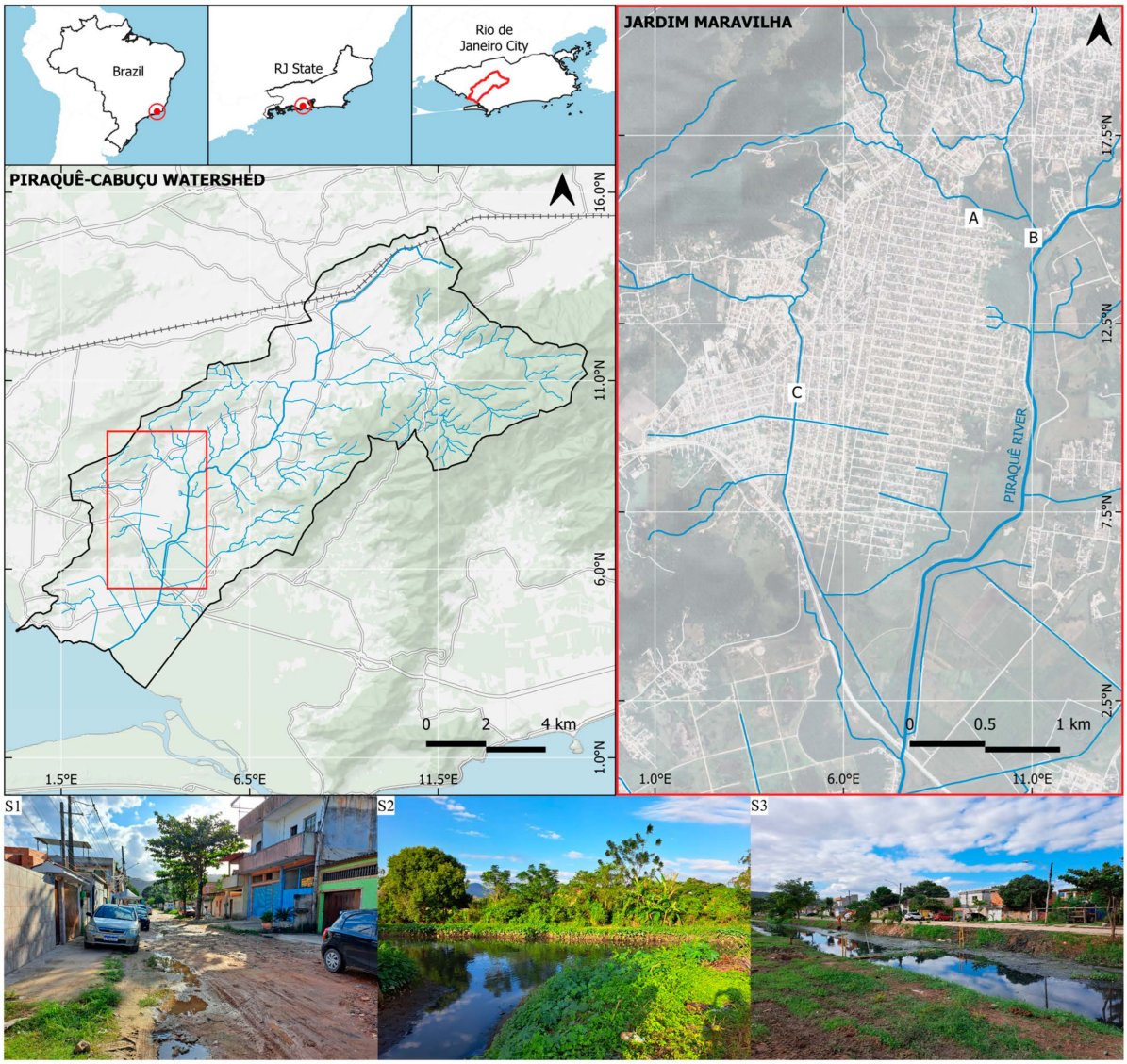


Figure 1. Location of the study area at different scales: in Brazil, in the state and city of Rio de Janeiro, and in the Piraquê-Cabuçu watershed, where Jardim Maravilha is located. Bottom images show photos of distinct points in the area, taken by the author.

4. Results

4.1. Design Alternatives

The three simulation scenarios incorporate a polder system to protect the Jardim Maravilha neighborhood, but they fundamentally differ in dike placement, leading to distinct solutions. They are all illustrated in Figure 2.

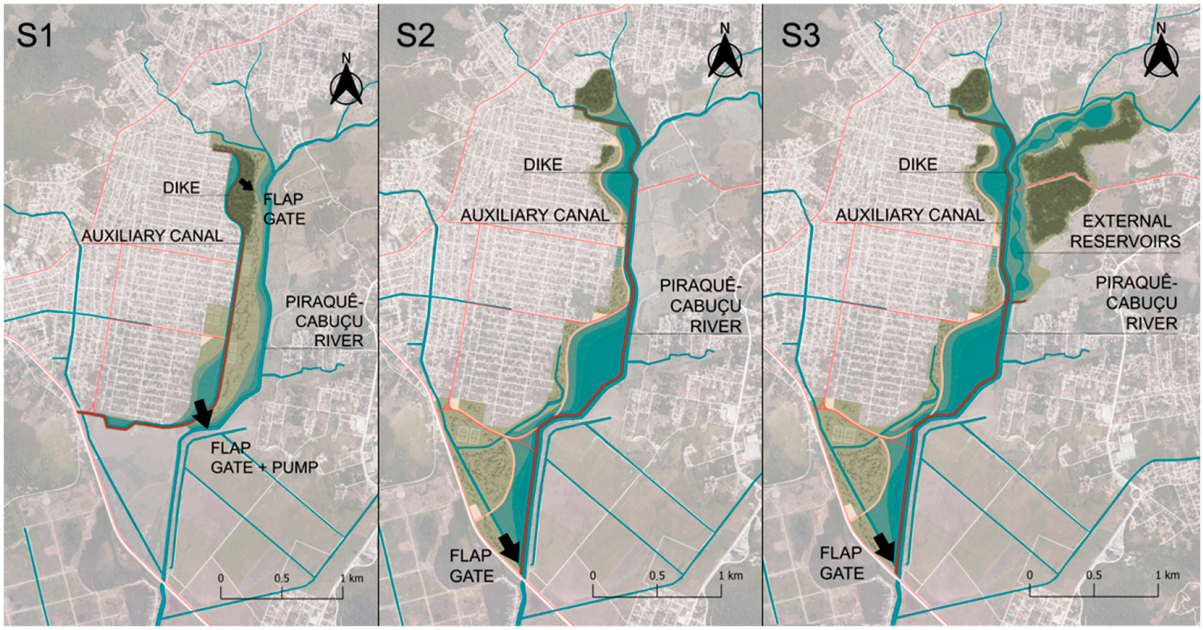


Figure 2. Proposed interventions for Jardim Maravilha in scenarios S1, S2 and S3.

In S1, the dike is positioned close to the urbanized area rather than near the river, greatly preserving the river's natural functions by maintaining transversal connections to both banks (although limiting the river flooding on the right banks, to protect the Jardim Maravilha neighborhood, settled in low-elevated and mild-slope areas). The left riverbank outside the protecting dike remains natural and can serve as an overflow area during heavy rainfall events. This space also has the potential to function as a fluvial park, benefiting from its connection to the river—even though it remains visually separated from the urban area due to the presence of the dike.

This configuration results in limited open space within the polder system, reducing the available internal water storage capacity. Inside the polder, an auxiliary canal runs parallel to the dike, channeling rainwater flows from Jardim Maravilha. There are three internal reservoirs connected to this canal, designed as floodable parks, providing a total area of 293,794 m^2 with 225,503 m^3 of internal storage. Since this capacity is insufficient (given the limited space), the system heavily relies on pumping to manage excess water. This solution features two pumps positioned adjacent to the internal reservoirs, with the main outlet consisting of three flap gates, each measuring 1.5 m in diameter.

In S2 and S3, the dike is positioned directly along the riverbank, eliminating the need for pumping by maximizing internal storage capacity within the polder, which spans approximately 858,200 m^2 and holds a volume of 943,763 m^3 after excavation to improve storage. This area is designed as a floodable park, incorporating multiple reservoirs also connected to an auxiliary canal. The outlet of the reservoirs, similarly to S1, is composed of three flap gates, each measuring 1.5 m diameter, but with no support from pumps. In these scenarios, the right bank of the Piraquê-Cabuçu River is completely constrained by the dike, allowing overflow only on the left bank.

To compensate for river constriction on one of its banks, S3 integrates additional measures, such as increasing the external storage capacity and retention (on the left bank) and dredging the main channel. Therefore, it corresponds to a solution similar to S2 but with additional measures for project optimization. The external reservoir covers an area of 244,500 m^2, with a storage capacity of 342,350 m^3 and an average depth of 1.40 m. Additionally, the river course dredging extends over 13.2 km. These interventions ensure that despite the modified riverbank, the system still supports the damping of part of the

peak flows. Besides that, dredging, in this case, recovers part of the natural discharge capacity lost with siltation due to lowland effects and tidal backwater effects. In this case, the increased conveyance can probably allow a faster opening in the flap gate operation without compromising downstream due to the increased storage capacity of the river's left banks. These suppositions will be tested mathematically with the hydrodynamic modeling process, intending to reach a better project compromise

In all scenarios, the dike can be integrated as a landscape feature, accommodating cycle paths and pedestrian walkways. Although the dike obstructs the direct view of the river, it can remain accessible—both physically and visually—by encouraging people to walk along its crest and cross designated paths.

4.2. Model Calibration

The MODCEL model was calibrated using data from an intense rainfall event in 2021, recorded at 15 min intervals by the three nearest Alerta Rio rainfall gauges: Bangu, Campo Grande, and Guaratiba. The calibration aimed to reproduce the flood map reported by the municipality, taking into account both the observed tide levels in Sepetiba Bay during the event and the hydrologic response of the Piraquê-Cabuçu River watershed. Tide data were obtained from the Directorate of Hydrography and Navigation (DHN), which provides measurements from the Port of Itaguaí, located within Sepetiba Bay. Following calibration, the design rainfall for scenario simulations was defined using an IDF (intensity–duration–frequency) curve based on data from the same three gauges, adjusted for a 25-year return period [40].

4.3. Long-Term Resilience Evaluation

4.3.1. Hydraulic Characteristics

In S1a, the freeboard of the polder reservoir reaches only 0.25 m, whereas in S2a and S3, it reaches 0.42 and 0.43 m, respectively. This indicates greater resilience in S2a and S3a, which could accommodate a larger volume in extreme events exceeding the reference rainfall simulated in the project. After the normalization function, S1 assumes the value of 0 while S2 and S3 assume 0.9 and 1, respectively. When simulating future climatic conditions, all scenarios show a reduction in freeboard, but all projects remain functional—there is no overflow of the internal reservoirs to the protected urbanized areas. In S1b, the freeboard decreases to 0.07 m, representing a reduction of over 86% compared to S1a. In S2b it reduces to 0.24 and in S3b it reduces to 0.25. After normalization, the scores for climatic conditions remain the same—that is, in stressed conditions, the scenarios behave similarly to their previous operation results, but they lose part of their safety buffer, with a negative highlight to S1, which almost reaches its limit.

Regarding storage capacity, S1a demonstrates the least resilience, with only 193,010 m^3 of available volume. In contrast, S2a provides 526,775 m^3 and S3a offers 520,833 m^3 of available volume—both approximately 2.7 times larger than S1a. It is important to note that this evaluation considers only the internal volume of the polder and not additional external storage—this is why the volumes in S2 and S3 are similar. After normalization, S1 scores 0, indicating the least favorable solution for this criterion, while S2a and S3a, being the optimal solution, both score 1. When under climate change effects, rising sea levels create a higher dead volume in reservoirs, reducing the available usable active storage. This occurs because the reservoirs can no longer be fully empty with higher mean sea levels. While all scenarios experience a reduction in volume, their proportional relationship remains unchanged. As a result, S1b scores 0, reflecting the least favorable option, while S2b and S3b both score 1, maintaining their status as similar optimal solutions.

In terms of coordination along the watershed, which is associated with the transfer of peak discharges to downstream areas, S2a demonstrates the greatest water transfer, with a 13% increase compared to S0a. The most favorable scenario for this criterion is S3a, with an 8% increase, while S1a shows an 11% increase. The respective scores for S1a, S2a, and S3a are 0.5, 0, and 1. Under climate change conditions, S1b increases by 20%, S2b by 28%, and S3b by 17% compared to S0a. After normalization, S1b scores 0.8, S2b remains the least favorable with a score of 0, and S3b retains its position as the most favorable with a score of 1. In this case, the artificial left bank storage provided in S3 shows a higher efficiency compared to the natural remaining right bank storage of S1.

4.3.2. Flood Mitigation

All projects effectively mitigate flooding, significantly reducing flood depths, as shown in Figure 3. In the current scenario (S0a), a large area—approximately 1,373,213 m^2—is subjected to water depths exceeding 1 m. In contrast, all three project scenarios (S1a, S1b, S2a, S2b, S3a, and S3b), show a substantial decrease in flood depths within urbanized areas, highlighting their effectiveness. Even under stressed climatic conditions (S1b, S2b and S3b), water depths are reduced compared to S0a, demonstrating the long-term efficiency of the projects. Figure 4 illustrates the difference in water depths, comparing the current situation with each project scenario. Darker shades of green indicate a greater reduction in flood depths.

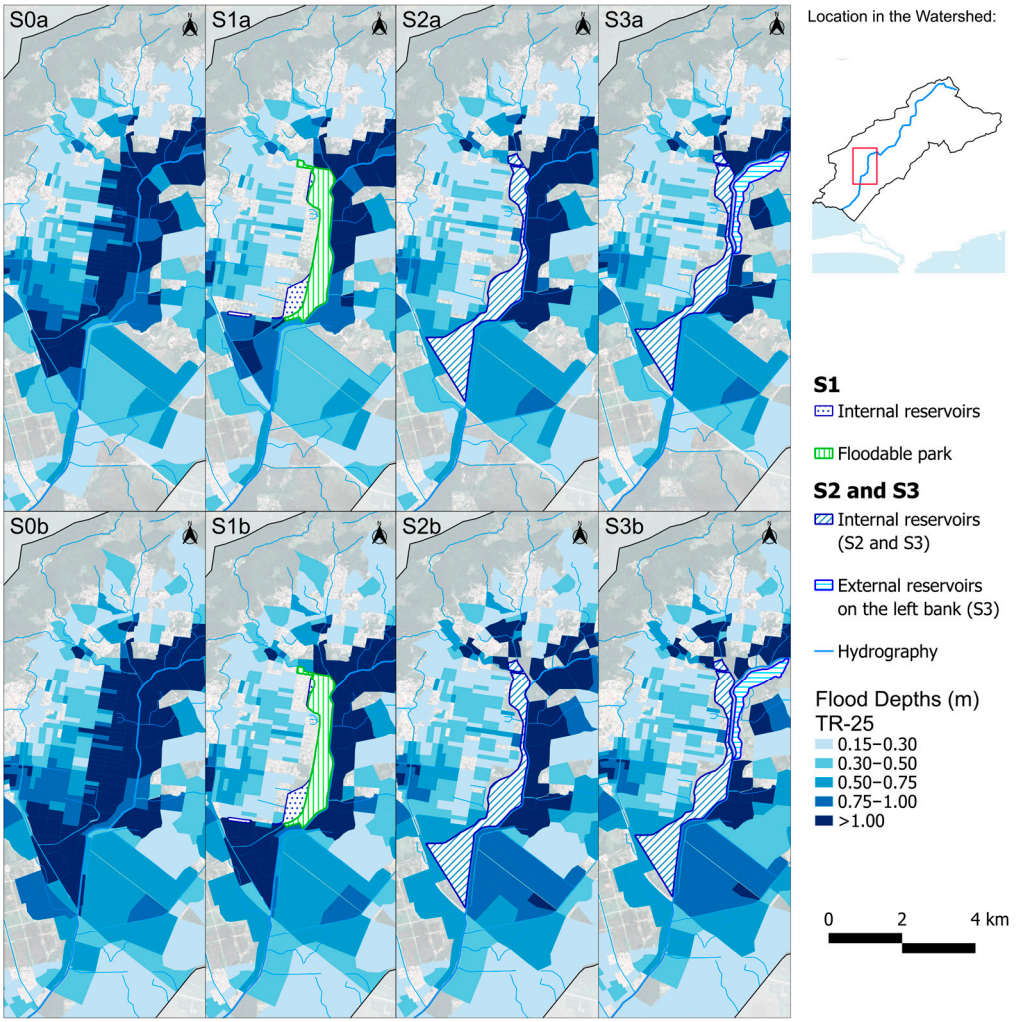


Figure 3. Water depths in Jardim Maravilha for all scenarios (S0a, S1a, S2a, S3a, S0b, S1b, S2b and S3b).

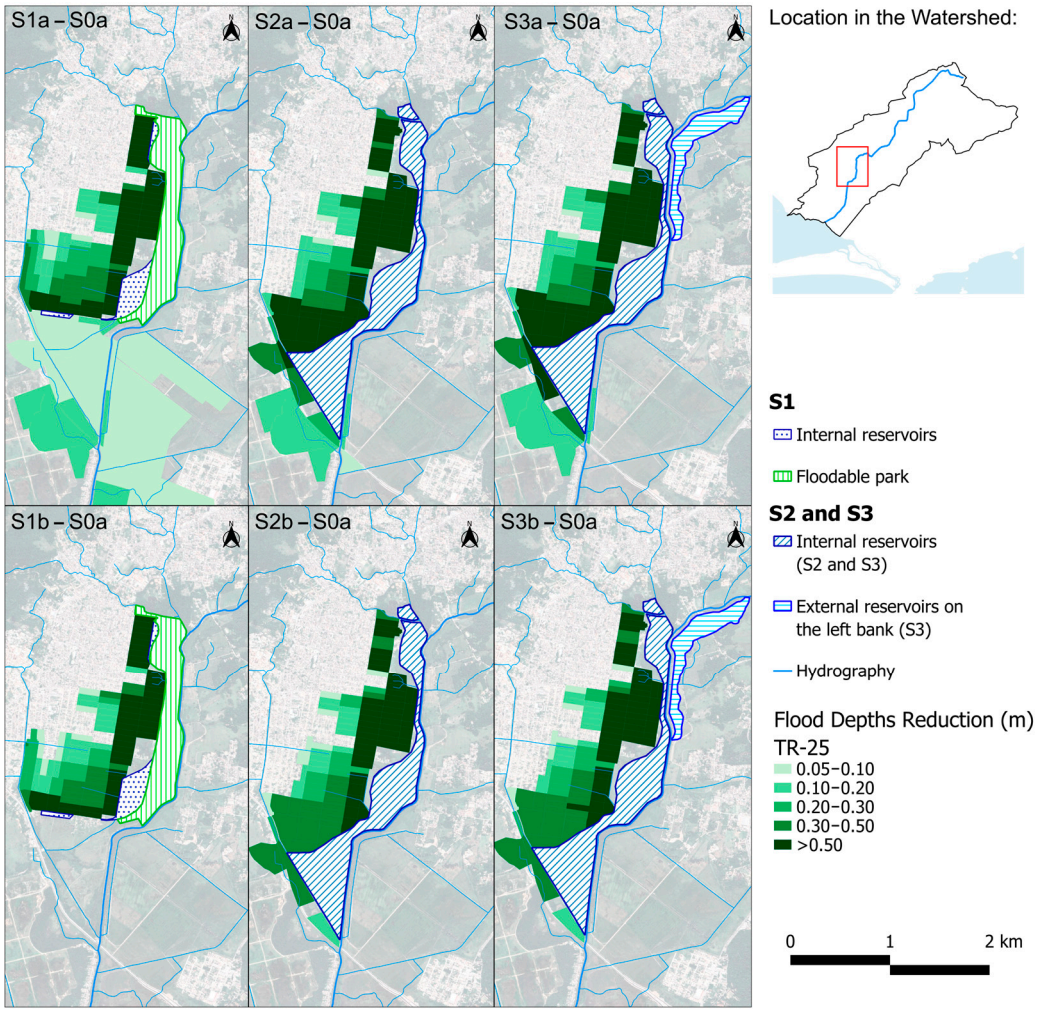


Figure 4. Water depths differences in Jardim Maravilha for all scenarios. For instance, S1a–S0a represents the change in water depths between scenarios S1a and S0a; similar comparisons apply to the other scenario pairs.

This analysis considered the reduction in water depths in urbanized areas, including Jardim Maravilha and the urbanized areas downstream. Water depths exceeding 30 cm were able to enter the local households. Scenarios S1a and S3a reached a 33% reduction in the area affected by such depths, while S2a saw a reduction of 32%. Water depths surpassing 50 cm can begin to threaten the structural integrity of buildings. The reductions in this case were 58%, 59%, and 60%, respectively, for S1a, S2a, and S3a.

In the most extreme cases of flooding above 1 m, S1a experiences an 82% reduction while S2a and S3a both reach 77% reduction. Since all projects are very close in efficiency and do not fail in the simulations, their attributed score is 1.

Under stressed climatic conditions (scenarios identified by variant b), the reduction in water depths is less pronounced compared to the current conditions (variant a), but water depths remain lower than in S0a. For areas with water depths exceeding 30 cm, S1b and S3b show reductions of 16% and S2b shows reductions of 15%. For flooded areas over 50 cm, S1b, S2b and S3b reduce water depths by 45%, 51% and 53%, respectively. For areas with depths over 100 cm, all climate change scenarios achieve a 54% reduction. Since all projects remain effective, the attributed score remains 1 for all scenarios.

4.3.3. Operational Feasibility

In terms of operational efforts, none of the scenarios assume the optimal setup, which would include a pumping system as a backup. Instead, S1 depends on pumping systems, while S2 and S3 operate solely by gravity, without incorporating redundant pumping systems. Therefore, for this criterion, S1 is assigned a value of 0, while both S2 and S3 are assigned a value of 0.5. This also applies to climate change variants. If climate change were able to make flood protection fail, pumping stations could be used to correct this issue, ensuring better protection in the present (with current redundancy) and assuming a dependency in the future. But this was not necessary in this case.

In terms of flap gate closing duration, S1a requires the shortest time, with the pumping system starting operation 4.25 h after the simulation begins. S2a and S3a take a significantly longer time, requiring 14.75 and 14.5 h, respectively. After normalization, S1a scores 1 while the others score 0. Under stressed climatic conditions, S1b maintains the time of 4.25 h, while in S2b and S3b, the time is prolonged to 17.5 and 17.25 h, respectively. The scores under these conditions remain unchanged from those under current conditions.

4.3.4. Interaction Between Hydraulic Structures and Urban Functions

The assessment of how well the solutions integrate into the urban fabric was conducted by scoring two criteria assessed subjectively: multifunctional spaces and urban continuity.

The multifunctional space criterion refers to the incorporation of multifunctional solutions within the project scenarios. The three design scenarios offer plenty of available multifunctional spaces: while S1 incorporates a fluvial park, S2 and S3 include floodable parks within the polder area. However, regarding the integration of these spaces, the placement of the dike significantly influences the landscape, reshaping the relationship between the urban fabric, the parks, and the river, as illustrated in Figure 5.

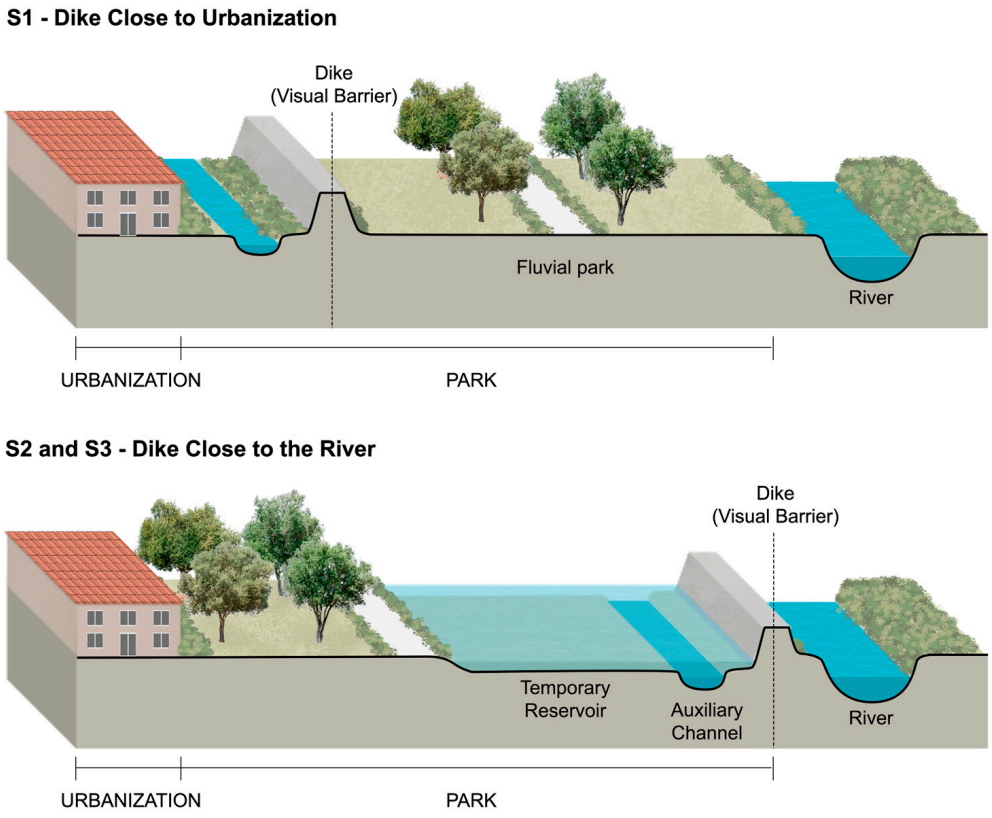


Figure 5. Schematic sections of the dike placement solutions.

Although the dike can serve as a landscape feature—incorporating walkways, cycle paths, and bridges to connect different areas—it still acts as both a visual and physical barrier. When the dike is positioned closer to the urbanized area (as in S1), the park can maintain a connection to the river, but this configuration creates a separation between the park, the river, and the urbanized zone. As a result, people in the urban area lose visual and physical access to both the park and the river, requiring them to cross the dike to reach these spaces. This setup may also lead to reduced safety in the park, as its remoteness could make it less livable and monitored. For this reason, S1 received a score of 0.5 for space integration.

Conversely, when the dike is placed closer to the river (as in S2 and S3), the park becomes disconnected from the river and is instead linked to the auxiliary channel and internal reservoirs of the polder, meaning it no longer functions as a true riverside park. However, this arrangement positions the park closer to the urbanized area, improving accessibility. While the dike still obstructs the population's view of the river from the city (a feature common to all scenarios), its placement in S2 and S3 ensures that the park remains visually accessible from the urban area, fostering a stronger connection between the community and the green space. This better integration earned S2 and S3 a score of 1 for space integration.

This applies equally to both current conditions and climate change variants.

4.3.5. Water Quality

For the water quality model calibration, the simulation results were compared with the data observed at the water quality monitoring station located on the Piraquê/Cabuçu River, which has systematic measurements between the years 2012 and 2023. It is important to highlight that in this study, water quality is measured solely in terms of BOD, and the observed data refer to the minimum and maximum concentrations, as well as the 25%, 50%, and 75% percentiles of BOD calculated from the historical data available at the monitoring station.

The determination of local sewage flow rates was based on public data for the local population, which defined the daily water consumption per capita (148.2 L/cap/day), the return coefficient (0.8), and the percentage of sewage that is neither collected nor treated (14.9%).

These data were loaded into QUAL-UFMG to determine the BOD concentration for the studied river. It is observed that the modeled BOD value was equal to 22 mg/L, which is between the first and third quartile of BOD calculated from the historical data available at the monitoring station. This result, showed in Table 3, indicates a good fit between the model and the reality. It should be mentioned that these high values of BOD concentration are influenced by the intense urbanized area upstream the studied area that faces issues with a proper sanitation.

Table 3. Comparison between observed data and results given by the QUAL-UFMG model.

Reference		BOD Concentrations (mg/L)
Water quality station (00RJ12PR0000)	Maximum concentration	33
	Third quartile of BOD concentration (75%)	25
	Second quartile of BOD concentration (50%)	21
	First quartile of BOD concentration (25%)	18
	Minimum concentration	12
QUAL-UFMG	$C_{simulated}$	22

To protect the reservoirs from potential discharges of sewage, a dry-weather flow interceptor is proposed to collect the sewage flowing in the storm drains during dry weather conditions and direct them to a wastewater treatment plan (WWTP). The layout of this interceptor can be seen in Figure 6. It should be emphasized, however, that this alternative only covers the region near Jardim Maravilha that contributes directly to the reservoirs. This means that this alternative does not aim to replace the implementation of an absolute separator sewage system for the whole neighborhood but rather to provide a redundant solution to the problem of water body pollution by sewage in a short time frame, bringing greater resilience to the local basin sanitation.

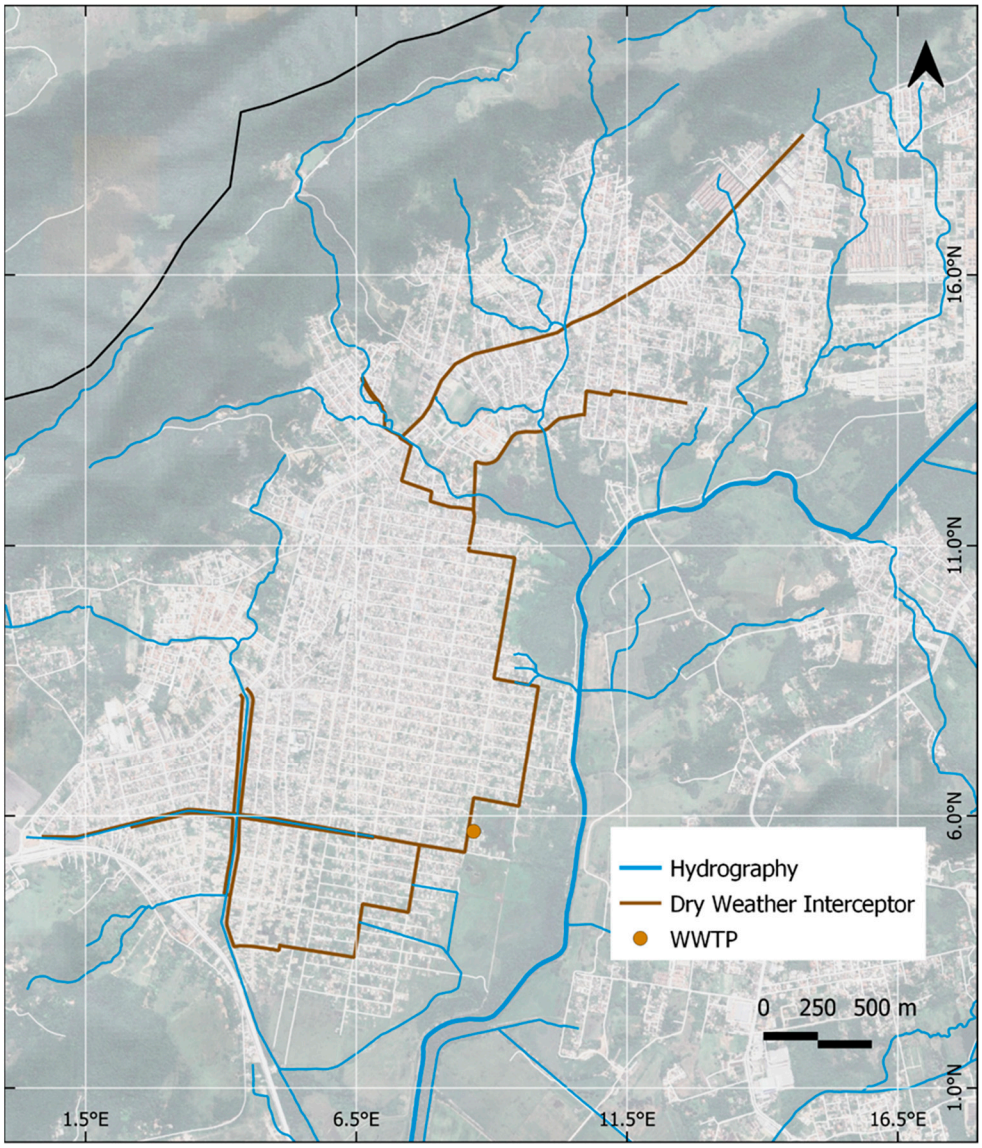


Figure 6. Layout of the dry-weather interceptor.

Considering only the area where the dry-weather flow interceptor is placed, it is observed that about 55% of the BOD load that would have previously reached the proposed reservoirs can be captured and sent to a WWTP, thus contributing to better preservation of water quality. As a result, the concentration of BOD in the reservoirs in S1a is 5.0 mg/L; in S2a, 1.8 mg/L; and S3a, 1.8 mg/L. When considering climate change, the water volume in each scenario increases, resulting in greater dilution. In this way, the concentration of BOD in the reservoirs in S1b is 4.5 mg/L; in S2b, 1.6 mg/L; and S3b, 1.6 mg/L.

It is observed that the values found for the BOD concentration in all scenarios, both with and without considering climate changes, are within the variation range of urban stormwater runoff concentration, which is from 0.67 to 10.74 mg/L, with a mean of 2.92 mg/L, according to [41].

Thus, it can be concluded that the interceptor design effectively fulfilled its role in safeguarding the quality of the water stored in the reservoir. Consequently, despite minor numerical variations, all scenarios demonstrate water quality within acceptable safety limits, and as such, after normalization, all are assigned the value of 1.

To calculate the emptying time of the reservoirs, the elevation of 0.8 was considered as the reference limit (for all scenarios). This choice represents a range where there is no direct dependence on the tide level (i.e., there may be backwater effects, but the tide does not directly close the gate at this level). Therefore, the analysis focuses on the gate closure due to flooding rather than direct tidal influence. Consequently, the emptying time of the reservoirs is defined as the time between the maximum water level reached in the reservoir and the water level dropping to the 0.8 threshold. S2a is the scenario that has the shortest time for emptying the reservoir (around 8.5 h). S1a and S3a take the longest time (9 h). After the normalization function, S2a assumes the value of 1, while S1a and S3a score 0. Under stressed climatic conditions, S2b and S3b suffer greater increases in the emptying time of the reservoir: S2b and S3b take 16.5 and 18 h to empty, respectively, while S1b takes only 11.25 h. In this case, S1a assumes the score of 1; S3b, of 0; and S2b, of 0.2. It must be remembered that S1a and S1b have the least available volume and the support of pumping.

4.3.6. Final Evaluation Matrix

The final evaluation matrix integrates all the criteria and assigns a score to each scenario based on every parameter. This approach facilitates clear visualization and straightforward interpretation, allowing for easy identification of the best- and worst-performing scenarios across the analyzed dimensions. The combined analysis of all these criteria corresponds to a comprehensive assessment of functional aspects and also long-term resilience to floods. A summary of each criterion evaluation and its normalized value is presented in Table 4, while the final evaluation matrixes are presented in Table 5 (for current climatic conditions) and Table 6 (for future stressed climatic conditions). The colors in Tables 5 and 6 are used to enhance readability and make interpretation more intuitive. For each row, the best result is highlighted in green, the worst in red, and the intermediate value in yellow.

Each criterion indicates better performance for different scenarios. Therefore, no single scenario outperforms the others across all criteria. This implies that the decision-making process should involve balancing priorities and will clearly vary from case to case and design alternative characteristics. This result was expected, and the proposed framework does not intend to indicate "the best" solution. The main aim of this framework is to highlight the various facets of possible design alternatives, giving the opportunity for the project designer to consider and explore all the significant possibilities.

In summary, for the analyzed case and considering the hydraulic characteristics, scenarios S2a and S3a have greater storage capacity due to their dikes being positioned near the riverbanks. Scenario S1a shows less flow transfer increase, making it more efficient in watershed coordination. All scenarios effectively mitigate floods in a similar way (this was a basic established design condition). Operationally, S1a is the least resilient due to its reliance on a pumping system, while S2a and S3a operate by gravity, reducing failure risks and maintenance. However, in S1, the pumps operate faster than the flap gates in S2 and S3, which is an advantage for S1. Water quality shows similar practical results (in terms pollution threat), but S1a has higher BOD concentrations, because of its lower volume, but

it compensates for them with shorter reservoir emptying time. Overall, S3a seems to be slightly better, but the final choice will depend on project priorities.

Table 4. Summary of each criterion evaluation and its normalized value.

Classification	Criteria	Scenario Evaluation					
		Project Scenario 1		Project Scenario 2		Project Scenario 3	
		A	B	A	B	A	B
Numerical	Polder reservoir free board (m)	0.25	0.07	0.42	0.24	0.43	0.25
	Storage volume (m^3)	193,010	172,644	526,775	485,438	520,833	483,731
	Coordination of action along the watershed (%)	11	20	13	20	8	17
	Reduction in flooded areas over 30 cm (%)	33	16	32	15	33	16
	Reduction in flooded areas over 50 cm (%)	58	45	59	51	60	53
	Reduction in flooded areas over 100 cm (%)	82	54	77	54	77	54
	Flap gate closed duration (h)	4.25	4.25	14.75	17.5	14.5	17.25
	Reservoir concentration of ODB (mg/L)	5.0	4.5	1.8	1.6	1.8	1.6
	Emptying time of the reservoir (h)	9	11.25	8.5	16.75	9	18
Non-numerical	Dependence of pumps	There is pump dependence		There is no pump dependence, nor are there any pumps to increase resilience		There is no pump dependence, nor are there any pumps to increase resilience	
	Multifunctional space	Plenty multifunctional areas		Plenty multifunctional areas		Plenty multifunctional areas	
	Park accessibility	Restricted access due to the presence of the dike		Fully accessible		Fully accessible	

Table 5. Final evaluation matrix for current conditions.

Dimension	Criteria	S1a	S2a	S3a
Hydraulic characteristics	Polder reservoir free board (m)	0	0.9	1
	Storage volume (m^3)	0	1	1
Flood mitigation	Coordination along the watershed (%)	0.5	0	1
	Reduction in flooded areas over 30 cm (%)	1	1	1
	Reduction of flooded areas over 50 cm (%)	1	1	1
	Reduction of flooded areas over 100 cm (%)	1	1	1
Operational feasibility	Dependence on pumps	0	0.5	0.5
	Flap gate closed duration (h)	1	0	0
Interaction between hydraulic structures and urban functions	Multifunctional spaces	1	1	1
	Urban continuity	0.5	1	1
Water quality	Reservoir concentration of BOD (mg/L)	1	1	1
	Emptying time of the reservoir (h)	0	1	0

These results highlight opportunities to optimize project designs and further improve their evaluation scores. The proposed method can serve as an iterative design tool, where initial evaluations can be used to inform project adjustments before reassessment. For instance, Scenario S3 could incorporate a redundant pumping system to enhance its score, though such modifications would need to balance technical benefits against constraints like operational budget considerations. However, complete optimization of all factors may not be feasible due to inherent trade-offs between different design choices. A clear example

is the relationship between reservoir volume and empty time: while increasing available storage capacity (as in S3) improves polder resistance, it simultaneously increases potential exposure to polluted water during extended retention periods. Such trade-offs highlight the critical need for sound decision-making judgment to prioritize among competing objectives based on the specific requirements of the project.

Table 6. Final evaluation matrix for future climatic conditions.

Dimension	Criteria	S1b	S2b	S3b
Hydraulic characteristics	Polder reservoir free board (m)	0	0.9	1
	Storage volume (m^3)	0	1	1
	Coordination along the watershed (%)	0.8	0	1
Flood mitigation	Reduction in flooded areas over 30 cm (%)	1	1	1
	Reduction in flooded areas over 50 cm (%)	1	1	1
	Reduction in flooded areas over 100 cm (%)	1	1	1
Operational feasibility	Dependence on pumps	0	0.5	0.5
	Flap gate closed duration (h)	1	0	0
Interaction between hydraulic structures and urban functions	Multifunctional spaces	1	1	1
	Urban continuity	0.5	1	1
Water quality	Reservoir concentration of BOD (mg/L)	1	1	1
	Emptying time of the reservoir (h)	1	0.2	0

The projects experience a loss in efficiency under stressed climatic conditions. However, the relative performance among the three scenarios remains largely consistent. This means that the best-performing scenarios for each criterion in the original assessment continue to outperform the others, even under stressed conditions. This is something interesting—in this case, the most critical change refers to mean sea level rise, but the proposed design alternatives have sufficient internal polder volumes to face the climate change threat, isolating the protected area from the worse river conditions, with a dike that sustains its functionality over time.

Table 7 presents the percentage loss in efficiency for each scenario, comparing the stressed conditions versions ("b" variants) with the current condition alternatives ("a" variants). Since the table measures efficiency loss, a higher percentage indicates worse performance. The color gradient in the table highlights the projects with the most significant losses in efficiency (darker red). Note that for one specific criterion—concentration of BOD—there is an increase in efficiency due to higher water flow rates acting to dilute BOD. As a result, the percentage loss in efficiency is expressed as a negative value.

The polder reservoir freeboard and storage volume are significantly reduced in S1 compared to the other scenarios. This is probably the most significant result, meaning that in terms of resilience, S1b is near its limits and shows less resilience than the other choices. Regarding flood mitigation, the loss in efficiency is more pronounced in S1 and the least significant in S3. However, the flap gate closed duration does not increase in S1 and increases by nearly 18% in the other scenarios. Regarding the concentration of BOD, all scenarios show improvement, but S2 and S3 perform slightly better than S1. However, this is a marginal gain from receiving greater rainfall and does not effectively come from a design choice. The emptying time of the reservoir experiences a greater increase in S2b and S3b than in S1b, since the latter has a pumping system. Figure 7 shows the difference in water depths—specifically, the increase in these water depths—for each scenario, comparing the stressed-condition alternative ("b") to the current-condition alternative ("a"). From this comparison, S1 sustains the internal polder results with greater efficiency.

Table 7. Reduction in efficiency under future climate conditions.

Dimension	Criteria	S1	S2	S3
Hydraulic characteristics	Polder reservoir free board (m)	72.00%	35.71%	37.21%
	Storage volume (m^3)	10.55%	7.85%	7.12%
	Coordination along the watershed (m^3/s)	8.84%	14.88%	8.88%
Flood mitigation	Reduction in flooded areas over 30 cm (%)	51.52%	53.13%	51.52%
	Reduction in flooded areas over 50 cm (%)	22.41%	13.56%	11.67%
	Reduction in flooded areas over 100 cm (%)	34.15%	29.87%	29.87%
Operational feasibility	Dependence on pumps	-	-	-
	Flap gate closed duration (h)	0%	18.64%	18.97%
Interaction between hydraulic structures and urban functions	Multifunctional spaces	-	-	-
	Urban continuity	-	-	-
Water quality	Reservoir concentration of BOD (mg/L)	−10.00%	−11.11%	−11.11%
	Emptying time of the reservoir (h)	25%	97.06%	100.00%

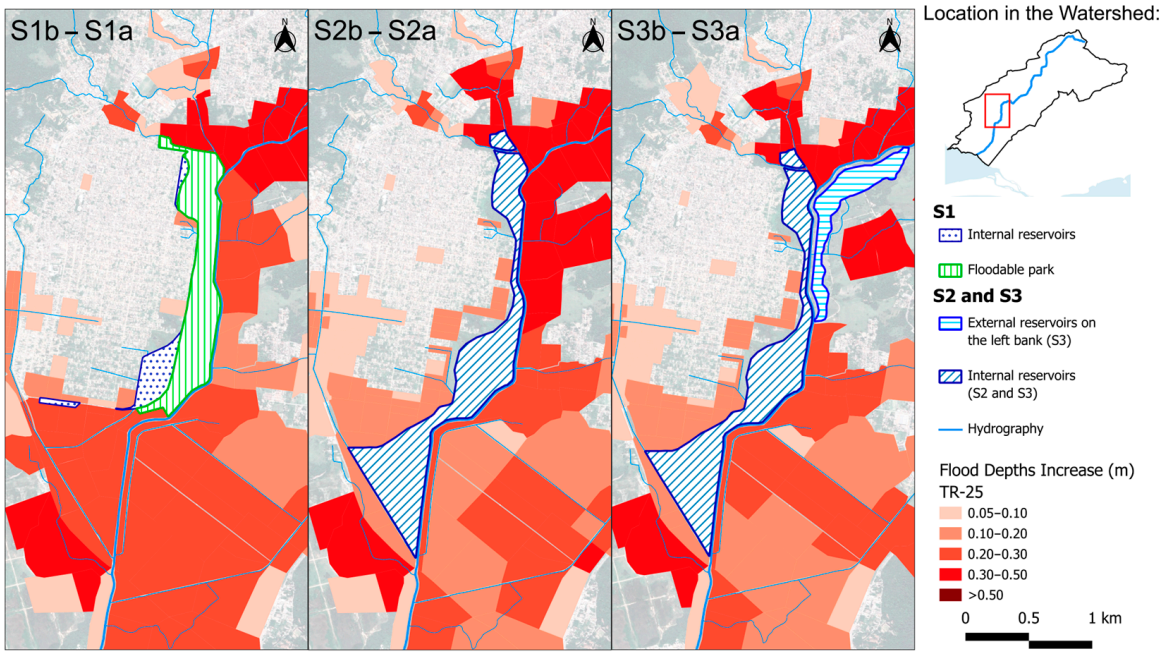


Figure 7. Flood depth difference assessing the loss in the efficiency of the scenarios under stressed climatic conditions. Each sub-figure represents a stressed scenario compared to its non-stressed version.

5. Discussion

The proposed framework integrates a variety of criteria that encompass different assessment layers for driving design alternatives in the case of fluvial polder projects, considering aspects of urban flood resilience, recognizing that analyzing only flood mitigation represents a simplistic and insufficient approach.

The framework also highlights an important aspect to consider when evaluating flood mitigation projects: their integration with city life, even during dry periods. Since it does not rain most of the time, it is crucial that these projects also serve as an enhancement to the city's normal functions rather than a hindrance. For this reason, the project must be systemically oriented and multifunctional, ensuring that it always remains useful and does not leave the area underutilized when not actively mitigating floods.

Another critical aspect is that flood control projects must be adaptable to future perspectives. The discussion on urban resilience emphasizes the need to not only address

current problems but also to develop solutions that are sustainable in the long term and adaptable to future changes. These changes may include urban growth—with increased population exposure—and the intensification of extreme events due to climate change. As a result, incorporating climate change perspectives into this evaluation has provided added value, ensuring that the proposed solutions remain relevant and effective in the face of evolving conditions. This approach may avoid a situation in which a project demonstrates superior performance compared to others under current conditions but could experience significant efficiency losses over time. This decline in performance may result in the project becoming less effective than its counterparts in the long run.

An advantage of the proposed framework is that it can incorporate both numerical and non-numerical criteria, transforming all into standardized scores that allow for direct comparison. This approach ensures that subjective aspects, such as multifunctional spaces and dependence on pumps, are evaluated objectively and integrated into the analysis (even if, in a simple way, these aspects are considered). Moreover, the method is relatively easy to apply, allowing criteria to be adapted, removed, or added according to the specific needs of each case study. The final result intended here does not point to "the best design guidelines"—this is something dangerous, since each physical and urban setup leads to different behaviors and different best solutions from one place to another. The idea is to provide a comprehensive and flexible assessment framework. This characteristic makes the method replicable in other contexts and case studies, requiring only minor adjustments to align with local particularities and the objectives of decision-makers.

Therefore, the main advantage of the proposed framework is the possibility of identifying vulnerable points in a polder project, allowing for the implementation of corrective measures during the design phase and re-assessing the new alternatives many times as needed with the aim of enhancing its long-term resilience.

Finally, the interpretation of results is simplified, as it is based on the comparison of scores assigned to each scenario. In the proposed framework, all criteria were considered equally important, which means that no different weights were assessed to each criterion. As the definition of weights can vary according to the study area and does not influence in the framework conception, no distinction was made between criteria. In future applications, it is possible to assign weights to each criterion, hierarchizing the perceived importance of each one and producing an integrated final number to support decision making when choosing the best design alternative. Well-known methods like AHP can be used to fulfill this aim. However, in this first version, our intention was to establish a basic framework to offer a wide view about design choices and their consequences, including water quantity control, water quality, urban interactions, and resilience coordination across the watershed. This aspect facilitates the communication of technical information to decision-makers, transforming complex data into accessible and comparable insights. This is particularly useful in the decision-making process, as it simplifies information from distinct fields of knowledge. While the technical details used for this assessment may not be easily understood by all stakeholders—such as governors, urban planners, or the community—the organization of these aspects into the final matrix is intuitive and easy to interpret, bridging the gap between technical expertise and practical decision-making.

6. Conclusions

The proposed evaluation framework for designing polders in coastal lowlands successfully integrated a multifunctional urban design approach with flood mitigation and urban service enhancement. By organizing 12 flood resilience-related criteria into a comprehensive matrix, the framework provides a holistic basis for analyzing design alternatives, balancing both quantitative and qualitative aspects of flood mitigation and urban flood

resilience. The criteria were categorized into five assessment dimensions and converted into standardized scores using the TOPSIS logic, allowing for an objective comparison of different design scenarios.

The application of this framework to Jardim Maravilha, a flood-prone neighborhood in Rio de Janeiro, Brazil, highlighted its comprehensive characteristic for evaluating three distinct polder designs under a 25-year return period rainfall event—which stands for the Brazilian major drainage design reference—and also for future climate change scenarios, including intensified rainfall and mean sea level rise. The conducted analysis demonstrated the different possibilities of design evaluation and did not even exhaust the design possibilities. The usual dike placement near the riverbank (explored in scenarios S2 and S3) performed better across most criteria compared to a dike placed near the urbanized area (scenario S1), except for a shorter reservoir emptying time for the latter. The optimized design (S3) outperformed the others by incorporating additional storage capacity in the opposite riverbank area, achieving balanced integration among operational demands, downstream results, and urban landscape integration.

A key advantage of the framework is its capacity to incorporate both numerical and non-numerical criteria, transforming them into standardized scores that allow objective assessment of subjective aspects, such as multifunctional spaces and pumping operational dependencies. This approach ensures that all relevant aspects are considered in the analysis, even if certain criteria are evaluated in a simplified manner. The flexibility of the framework enables easy adaptation, allowing criteria to be modified, added, or removed to align with the specific needs of different case studies and contexts.

The framework's applicability to future climate scenarios is a significant strength, ensuring that flood mitigation projects remain effective over time. By including climate change perspectives, this method helps to avoid scenarios where initially effective solutions may lose efficiency under evolving conditions, such as urban growth and more extreme weather events. This forward-looking approach supports the development of sustainable, long-term infrastructure solutions that maintain resilience against future risks.

Another notable benefit of the framework is its ability to identify vulnerable points in the design phase of a project. This feature allows for the implementation of corrective measures in the early process and facilitates iterative re-assessment of design alternatives as needed. Such a proactive method can enhance the overall resilience of the project and ensure that it remains effective throughout its lifecycle.

Moreover, the framework can also improve the decision-making process by simplifying the understanding of complex data. The matrix format enables clear and intuitive comparisons between design scenarios, bridging the gap between technical assessments and practical urban planning with more transparent and informed decisions.

Finally, it is necessary to highlight that the framework does not seek to establish a unique design answer but rather provides a structured and adaptable tool for evaluating flood mitigation projects. This ensures that the assessment remains sensitive to the specific physical, urban, and cultural contexts of each project, avoiding the pitfalls of a one-size-fits-all approach.

A gap to be addressed in future research refers to the implementation of economic assessment indicators. Different alternatives, with varying performance levels, also have different costs and co-related avoided losses, consequently leading to different benefit–cost relations. Additionally, the inclusion of statistical methods to assess potential operational failures could be an interesting evaluation to incorporate into the framework. These aspects can bring significant improvement to the method.

In conclusion, the proposed framework is a consistent, adaptable, and comprehensive tool that can enhance the assessment of fluvial polder projects and support the creation of more resilient and adaptable urban environments.

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Abbreviations

The following abbreviations are used in this manuscript:

BGI	Blue–green infrastructure
SDGs	Sustainable Development Goals
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
MODCEL	Urban Flow Cell Model
BOD	Biochemical oxygen demand
S0a	Current situation, variant a
S0b	Current situation, variant b
S1a	Scenario 1, variant a
S1b	Scenario 1, variant b
S2a	Scenario 2, variant a
S2b	Scenario 2, variant b
DO	Dissolved oxygen
WWTP	Wastewater treatment plan

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