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Integrating Nature-Based Solutions for Increased Resilience to Urban Flooding in the Climate Change Context

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Abstract: As climate change intensifies with more frequent and severe flood events, urban areas face increasing challenges to protect population wellbeing. Amid urban development challenges, political uncertainty, and socioeconomic pressures, finding sustainable solutions to enhance urban resilience has become urgent and complex. This article explores the limitations of traditional drainage systems in an urban zone of Bucharest, Romania, and the integration of nature-based solutions for flood mitigation. We compare the existing situation with those simulated in a climate change scenario before and after implementing green solutions. The imperviousness of parking lots was set at 60%, that of green roofs at 65%, and that of parking lots at 85%. A hydraulic model was used for this purpose. The results demonstrate that the current stormwater systems struggle to meet the demands of increasing rainfall intensity and highlight how sustainable strategies can effectively address extreme weather challenges while contributing to the restoration of natural environments within the city. In the case of using 'gray' solutions, only 10–20% of the area affected by floods is reduced. In comparison, a combination of gray and green infrastructure achieved an average reduction in peak water levels of 0.76 m.

Keywords: sewerage network; hydraulic modeling; nature-based solutions; climate change

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1. Introduction

Urban areas are increasingly susceptible to the adverse impacts of climate change, including more frequent and intense flooding, heat waves, and biodiversity loss [1–4]. This vulnerability is exacerbated by rapid urbanization [5,6], which leads to the proliferation of impervious surfaces [7] and places significant strain on existing stormwater management systems [5,8,9]. Traditional urban drainage infrastructure, often designed based on historical hydrological data, is limited in terms of handling the escalating intensity and frequency of extreme weather events brought about by climate change [10]. A study conducted in Vietnam [11] indicates that an increase in urban zones of 55% led to a runoff increase of 21%. Previous research [12] indicates that the average annual runoff could register an augmentation of 50% (320%) when impervious surfaces are increased by 10% (70%). Bibi et al. [13] found that the peak flow increased 1.5 times, due to an augmentation of the impervious surfaces by 60%. These challenges have driven the exploration of nature-based solutions (NbSs) as innovative and sustainable approaches for enhancing urban resilience while providing multiple environmental and social co-benefits [14].

NbSs encompass various interventions that leverage natural processes to address urban challenges [15–17]. These include green roofs [18,19], permeable pavements [20], vegetated swales, bioretention cells [21], and constructed wetlands, among others. Collectively, these measures are effective at reducing stormwater runoff, enhancing water infiltration, and restoring natural hydrological cycles in urban environments [22,23]. For example, green roofs have been shown to retain up to 62% of rainfall, significantly alleviating the load on drainage systems during heavy precipitation events [24–26]. Bioretention systems and permeable pavements can decrease peak flow rates by up to 60% while mitigating non-point-source pollution by up to 80% [23,27,28]. These solutions are integral to achieving sustainable stormwater management, particularly in the face of increasing precipitation intensities due to climate change [29–31].

Studies from urban areas worldwide provide evidence of the effectiveness of integrating NbSs with traditional infrastructure [32]. Previous simulations [33–35] demonstrated that combining low-impact development (LID) practices with existing drainage systems could reduce flood volumes and impacted areas significantly, even under future climate change scenarios [36,37]. A case study in the Guangdong–Hong Kong–Macao Greater Bay Area projected that areas with medium and high flood susceptibility would increase by 9.5% to 14.4% by 2050 under various socioeconomic pathways, emphasizing the need for NbSs to address these growing risks [38]. The same idea is found in a study from Dresden [39], with climate change projections indicating an increase in precipitation (floods and surface runoff, respectively) by a maximum of 17.10% (63.26%, and 12.66%, respectively).

Sustainable urban development can be achieved by integrating NbSs into urban planning for adaptation to climate change [40,41]. The integration of NbSs must be accomplished by the municipalities, which are also responsible for implementing laws [42]. Despite the NbS concept being widely recognized by researchers and policymakers, it is necessary to clarify the specific role and potential of NbSs in sustainable urbanization. Various frameworks for NbSs have been developed. Still, implementing NbSs is in its early stages, with two pioneering countries being Sweden and Germany [43]. Some implemented projects are presented by Kiss et al. [44]. However, none of these previous studies refer to the problem discussed in this article (i.e., adapting stormwater management systems to the impacts of climate change).

In addition to stormwater management, NbSs provide a range of co-benefits that enhance urban sustainability. Green infrastructure, such as urban forests and vegetated swales, contributes to urban cooling, reduces the urban heat island effect, and improves air quality, thereby enhancing the overall livability of cities [11]. NbSs also creates habitats for diverse species, promoting biodiversity and ecosystem health [45]. Moreover, these measures improve water quality through natural filtration, addressing urban pollution challenges. The multifunctionality of NbSs makes them cost-effective in the long term as they simultaneously address various urban challenges while reducing reliance on resource-intensive gray infrastructure [32,46].

Despite its numerous advantages, the implementation of NbSs faces several challenges. Variability in performance across different climatic and urban contexts introduces uncertainties that complicate planning and design processes [32]. Financial and institutional barriers, including high initial costs and inadequate regulatory frameworks, often hinder their widespread adoption [11,47]. Additionally, the effectiveness of NbSs is highly dependent on local environmental and socioeconomic conditions, as well as adequate maintenance and stakeholder engagement [32]. These factors underscore the need for robust governance frameworks and interdisciplinary collaboration to ensure the successful implementation and scaling up of NbSs.

Addressing these challenges requires coordinated efforts among policymakers, urban planners, researchers, and communities. Programs such as the EU Horizon 2020 initiative have been instrumental in promoting NbSs as integral components of urban resilience strategies, providing valuable frameworks for their application across diverse urban contexts. Additionally, advanced modeling tools [48,49] and scenario analyses, such as those used in Shanghai [50], offer critical insights into the effectiveness of NbSs and guide future planning efforts. By integrating ecological principles with urban infrastructure, NbSs hold transformative potential to build adaptive, resilient, and sustainable cities capable of thriving due to climate change [23,51,52].

Bucharest, the capital of Romania, has a population exceeding 2 million residents, making it the most populous city in the country. Its urban expansion has resulted in high population density, with significant portions of the land being converted into impervious surfaces, such as buildings, roads, and parking lots. These developments exacerbate the challenges associated with stormwater management, particularly during intense rainfall. As climate change is anticipated to increase both the intensity and frequency of extreme weather events [10], this research addresses critical gaps in infrastructure design and planning, offering innovative solutions that combine traditional and nature-based methods to enhance the city's adaptability and sustainability.

By integrating advanced hydraulic modeling and applying both synthetic rainfall scenarios and projections for climate change impacts, this research provides a robust framework to assess the sewerage system's performance and the efficacy of flood mitigation strategies.

This study provides practical solutions to one of the most pressing challenges in urban planning: adapting stormwater management systems to the impacts of climate change. By focusing on Bucharest (Romania), a city facing recurrent urban flooding due to outdated infrastructure, this research develops a replicable framework that integrates traditional engineering approaches with innovative NbSs. The findings are directly applicable to urban areas worldwide, offering a blueprint for enhancing the stormwater infrastructure's capacity to handle intensified rainfall.

In addition to validating the benefits of NbSs for urban flood mitigation, this study provides novel insights into the long-term feasibility and sustainability of retrofitting interventions. Previous research has raised concerns regarding the effects of aging on the hydrological performance of green roofs, particularly in Mediterranean climates [19], and the challenges posed by rainfall intensification on the effectiveness of various SuDS systems in urban environments [18]. This work addresses these challenges by tailoring retrofitting interventions—combining gray and green infrastructure—to the unique characteristics of Bucharest, a highly urbanized area. The approach demonstrates not only the effectiveness of hybrid solutions in mitigating climate-driven flood risks but also their practical adaptability to the specific hydrological and spatial constraints of the study area, offering a replicable model for other urban contexts.

2. Methodology

2.1. Study Area

Bucharest is situated in a temperate-continental climate zone characterized by distinct seasons. Average annual temperatures range between 10 °C and 12 °C, while precipitation levels average around 580–650 mm annually [53]. Rainfall patterns, however, are highly irregular, with intense short-duration rainstorms frequently overwhelming the city's aging sewerage infrastructure.

Its infrastructure, designed years ago for a precipitation frequency of 1/2 (designed based the IDF curves from normative STAS 1846-9), was constructed to handle precipitation events based on historical IDFs, leaving it ill-equipped for modern-day challenges exacerbated by urbanization and climate change. The city's stormwater sewerage system predominantly relies on gravitational pipes to collect and transport rainwater to retention basins and eventually to the central collector.

In highly urbanized districts such as Sector 6 (Figure 1), impervious surfaces account for over 70% of the area [8], reducing natural infiltration and increasing surface runoff. Recent studies have revealed that the existing system frequently fails under high-intensity storms, leading to urban flooding, property damage, and disruptions to daily life.

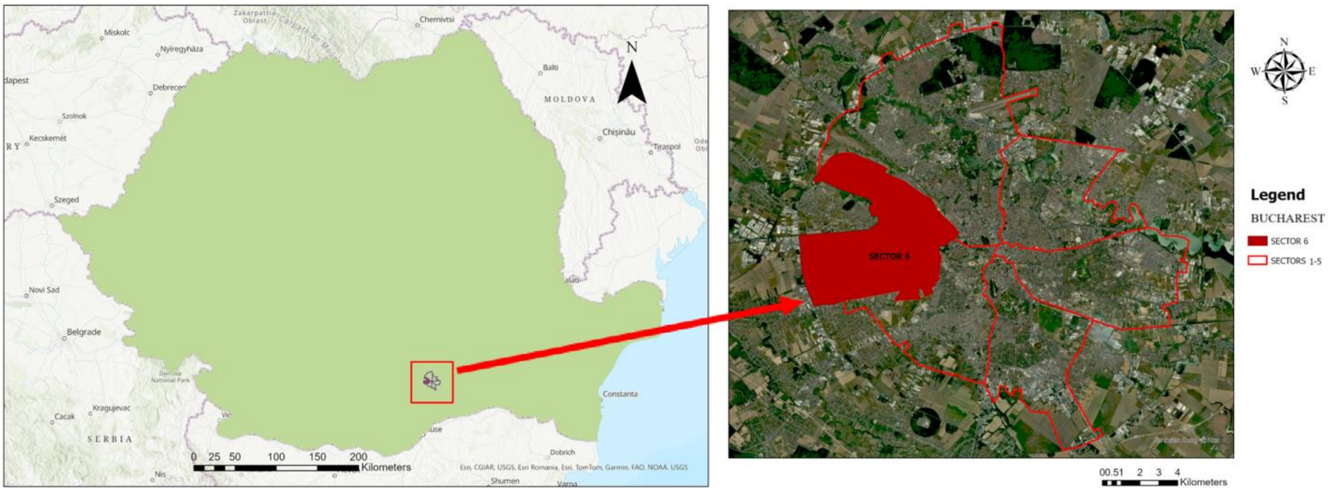


Figure 1. Map of Romania, Bucharest (**left**), and the study zone—Sector 6 of Bucharest (**right**).

This study specifically targets two residential neighborhoods in Sector 6 (Figure 2), representing a combined area of 27.58 hectares; 28.30% of this is classified as pervious surfaces, primarily consisting of green spaces and grassy areas, while 71.70% is classified as impervious surfaces, occupied by buildings, streets, parking lots, and sidewalks.

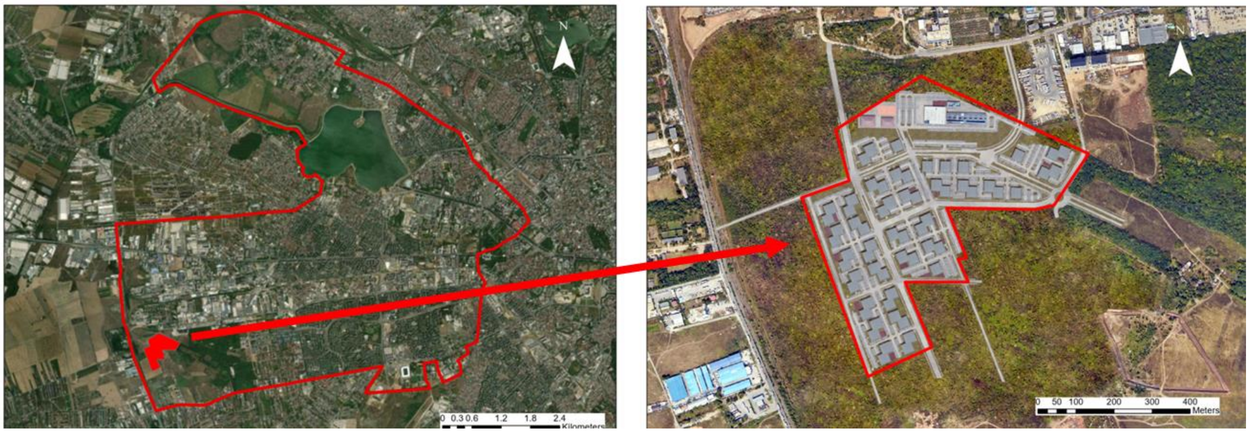


Figure 2. Sector 6 (**left**) and the study zone (**right**).

A topographical survey conducted for the area indicates elevations between 88.00 m and 91.50 m. A geotechnical survey indicates a terrain stratification composed of soil from 0.00 m to 0.30–0.50 m, landfilling from 0.30–0.50 m to 0.70 m, and dusty brown clay with limestone concretions from 0.70 m to 2.00 m.

The sewerage network primarily consists of gravitational pipes (with diameters between DN300 mm and DN900 mm) designed to collect and transport rainwater to two retention basins. The water is subsequently pumped to a main collector in the Bucharest sewerage network.

2.2. Data Series Necessary for Simulation

The simulation was conducted using a hydraulic model. Certain data regarding the sewerage network and the environment were needed to build it. Regarding the sewerage network, both geometrical and topographical data related to the network's elements were considered. This included information such as the diameter and material of pipes, the ground level, bottom level, and diameter of manholes, the volume of pumping stations, and the volume of retention basins. Operational data on the network, including the functional Q-h (pumped flow and pumping level) curves of pumps, as well as their start and stop levels, were also utilized. All the data were obtained from technical documentation and technical drawings.

Data obtained from the topographical and geotechnical surveys provided environmental information that was essential for constructing the hydraulic model and implementing the proposed technical solutions for flood mitigation. Synthetic rainfall, generated based on intensity-duration-frequency (IDF) curves [54], together with rainfall adjusted for climate change conditions, was applied to the hydraulic model within the study's scenarios.

Global circulation models are complex mathematical models that simulate the physical mechanisms of the atmosphere and oceans for future global and regional climate predictions. In this study, we used the HadCM3 global circulation model. This is a coupled atmosphere–ocean circulation model that includes an atmospheric component with 19 vertical levels and a horizontal resolution of 2.5° latitude by 3.75° longitude, forming a global grid of 96 by 73 cells (a total of 7008 grid cells). This configuration provides a surface resolution of approximately 417 km by 278 km, or 115,926 km^2, at the Equator, which reduces to 295 km by 278 km, or 82,010 km^2, at a latitude of 45°. In contrast, the oceanic component of HadCM3 has 20 levels with a finer horizontal resolution of 1.25° by 1.25°. This level of resolution enables this global circulation model to capture important details of oceanic structures, leading to better results [55,56].

2.3. Hydraulic Model and Scenarios

The hydraulic model of the stormwater sewerage network was built using the modeling software MIKE+2024, developed by the DHI (Danish Hydraulic Institute) [49]. MIKE+ operates based on the finite difference method and facilitates the construction and management of hydraulic models using a geographic information system (GIS), with the data being stored in SQLite or PostGIS databases.

The model is a coupled one-dimensional–two-dimensional hydrodynamic model that includes all the representative elements of the sewerage network, including manholes, pipes, pumps, retention basins, and the discharge point for stormwater into the main collector, implemented according to the technical documentation, thereby ensuring an accurate representation of the network's structure and functionality.

Hydrological modeling was incorporated into the hydraulic model by including catchment areas (hydrological basins) to determine the volume of precipitation that reaches the sewerage network. These catchment areas were generated automatically in MIKE+ using Thiessen polygons [57], based on the distribution of manholes within the network. The hydrological model utilized is the Time/Area model [58], which characterizes the proportion of the catchment area impacted by precipitation and describes the drainage flow across the surface of the catchments. The Time/Area model was selected for its effectiveness in simulating precipitation runoff over large urban catchments, similar to the ones used for this model [32].

The stages of building the hydraulic model were as follows.

(a) *Input data analysis and processing.*

This stage involved collecting and analyzing the sewerage network's geometrical and operational data. Geometrical data included pipe diameters (ranging between DN300 mm and DN900 mm), lengths, slopes, and materials, as well as details about manholes (ground levels, bottom levels, and diameters) and retention basins (volumes). Operational data included Q-H curves (flow and head curves) for the pumps and the start/stop levels of pump operation. Environmental data were also processed from topographic and geotechnical surveys, including terrain stratification and digital elevation models (DEMs). These datasets were pre-processed to ensure consistency and accuracy before integration into the hydraulic model.

(b) *Building the one-dimensional sewerage network hydraulic model.*

This model is represented by a mesh of computational elements, interpolated using the Natural Neighbor method [59] with a Digital Elevation Model (DEM). This interpolation was performed to accurately characterize the land surface, with further refinement achieved by incorporating a terrain roughness file. The mesh consisted of triangular elements with areas ranging from 5 m^2 to 40 m^2, depending on the modeled area. Additionally, the building footprints were excluded from the mesh, as it is assumed that water would bypass the buildings in a real-life flooding scenario.

Figure 3 represents the hydraulic model of the stormwater sewerage network, which contains the network's manholes (marked by green points), basins (represented by rectangular elements), outlets (represented by triangular elements), junctions (marked by white points), pipes (gravitational and pressure pipes, represented by green and red lines), and catchments created for the model.

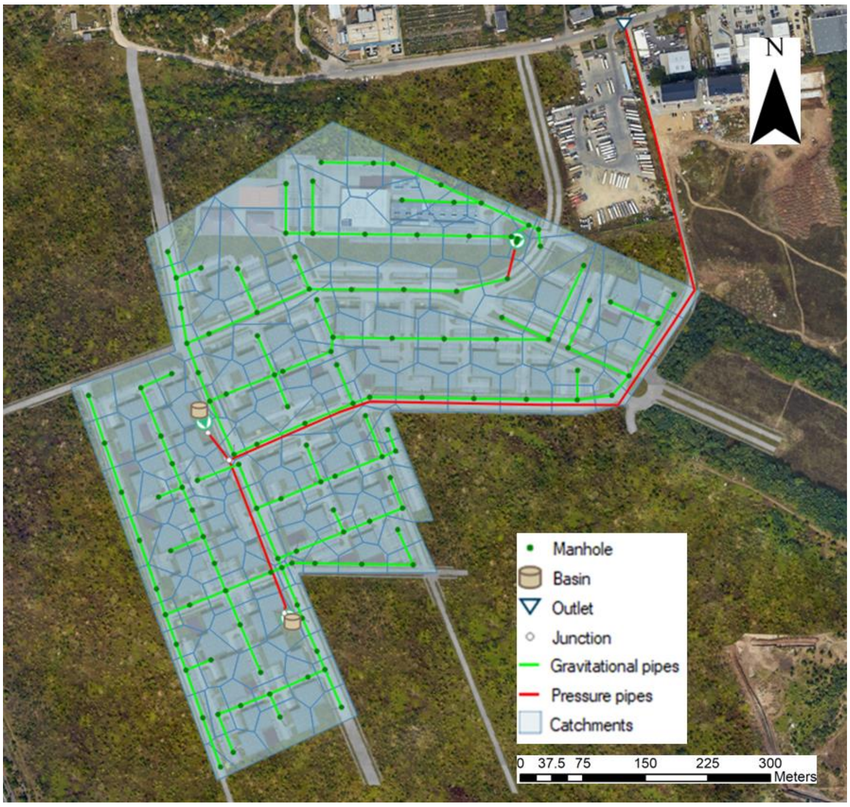


Figure 3. The one-dimensional hydraulic model of the stormwater sewerage model.

(c) *Building and configuring the hydrological model.*

The hydrological model was developed to calculate the volume of precipitation runoff entering the sewerage network. It was achieved using the Time -Area method, which models runoff based on catchment response times. Catchment areas were delineated using Thiessen polygons generated around manholes. Parameters such as infiltration rates, initial abstraction, and concentration time were set based on the field data and literature values. The hydrological equations employed ensured accurate modeling of precipitation–runoff relationships under urban conditions.

(d) *Construction of the two-dimensional model.*

The two-dimensional model (Figure 4) was constructed to simulate surface water flow across the study area. This model used the finite difference method to solve shallow water equations. The parameters configured in this step included Manning's roughness coefficients to represent the surface characteristics, boundary conditions for external inflows, and the initial conditions for the terrain.

Figure 4. Two-dimensional model mesh of the collection system.

The 2D model provides a spatially detailed view of potential flood extents, complementing the one-dimensional sewerage network model.

(e) *Coupling the one-dimensional and two-dimensional models to obtain a continuous representation of the flooded area in case of heavy precipitation.*

The one-dimensional sewerage network model was coupled with the two- dimensional surface flow model to represent flooding scenarios comprehensively. This integration was performed using dynamic boundary conditions, allowing a bidirectional water exchange between the sewerage system and the surface. Coupling ensured that overflow from the sewerage network could flow onto the surface while surface runoff could re-enter the network through manholes, replicating real-world interactions.

(f) *Configuring the boundary conditions for the coupled one-dimensional–two-dimensional hydraulic model.*

The boundary conditions were defined to represent realistic scenarios for rainfall events and system responses. Rainfall events were modeled using hyetographs derived from Intensity-Duration-Frequency (IDF) curves. We used the official available IDF curves determined by the normative [54] for the design frequency of 1/2, for which the sewerage system was initially designed. For climate change scenarios, adjusted hyetographs reflecting future rainfall intensities were determined. External boundary conditions included discharge points where water exited the model domain. These configurations ensured that the model accurately simulated the behavior of the network and the surrounding terrain under various precipitation scenarios.

The hydraulic model of the stormwater sewerage network was analyzed under three scenarios (Table 1).

Table 1. Simulation scenarios.

No	Scenario	Rainfall	Description
1	Baseline	Frequency 1/2	The sewerage network was tested for the design rainfall.
2	Climate change (CC)	Simulated from HadCM3	The sewerage network was tested without implementing any solution for flood mitigation.
3	CC with flood-mitigating solutions	Simulated from HadCM3	The sewerage network was tested after implementing any solution for flood mitigation.

Scenario 1, which served as the baseline, considered a rainfall event with a frequency of 1/2 (occurring once every two years), as the network was initially designed based on this rainfall conditions. The rainfall used in Scenarios 2 and 3 was calculated using the global circulation model HadCM3 (so, in the climate change scenario). In Scenario 2, the network was tested for its transport capacity under the precipitation levels projected for the year 2100 when no green solution had been implemented. In Scenario 3, nature-based flood mitigation solutions were applied, and we tested the sewerage network transport capacity under the precipitation levels projected for the year 2100. For each scenario, a precipitation boundary condition was applied to the model. The boundary condition for rainfall with a frequency of 1/2 was represented by a hyetograph (Figure 5), calculated according to the national technical standards.

For Scenarios 2 and 3, the boundary condition was represented by a hyetograph calculated based on the global circulation model for the year 2100, using the rainfall data of the first scenario. After analyzing the output, the values of the initial hyetograph were multiplied with an indicated coefficient equal to 1.43. The obtained results were validated by how the hydraulic model responded to rainfall corresponding to a frequency of 1/2, the rainfall used for designing the sewerage network. Following the initial simulations, the results were directly compared with those obtained through design calculations and were found to be similar.

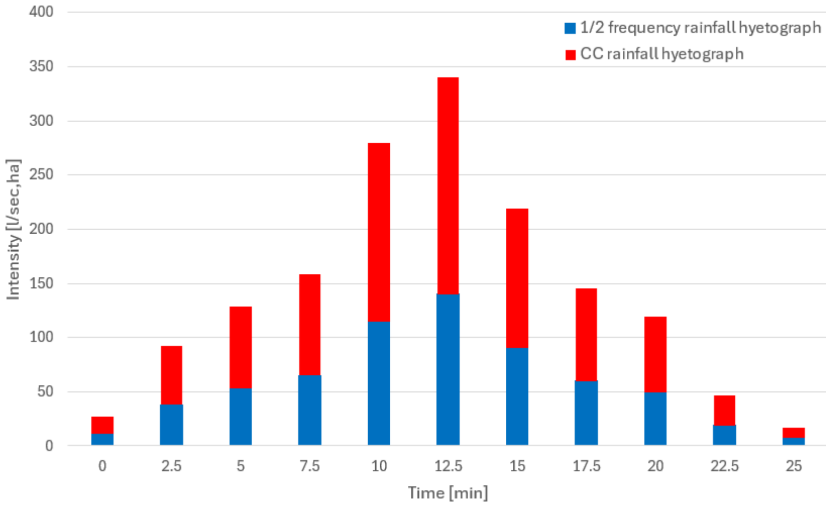


Figure 5. Hyetographs used for the scenarios on which the model was tested.

2.4. Flood Mitigation Solutions

After analyzing the results of the abovementioned scenarios, several technical solutions for flood mitigation were proposed. Initially, the proposed flood-mitigating solutions were represented exclusively traditional "gray" infrastructure. Specific nature-based "green" solutions were also considered, to complement the traditional infrastructure. Bio-retention cells, porous pavements, and green roofs were implemented and tested alongside the "gray" solutions as an integrated approach. All the suggested NbSs are forms of LID practices used in urban settings to mitigate the hydrological effects of stormwater runoff and improve water quality [25,27].

The proposed bio-retention cells were implemented in two distinct locations. In the first location, represented by zone 1 in Figure 6, two bio-retention cells are grouped and configured for spot infiltration, while in the second location, represented by zone 2, four bio-retention cells were grouped and placed alongside one of the stormwater sewerage network's most important and problematic collectors.

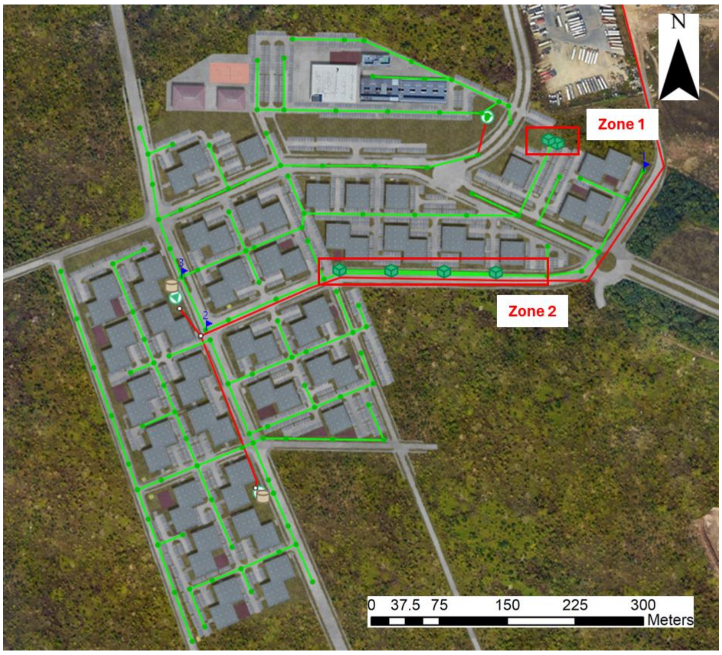


Figure 6. The implemented NbSs.

The bio-retention cells from zone 1 have a length equal to 1.00 m, a width equal to 1.00 m, and a depth of 1.50 m, with a total volume of 1.50 m^3, a retention capacity of 1.395 m^3, a porosity of fill material of 0.7, and an infiltration rate of 0.864 m/d, while the bio-retention cells from zone 2 have a length equal to 12.00 m, a width equal to 2.50 m, and a depth of 1.50 m, with a total volume of 45.00 m^3, a retention capacity of 41.85 m^3, a porosity of fill material of 0.7, and an infiltration rate of 0.864 m/d. To ensure the effectiveness of the bio-retention cells as a low-impact development solution, the design and implementation guidelines from the PGC (2007) Bioretention Manual [28] were followed. Each structure was designed and placed in light of the environmental conditions, such as soil type, slope, and hydrology, as presented in the manual.

When proposing the locations for porous pavement implementation, the focus was put on the parking lots around flood-prone areas. Each location was analyzed following the guidelines presented in the Minnesota Stormwater Manual [9], which outlines the best practices for designing, placing, and maintaining porous pavement for stormwater management. We considered parking lots the most fitting locations for this type of low-impact development structure because the porous pavement is suitable for low-volume roads or low-speed areas [9]. Green roofs were proposed for buildings situated near areas prone to flooding. This type of low-impact development was considered for implementation because it enhances stormwater retention [45] and provides additional benefits such as improved building insulation [26].

Modeling the proposed green structures followed a relatively straightforward approach. The bioretention cells were represented through soakaway elements configured based on the bio-retention cells' mentioned characteristics. Soakaway elements were employed to simulate green infrastructure solutions in hydraulic modeling, serving as a flexible type of LID control [22], capable of representing a wide range of Water Sensitive Urban Design (WSUD) practices [49].

The imperviousness of catchments like parking lots and buildings was reduced by implementing porous pavements and green roofs. Specifically, the imperviousness of parking lots with porous pavements was reduced from 85% to 60%, while the imperviousness of buildings with green roofs was decreased from 90% to 65%.

Initially, the imperviousness of the parking lots was defined as 85%, taking into account possible cracks in the concrete, which can be numerous and of varying sizes, through which water could infiltrate; thus, 100% imperviousness was unrealistic. The imperviousness chosen for the permeable parking lot, set at 60%, was applied by considering factors such as a balance between the drainage capacity of the parking lot and structural resistance to traffic.

In the case of buildings, the initial imperviousness was considered to be 90% for the same reason, in the context of the cracks that may be found on top of flats. The imperviousness value of 65% for green roofs was chosen not only because a roof that is 100% green is not possible but also to encourage the use of partially green roofs, which should be easier to implement.

3. Results and Discussion

As already mentioned, various technical solutions for flood mitigation have been proposed. The first solution involved increasing the diameters of certain pipes located in flooded areas and building a new retention basin with a volume of 150 m^3. Due to spatial constraints, implementing the retention basin in the required location was considered unfeasible, leaving pipe diameter enlargement the only applicable solution. However, increasing the pipes' diameters did not lead to satisfactory results, as flooding was mitigated by only 10% to 20% in the affected areas. Therefore, we focused on the complementary effect of all flood mitigation measures.

In Scenario 1, when applying a rainfall event with a frequency of 1/2 to the hydraulic model, the simulation results (Figure 7a) demonstrate that the stormwater sewerage network has sufficient transport capacity to manage stormwater runoff effectively.

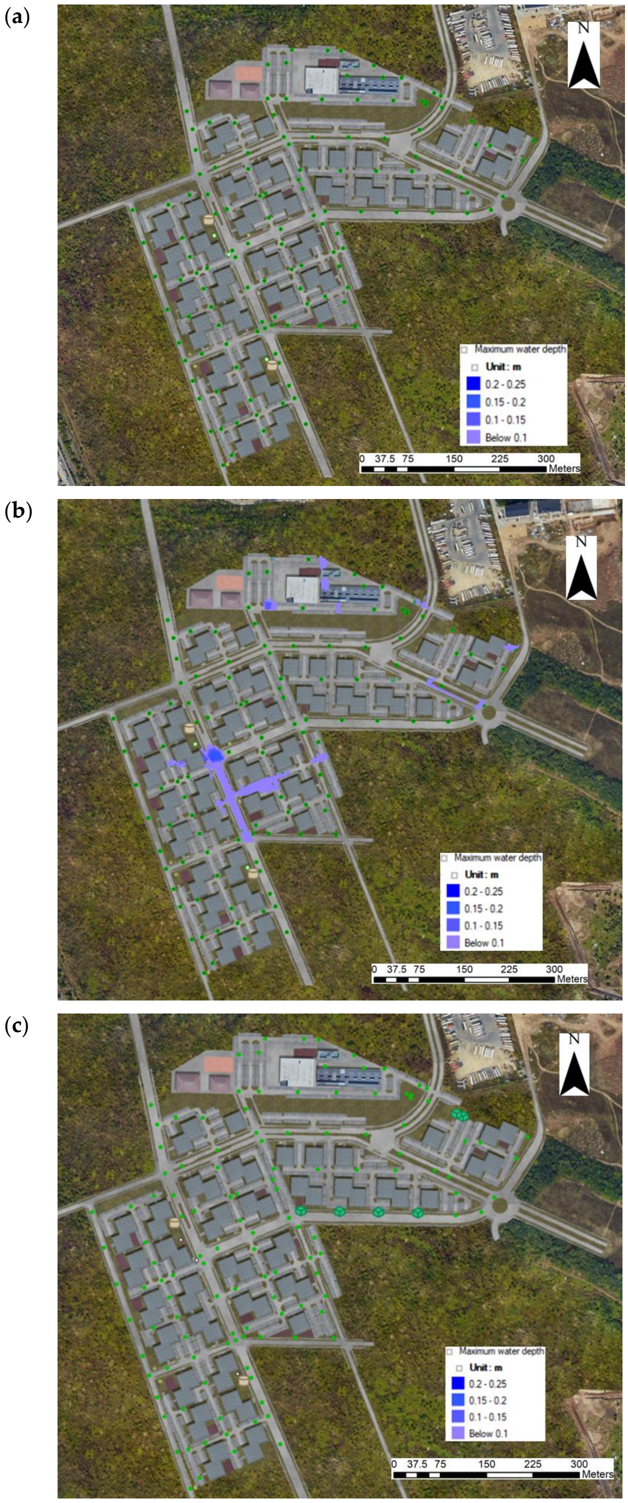


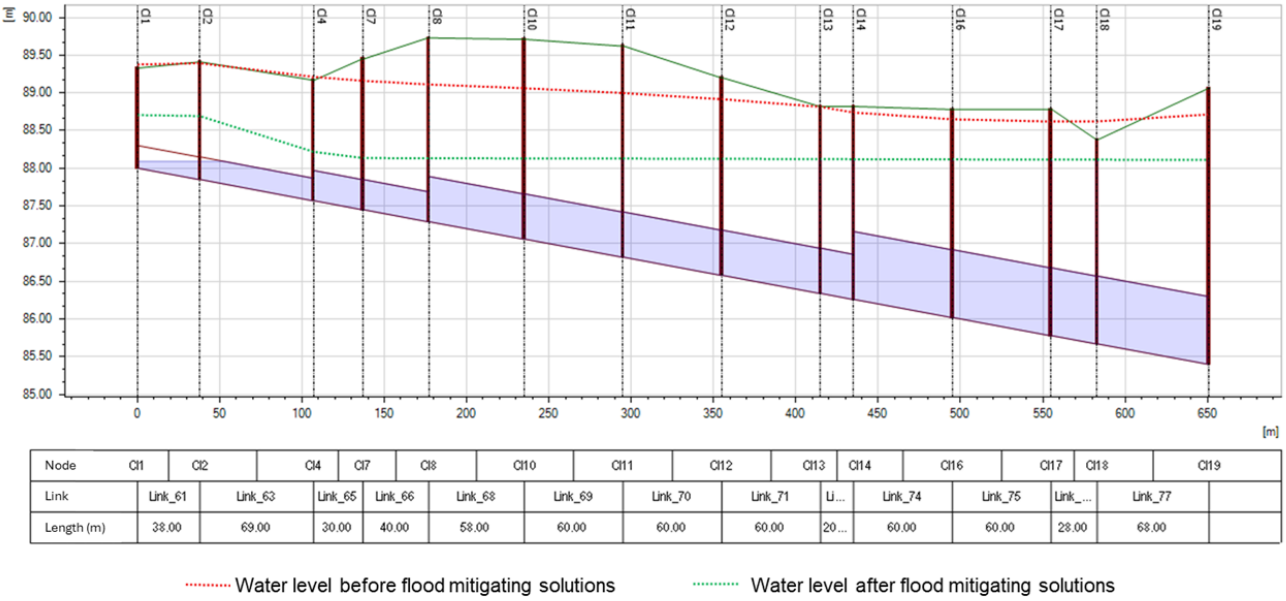
Figure 7. Results of (**a**) Scenario **1**: 1/2 frequency rainfall; (**b**) Scenario **2**: climate change with the actual situation; (**c**) Scenario **3**: climate change with implemented technical flood mitigation solutions.

Under this moderate storm scenario, the sewerage system operates without overflow, successfully transporting rainwater to the collector into which it is discharged. This outcome suggests that the network is adequately designed to handle at least this level of rainfall, ensuring resilience against common storm events.

In Scenario 2, under the calculated climate change rainfall projected for the year 2100, the hydraulic model of the stormwater sewerage network reveals that the system's designed transport capacity would be surpassed. Figure 7b shows that the network cannot convey stormwater efficiently due to higher rainfall volumes, leading to widespread overflow and urban flooding. The findings underscore the need for substantial upgrades to the sewerage infrastructure to adapt to future climate conditions, as the existing network will be insufficient to prevent flooding. They highlight the vulnerability of urban stormwater systems to climate-driven increases in precipitation, calling for proactive planning to enhance resilience against anticipated extreme weather patterns.

In Scenario 3 (climate change with implemented flood mitigation solutions), after implementing the integrated flood mitigation solutions, which consist of a combination of traditional "gray" infrastructure and NbSs, the sewerage network's capacity to manage the intensified rainfall patterns associated with climate change increased considerably. The results (Figure 7c) indicate that the network can effectively transport stormwater, mitigating the risk of overflow and urban flooding, even under climate change conditions.

A longitudinal profile (Figure 8) can help us better observe the advantages of this flood-mitigating approach. The longitudinal profile goes through the rainwater collector, alongside which the 4 bio-retention cells from zone 2 were implemented. It shows that the collector's maximum water level is reduced by an average of 0.76 m, which is a significant improvement in the network's behavior.



Node	CI1	CI2	CI4	CI7	CI8	CI10	CI11	CI12	CI13	CI14	CI16	CI17	CI18	CI19
Link	Link_61	Link_63	Link_65	Link_66	Link_68	Link_69	Link_70	Link_71	Li...	Link_74	Link_75	Link_...	Link_77	
Length (m)	38.00	69.00	30.00	40.00	58.00	60.00	60.00	60.00	20...	60.00	60.00	28.00	68.00	

Figure 8. Longitudinal profile indicating climate change adaptation.

Analyses of the sewerage network's overall average water level (Figure 9) confirm the effectiveness of the implemented solutions. The chart illustrates the modifications that climate change can produce on rainfall events and demonstrates how implementing flood mitigation solutions can enhance their adaptability to climate change. Under climate change conditions, the network experiences significantly higher peak water levels (the red curve in Figure 9) and prolonged drainage times, indicating its vulnerability to heavier storm events.

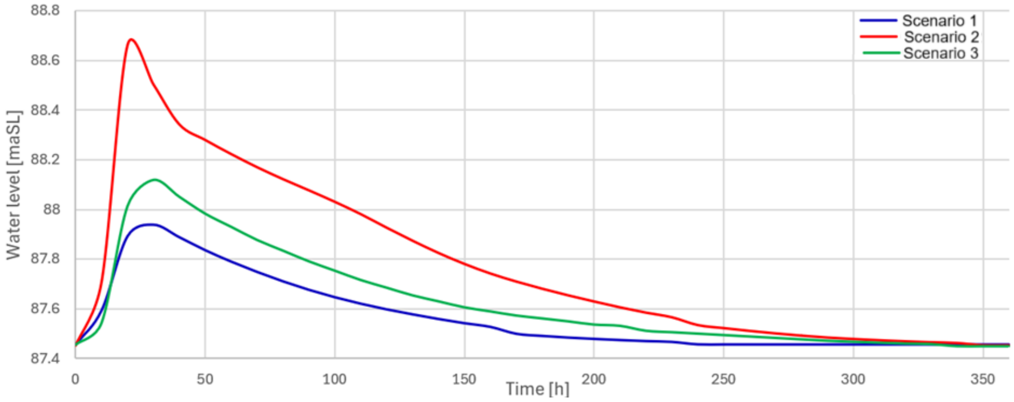


Figure 9. Stormwater sewerage network: overall average water level (above sea level).

Peak water levels were noticeably reduced when the proposed mitigating solutions were applied, and recovery time improved. Compared to Scenario 2, in Scenario 3 (green curve in Figure 9), the peak water level decreased by more than 0.5 m. These findings demonstrate that a hybrid approach combining gray and green infrastructure can restore and even improve the network's transport capacity in the CC scenario, ensuring sustainable urban areas and urban flood management for the future.

The findings from this study align well with previous research on NbSs and the use of permeable pavements as effective tools for urban flood mitigation. Fini et al. [60] demonstrated that porous pavements significantly enhance water infiltration and mitigate urban heat islands compared to impermeable alternatives. Similarly, Raimondi et al. [61] highlighted the dual functionality of permeable pavements in stormwater management and roof development beneath urban trees, noting a strong dependence on infiltration rates and storage layer thickness. Fernández-Gonzalvo et al. [62] found that permeable pavements perform well in both Atlantic and Mediterranean rainfall regimes, with pollutant retention capacities varying based on environmental conditions. In our study, the integration of porous pavements into the sewerage network significantly reduced surface runoff and localized flooding in Bucharest, echoing the findings of these earlier works. However, this research also extends our understanding of NbSs by quantifying their impact on reductions in peak water levels under future CC scenarios, showcasing their role in enhancing urban resilience. This is the first study of this type conducted in Romania.

The combination of gray and green infrastructure achieved an average reduction of 0.76 m in peak water levels, surpassing the improvements reported in isolated NbS applications, which underscores the benefits of a hybrid approach. The greatest impact came from implementing NbSs, which accounted for approximately 80–90% of the improvements. Expanded sewer pipes enhanced the system's overall transport capacity, while bioretention cells and porous pavements facilitated localized infiltration and reduced surface runoff, effectively mitigating flooding risks. These results not only validate the utility of NbSs but also emphasize the need for tailored implementation strategies that consider specific climatic and urban conditions.

These findings are consistent with studies in the Greater Bay Area [38] and Shanghai [50], which also highlighted the efficacy of integrated approaches under similar climate scenarios. Moreover, the co-benefits of NbSs, such as urban cooling, improved water quality, and reduced imperviousness, underscore their role as multifunctional tools for sustainable urban development. However, the effectiveness of these interventions is highly dependent on site-specific factors, including soil permeability, maintenance regimes, and proper configuration, emphasizing the need for tailored implementation strategies. These insights provide a practical foundation for designing resilient urban stormwater solutions.

We must note that NbSs cannot entirely replace the typical drainage system for runoff control. To achieve this aim, the conventional sewerage system must incorporate LID practices [34,63].

The limitations of this study come primarily from a lack of available data. The land-use modifications were not taken into account, and the economic aspect of implementing NbSs was not discussed. These aspects could constitute other subjects of research.

4. Conclusions

The study demonstrates the performance of a stormwater sewerage network under different scenarios. The hydraulic model for the actual situation demonstrates that existing sewerage networks can handle moderate rainfall events without significant issues, whereas the projections for future climate conditions reveal their limitations. This analysis emphasizes the urgent need to adapt urban stormwater management systems to meet the evolving challenges of climate change.

In Scenario 1, the network effectively managed rainfall events with a 1/2 frequency without overflow, indicating its adequacy for moderate storm events. However, in Scenario 2, the projected climate change rainfall for 2100 overwhelmed the network, leading to significant overflow and widespread urban flooding, highlighting its vulnerability to increased precipitation intensities. Scenario 3 showcased the efficacy of an integrated approach combining gray infrastructure upgrades and NbSs. These measures improved the network's capacity, reducing peak water levels by an average of 0.76 m and mitigating flooding, even under intensified rainfall conditions. The results emphasize the potential of hybrid solutions to enhance urban resilience and adapt to climate change impacts.

The proposed hybrid approach, combining traditional gray infrastructure with NbSs represents a sustainable pathway for addressing these challenges. Implementing expanded sewerage pipes, bio-retention cells, porous pavements, and green roofs markedly improves the network's performance under simulated climate change scenarios. Even considering conservative values of permeability for the NbSs (and a partial adoption of green roofs), these measures are shown to be effective at reducing flood risk.

Our simulation results showed that this integrated solution can restore the sewerage network's capacity under future climate conditions. As demonstrated in this case study, properly configuring bio-retention cells and porous pavements can significantly mitigate flood risks while optimizing resource utilization [50].

This research offers a replicable framework for other urban centers and contributes valuable insights into the potential of hybrid infrastructure solutions to address complex environmental challenges. Furthermore, it underscores the critical importance of strategic planning and design in implementing NbSs. Local environmental, climatic, and socio-economic conditions strongly influence the effectiveness of these solutions [18].

One key aspect is the feasibility of the retrofitting intervention, which was designed specifically to address the unique characteristics of the study area.

Beyond technical considerations, this research highlights the need for interdisciplinary collaboration and robust policy support to mainstream hybrid flood mitigation strategies. Policymakers, urban planners, and local communities must work together to address the institutional and financial barriers that often hinder the adoption of such innovative solutions. Long-term investment in research and advanced modeling tools, like the MIKE+ system employed in this study, is essential for accurately assessing the impact of proposed interventions and refining future strategies.

Ultimately, preparing urban areas for the uncertainties of climate change requires a paradigm shift in how we design and manage infrastructure. By embracing integrated approaches that leverage traditional engineering and ecological principles, cities can enhance their resilience, protect vulnerable populations, and foster sustainable urban development.

Future research could focus on the long-term monitoring and evaluation of hybrid solutions to assess durability, adaptability, and cost-effectiveness while expanding their application to diverse urban and climatic contexts to test their scalability. Improved climate models with localized data could enhance the accuracy of adaptation strategies. Studies on stakeholder engagement may reveal effective approaches for ensuring public acceptance and maintenance of these systems, while cost-benefit analyses, including co-benefits like biodiversity and urban cooling, could support broader adoption. Exploring the integration of NbSs with smart water management technologies and developing policy frameworks to overcome institutional and financial barriers are also vital. Additionally, quantifying ecosystem services, addressing social equity implications, and refining hybrid system designs under varying conditions could provide valuable insights for sustainable and inclusive urban planning.

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