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Urban Regeneration for the Resilient City: Implementation of Sustainable Urban Drainage Solutions in Pisa's High Flash Flood Risk Areas

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Abstract

Policies and international cooperation widely acknowledge the imperative to enhance the resilience of cities, ensuring effective multi-risk disaster management. Nature-based solutions (NBS) provide approaches aimed at conserving, sustainably managing, and preserving natural ecosystems. This research, funded by UNIPI PRA_2022_22, titled “Mitigating Risks in Urban Areas”, aims to develop a methodology to analyse and evaluate the benefits of increased resilience in urban contexts following the implementation of NBS. To control water runoff sources, improve soil infiltration, retain, or detain water volume, and filter contaminants, we designed small-scale sustainable urban drainage interventions in 4 areas of the city of Pisa prone to high hydraulic and flash flood risk. To verify their impact on stormwater management, the i-tree Hydro Plus was used. We tested the software using input data that simulated generic interventions, such as green roofs, permeable pavements, and rain gardens. The application showed promising results, but several challenges were encountered in data acquisition, as much of the data was not readily available, requiring the use of default values in some cases. Additionally, the complexity of the i-Tree Hydro Plus software limited its practical application to those with specialized expertise and, in its current state, unfortunately, it is not an accessible tool for local authorities.

Keywords

Nature-Based Solutions, Urban Resilience; i-Tree toolset, stormwater management, flash flood propensity.

1. Introduction

The escalating frequency and intensity of extreme weather events driven by climate change underscore the critical need to strengthen urban resilience. Global frameworks such as the 2030 Agenda for Sustainable Development and the Sendai Framework for Disaster Risk Reduction (2015-2030) emphasize multi-hazard disaster management and the enhancement of resilience in urban areas. As governments and researchers increasingly focus on prevention, mitigation, and risk management strategies, Nature-Based Solutions (NBS) have emerged as a promising approach

(Chen et al., 2021). With this term, the European Commission conceptualizes "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits, and help build resilience". Such solutions bring more nature and a greater diversity of natural features and processes into cities, landscapes, and seascapes through locally adapted, resource-efficient, and systemic interventions (European Commission: Directorate-General for Research and Innovation, 2015). NBS involves implementing strategies and policies that identify natural capital and ecosystem services as fundamental elements of new urban models. Key components of this approach, such as Green Infrastructure (GI) and Sustainable Urban Drainage Systems (SUDS), play a crucial role in building urban resilience, SUDS, for instance, introduce natural elements to urban water management systems, reducing surface runoff velocity, enhancing water infiltration, and retaining water for gradual release (Zölch et al. 2017). These systems provide additional benefits, such as recharging groundwater, improving urban vegetation, creating favorable microclimates, and adding aesthetic and environmental value (Veerkamp et al., 2021; Biswal et al., 2022; Johnson et al., 2022).

NBS, especially SUDS-based approaches, offer effective methods to address these challenges through:

- slowing down surface water runoff;
- attenuation and infiltration through the soil towards the shallow and deep aquifers;
- retention in depressions and volumes specifically designed for gradual water release over time;
- storage of water resources for subsequent use.

For a definition and classification of NBS, refer to the report by the International Union for Conservation of Nature (IUCN), one of the largest and most diverse environmental networks in the world (Cohen-Shacham et al., 2016). For a detailed examination of various NBS solutions and applications, consult the extensive scientific literature (Jones et al, 2022).

The effectiveness of green and sustainable systems for water flow control (NBS, GI, and SUDS) has now been demonstrated in numerous scientific studies and research that address their application in various contexts. Among these, with the aim of simulating the effects of NBS on the hydrological system, the i-Tree Hydro software has been developed. i-Tree Hydro Plus is part of the i-Tree suite, developed by the USDA Forest Service and available online at (USDA, n.d.). The suite is a collection of tools for assessing and managing urban greenery and ecosystem services. It includes modules for tree canopy assessment, carbon storage, and hydrological modeling. i-Tree Hydro Plus is a module specialized in urban hydrological modeling, which allows for simulating water movement based on land cover, soil type, vegetation, and precipitation patterns.

Within the studies that apply i-Tree Hydro, we can mention the research by Song (Song et al., 2020), which involves the application of i-Tree Hydro to evaluate the impact of urban green space in regulating runoff in the city of Luohe (China). Among the applications in the European context is the research by Csete & Gulyás (2021), which focused on the districts of Szeged (Hungary), the application of i-Tree Hydro in the Green Plan of Padua (Italy) (Comune di Padova, n.d., Bortolini & Brasola, 2022 and Semenzato & Bortolini, 2023) and the application of i-Tree Hydro in "Le Vallere" Park, Turin (Italy) by Busca & Revelli (2022).

Given that NBS are key solutions for enhancing urban resilience, it is crucial to implement policies and incentives at national, regional, and local levels to promote their integration into urban infrastructure development (Štrbac et al., 2023). Despite this, NBS are still not widely adopted in urban resilience strategies and are rarely integrated into urban planning (Cortinovis & Geneletti, 2018). Although research has investigated the implementation of NBS, comprehensive quantitative analyses of their effects on urban hydrology are lacking. This deficiency affects the ability of policymakers and urban planners to make informed decisions about adopting NBS to enhance resilience. To address this challenge, this study uses the i-Tree Hydro Plus modeling tool in the city of Pisa, Tuscany, Italy.

Tuscany is located in the so-called Mediterranean hotspot, an area identified by the Italian National Climate Change Adaptation Plan (approved in 2023) as highly vulnerable to climate change. Additionally, the latest ISPRA report, titled 'Hydrogeological Instability in Italy: Hazard and Risk Indicators' (ISPRA, 2021), identifies Tuscany as one of the regions with the highest population living in landslide and flood risk areas. According to meteorological data collected by the Intergovernmental Panel on Climate Change, a United Nations body operating from 1981 to 2020, Pisa is located in homogeneous climate macro-region 1 and belongs to cluster C (The Environment and Protection of Land and Sea, n.d.). For this cluster, projections for 2021–2050 indicate an overall increase in both ordinary and extreme precipitation events (short-duration, high-intensity concentrated rains). These factors, combined with extensive soil impermeabilization, artificialized watercourses, and inadequate drainage systems, exacerbate the risk of pluvial flooding and emphasize the importance of sustainable water management strategies in Pisa, making it an ideal case study for the implementation of NBS.

The present study aims to provide a localized assessment of NBS' impact on urban water systems in Pisa. The research methodology involves five key phases: 1) Conducting a territorial analysis to identify the study area; 2) Performing a GIS-based analysis to quantify key model inputs; 3) Developing NBS intervention scenarios by modifying model inputs; 4) Applying i-Tree Hydro Plus to simulate both current and future scenarios; 5) Comparing results to evaluate the effectiveness of NBS interventions.

2. Materials and Methods

2.1. Study Area

The study focused on four distinct urban zones within Pisa, Italy, selected based on land use, vegetation cover, and hydrological characteristics. The zones represent a range of urban typologies, including parks, residential neighborhoods, commercial districts, and industrial areas.

The macro-area of interest was delineated using GIS-based analysis, incorporating base data provided by the Northern Apennine Basin Authority. The analysis involved overlaying Flood Hazard and Flash Flood Propensity maps focusing on hazard levels P3 and P2 combined with Very High and High propensities. This revealed areas with simultaneous susceptibility to flooding events with return periods (TR) of up to 200 years and flash flood phenomena. Such risks are exacerbated by climate change and urban expansion.

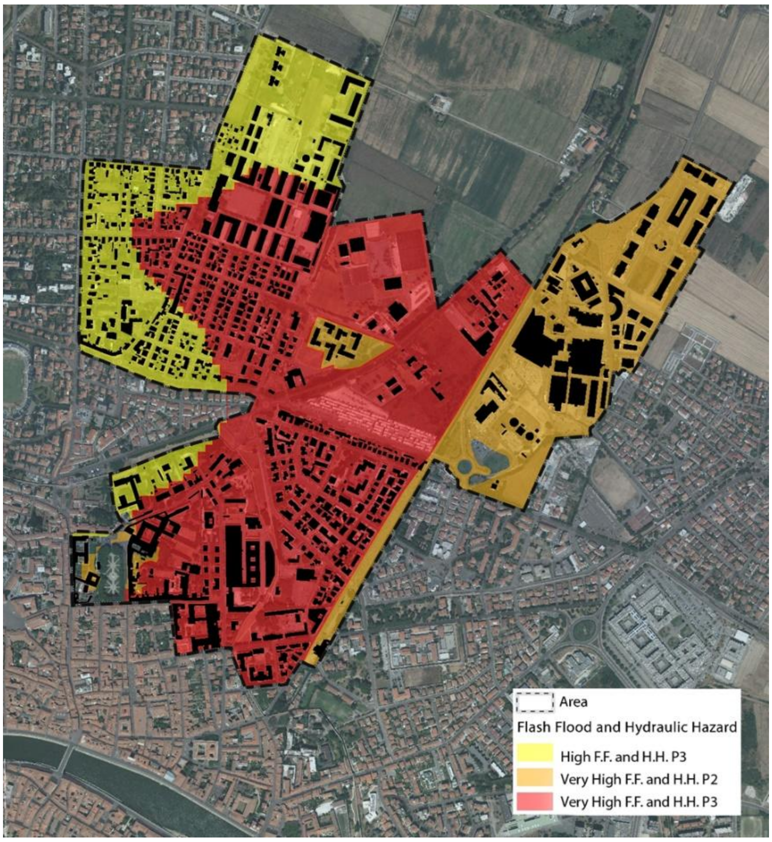

Figure 1: Map of the areas where flood hazard (P3 and P2) overlaps with a high propensity to flash flood phenomena (very high and high), identifying the study macro-areas. (Data source: Northern Apennine District Basin Authority; image by the authors)

The highest-risk area, identified as a “red zone”, lies to the north of the Arno River (Figure 1). The macro-area boundary was defined by analysing the urban fabric of the most affected blocks, while agricultural areas were excluded due to their lower risk. Conversely, the commercial district within San Giuliano Terme (a municipality bordering Pisa) was included due to its higher flood susceptibility. The macro-area was further subdivided into four zones (Z1-Z4) based on the urban configuration, building density and hydrogeological data (Figure 2).

2.2. Input Data

The data collected and utilized for this research encompasses various aspects crucial for the comprehensive analysis of NBS interventions and their potential impacts on urban hydrology. Key input data categories include:

- Methereological Data: Hourly weather data were sourced from Pisa Weather Station (#TOS01000544, Facoltà di. Agraria), The data set includes hourly precipitation, temperatures, humidity, wind speed and direction.
- Land Use and Cover Data: Land cover data were derived from satellite imagery, supplemented by on-site inspections for classification accuracy. These data informed the assessment of NBS feasibility. The land cover distribution is presented in Figure 3 and Tables 1 and 2
- Subsoil Characteristics: Urban subsoils, influenced by anthropogenic factors, were mapped using geotechnical data from the 2019 Structural Plan of Pisa, GEOscopio portal and the National Archive of Subsoil Surveys (accessible at https://sgi2.isprambiente.it/mapviewer/). Soil permeability was calculated based on technical guidelines (Soil Science Division Staff. 2017).
- Digital Terrain Model (DTM): A high-resolution Digital Terrain Model (DTM), with a 1m × 1m grid, was obtained from the Regional Mapping Portal for topographic analyses
- Digital Terrain Model (DTM): A high-resolution Digital Terrain Model (DTM), with a 1m × 1m grid, was obtained from the Regional Mapping Portal for topographic analyses.
- Directly Connected Impervious Area (DCIA): The DCIA, a critical factor for surface runoff, was estimated as a percentage of impervious surfaces based on land use and EPA guidelines (Soil Science Division Staff, 2017).

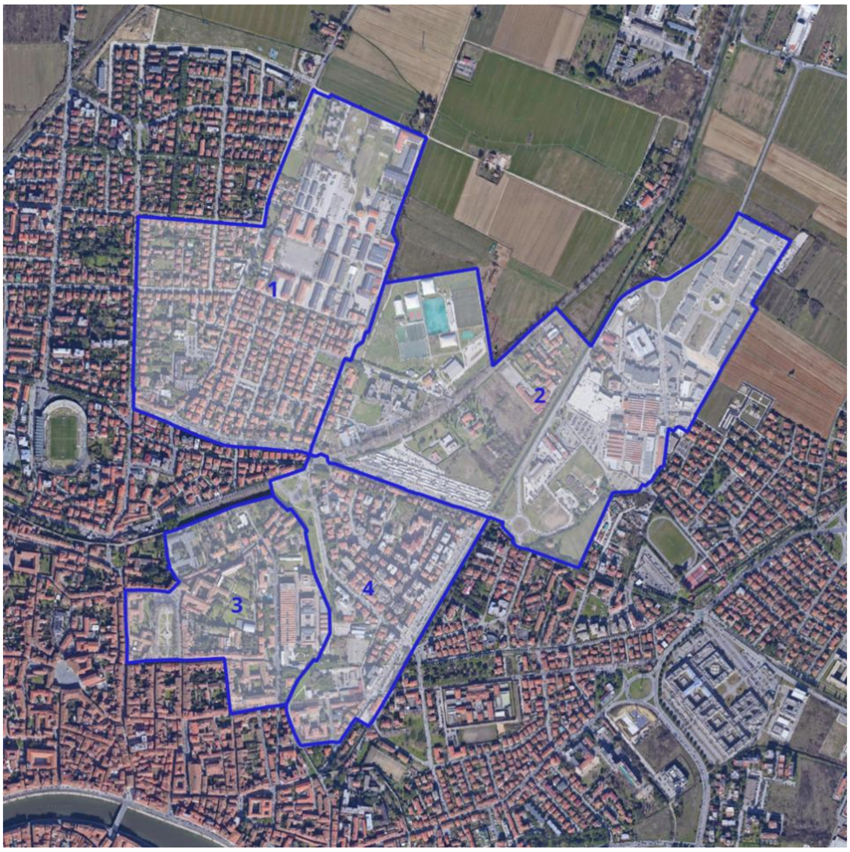

Figure 2: Map of the study areas (image by the authors)

Figure 3: Land cover of the study area (image by the authors)

2.3. i-Tree Hydro Plus

To model hydrological impacts, the study employed i-Tree Hydro Plus, a module within the i-Tree suite developed by the USDA Forest Service. This tool simulates urban water movement by accounting for land cover, soil properties, vegetation, and precipitation patterns. It integrates the UFORE-Hydro model and features statistical tools derived from the EPA SWMM model for evaluating green infrastructure.

Key input datasets include the Digital Elevation Model, meteorological data, land cover characteristics, and soil properties. The software outputs detailed hydrological metrics, including runoff, water quality, vegetation-related impacts, and subsurface hydrology. While the tool provides precise results, its complexity and intensive data requirements make it most suitable for expert use.

2.4. Scenarios

Four scenarios were modeled to assess the hydrological impacts of NBS interventions (Table 3). The baseline scenario represents 2022 conditions. In the Green Roof (GR) scenario, 75% of flat roofs are converted into vegetated surfaces. The Permeable Pavements (PP) scenario assumes that 50% of public parking areas and 10% of private parking surfaces are replaced with permeable materials.

Table 1: Description of land cover in the four areas

	Z1		Z2		Z3		Z4	
	km^2	Z1 area distribution	km^2	Z2 area distribution	km^2	Z3 area distribution	km^2	Z4 area distribution
Impervious Cover	0,362	69%	0,429	65%	0,128	60%	0,171	70%
Pervious Cover	0,161	31%	0,230	35%	0,087	40%	0,074	30%
Total	0,523		0,659		0,215		0,245	

Table 2: Components of Impervious Cover area distribution divided by areas

	Z1		Z2		Z3		Z4	
	km^2	Z1 Impervious Cover area distribution	km^2	Z2 Impervious Cover area distribution	km^2	Z3 Impervious Cover area distribution	km^2	Z4 Impervious Cover area distribution
flat roof	0,042	8%	0,013	2%	0,014	6,5%	0,014	6%
parking	0,060	11%	0,009	1%	0,014	6,5%	0,014	6%
other	0,260	50%	0,407	62%	0,100	47%	0,143	58%
Total	0,362	69%	0,429	65%	0,128	60%	0,171	70%

Table 3: Description of scenarios

Scenario	**Strategy**	**Description**
Base	-	Current state
GR	Green Roof	Transform 75% of flat roofs into green roofs
PP	Permeable Pavement	Convert 50% of the areas currently designated for parking and 10% of the predominantly pervious private areas into Permeable Pavements.
RG	Rain Garden	Creation of rain gardens within existing green areas

The Base scenario refers to the input data from 2022, while the other scenarios hypothesize the implementation of NBS systems.

In the GR scenario, it was assumed that 75% of flat roofs would be converted to green roofs.

The PP scenario involves the installation of permeable pavements on 50% of public parking surfaces and 10% of private parking areas.

In the RG scenario, the implementation of rain gardens was evaluated for an area equivalent to 10% of green spaces and residual green areas in zones Z1, Z3, and Z4, while in zone Z2, it was evaluated at 50%. This difference in distribution is related to the characteristics and extent of green areas in the various zones: Z2 is a peripheral and much less urbanised area compared to the other three and is characterised by large tracts of abandoned land.

The land cover distributions for each scenario and the baseline condition are outlined in Table 4

Table 4: Description of land cover in the four scenarios

	Z1							
	Base		GR		PP		RG	
	km2	%	km2	%	km2	%	km2	%
Tree Cover	0,007	1,32%	0,007	1,32%	0,008	1,50%	0,007	1,32%
Pervious Cover	0,158	30,27%	0,161	30,84%	0,163	31,10%	0,158	30,27%
Impervious Cover	0,358	68,41%	0,355	67,84%	0,353	67,41%	0,358	68,41%
	Z2							
	Base		GR		PP		RG	
	km2	%	km2	%	km2	%	km2	%
Tree Cover	0,014	2,13%	0,014	2,69%	0,015	2,27%	0,014	2,13%
Pervious Cover	0,226	34,35%	0,250	47,74%	0,234	35,50%	0,226	34,35%
Impervious Cover	0,419	63,52%	0,395	75,56%	0,410	62,23%	0,419	63,52%
	Z3							
	Base		GR		PP		RG	
	km2	%	km2	%	km2	%	km2	%
Tree Cover	0,004	1,70%	0,004	0,70%	0,005	2,12%	0,004	1,70%
Pervious Cover	0,084	38,98%	0,091	17,38%	0,085	39,50%	0,084	38,98%
Impervious Cover	0,127	59,32%	0,120	22,97%	0,125	58,38%	0,127	59,32%
	Z4							
	Base		GR		PP		RG	
	km2	%	km2	%	km2	%	km2	%
Tree Cover	0,010	4,24%	0,010	1,98%	0,011	4,60%	0,010	4,24%
Pervious Cover	0,069	28,08%	0,077	14,67%	0,070	28,78%	0,069	28,08%
Impervious Cover	0,166	67,69%	0,158	30,13%	0,163	66,62%	0,166	67,69%

3. Results

The analyses carried out using the UFORE-Hydro model provide an assessment of the total surface runoff, dividing it into: Pervious Area Runoff, flow generated when the intensity of rain on a permeable surface exceeds the soil's infiltration capacity or when the soil is saturated; Impervious Area Runoff, when the amount of rain exceeds the retention capacity of impermeable surfaces; and Subsurface Runoff, flow generated by water filtering through the soil, influenced by soil transmissivity, slope, and soil water content.

In the following figures (Figures. 4, 5, 6, and 7), the results for each area can be seen.

In area Z1 (Figure 4), characterised half by a predominantly residential fabric with numerous green and/or equipped areas and the other half by a military area, the PP scenario significantly reduces total runoff, demonstrating greater effectiveness in stormwater management compared to other configurations.

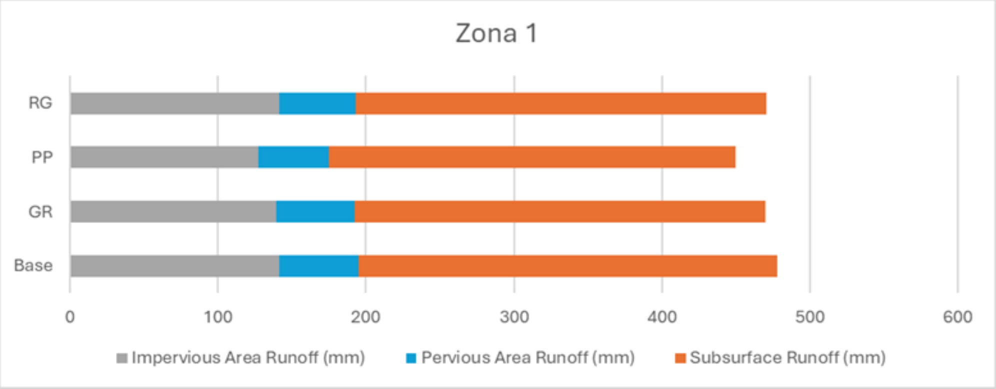

Figure 4: Results for Zone 4(source: by authors)

Z2 (Figure 5), on the other hand, is a peripheral area predominantly commercial with many unorganized green areas. In this case, the PP scenario is particularly effective in reducing runoff from both impervious and pervious areas. However, the RG configuration stands out for the greater reduction in subsurface runoff, suggesting excellent infiltration management. Overall, RG reduces total runoff by about 64.78 mm compared to the current situation, making it the most effective for overall water management.

Z3 (Figure 6) falls within the historic centre of the city of Pisa and differs from the other areas due to the marked presence of school buildings and public green areas. The GR scenario significantly reduces the total runoff in Z3, showing greater effectiveness in stormwater management compared to other configurations.

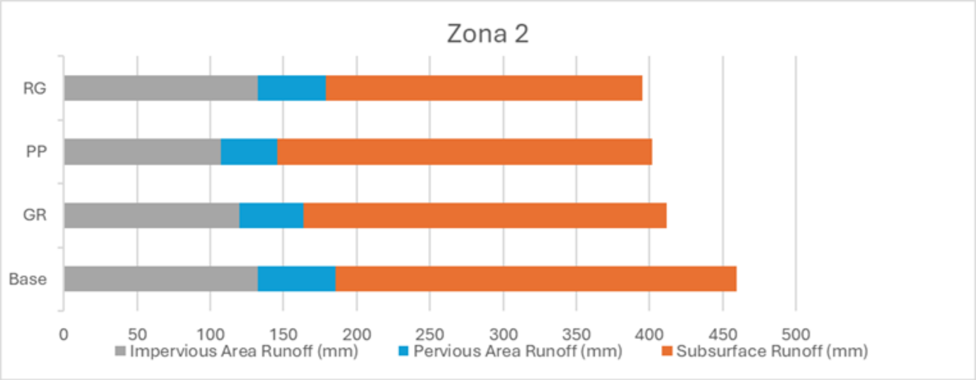

Figure 5: Results for Zone 2(source: by authors)

In Z4 (Figure 7), an area closer to the historic centre characterised by a dense residential fabric, the GR and PP scenarios similarly reduce runoff from impervious areas. However, GR is the most effective in reducing total runoff compared to the current situation, making it the best in stormwater management.

The results obtained show that, in general, the installation of permeable pavements (PP scenario) is effective in reducing runoff from both impervious and pervious areas, particularly suitable for Z1 and Z2, while the installation of green roofs (GR scenario) seems effective in reducing subsurface and total runoff and is particularly suitable for Z3 and Z4 areas. The creation of rain gardens (RG scenario) has variable effects, sometimes reducing runoff more than other configurations (Z2) and sometimes less (Z3 and Z4).

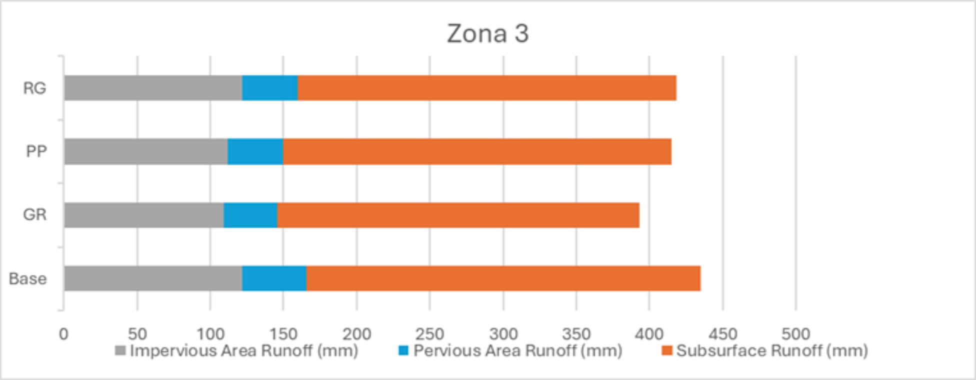

Figure 6: Results for Zone 3(source: by authors)

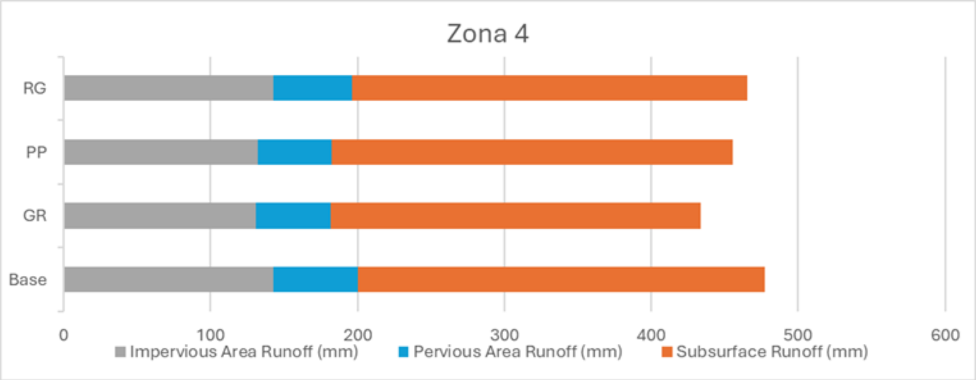

Figure 7: Results for Zone 4(source: by authors)

4. Discussion

This study evaluated the potential of NBS, specifically green roofs, permeable pavements, and rain gardens, for improving stormwater management and mitigating flood risks in urban areas. Using i-Tree Hydro Plus, the research focused on four zones in Pisa, Italy, and demonstrated that NBS can significantly reduce surface runoff, thereby enhancing urban resilience to flooding and contributing to sustainable development. However, the study also underscored substantial challenges associated with hydrological modeling and the practical implementation of NBS in urban contexts.

The hydrological benefits observed in Pisa align with findings from other cities. For example, research by Song (Song et al., 2020) has shown that although increasing urban green spaces have a positive impact on stormwater management, particularly influencing runoff, their mitigation remains limited unless accompanied by other NBS solutions, such as green roofs and significant reductions in impervious surfaces. Bortolini and Brasola (2022) reported that rain gardens in Padua reduced runoff by 34–41%, while our study highlighted the complementary effects of combining green roofs and permeable pavements. Similarly, Busca and Revelli (2022) demonstrated significant runoff reductions in "Le Vallere" Park, Turin, emphasizing the role of urban green spaces in improving water management. In Szeged, Hungary, Csete & Gulyás (2021) found that districts with higher vegetation and pervious surfaces achieved better hydrological outcomes, echoing our findings that Pisa's zones with higher impervious surfaces experienced more runoff. Collectively, these results confirm that targeted, context-specific interventions are critical for maximizing the benefits of NBS.

Despite these promising outcomes, the study identified key barriers. Accurate modeling using i-Tree Hydro Plus requires detailed input data, such as meteorological variables, land cover, soil properties, and pollutant levels. Many of these datasets were either unavailable or insufficiently detailed, necessitating reliance on default values that may compromise model accuracy. This issue mirrors challenges reported in studies from Turin and Szeged, where data scarcity similarly limited the precision of simulations. Additionally, the complexity of i-Tree Hydro Plus presents a significant hurdle. Its steep learning curve and non-intuitive interface make it difficult for non-specialists to use, restricting its broader application in public planning contexts. Effective implementation also requires interdisciplinary collaboration among hydrologists, urban planners, geologists, and agronomists, resources often unavailable to public entities.

The challenges associated with maintaining and implementing NBS are particularly relevant in urbanized and historic settings. Similar to Padua, where Bortolini and Brasola (2022) emphasized the need for ongoing maintenance to ensure the functionality of NBS, Pisa will also require consistent upkeep to sustain these systems. Historical preservation regulations may further constrain large-scale interventions in Pisa's historic zones, adding an additional layer of complexity to their implementation.

Overall, this study highlights both the potential and limitations of i-Tree Hydro Plus as a tool for evaluating NBS systems. While it provides valuable insights into the hydrological benefits of these solutions, its operational challenges, including data requirements, technical complexity, and reliance on multidisciplinary expertise, limit its accessibility beyond research contexts. Addressing these barriers is critical to scaling up the application of NBS and bridging the gap between research and real-world implementation.

Future efforts should prioritize the development of user-friendly modeling tools with streamlined interfaces and automated data integration, reducing reliance on technical expertise. Enhanced access to comprehensive, up-to-date environmental datasets would also improve modeling accuracy and simplify data collection processes. Furthermore, fostering interdisciplinary training programs and collaborations among urban planners, hydrologists, and environmental scientists is essential for effectively integrating NBS into urban planning. Finally, future research should expand on this study by exploring the long-term impacts of NBS on water quality, pollutant removal, and urban ecosystem health, ensuring that these solutions are fully optimized for diverse urban contexts

5. Conclusion

This study explored the potential of NBS, such as green roofs, permeable pavements, and rain gardens, to enhance stormwater management and mitigate flood risks in four zones of Pisa, Italy. Using i-Tree Hydro Plus software, the findings revealed that NBS can significantly reduce surface runoff, contributing to urban resilience and sustainable development. These results align with similar studies in Padua, Turin, Szeged and Luha, confirming the capacity of NBS to address urban hydrological challenges and adapt to climate change.

While the hydrological benefits of NBS are evident, the study also revealed substantial challenges that limit their practical application. The lack of detailed, localized data, reliance on default software inputs, and the technical complexity of tools like i-Tree Hydro Plus hinder accessibility for non-specialists and public entities. Moreover, the requirement for interdisciplinary expertise, spanning hydrology, agronomy, and urban design, creates additional barriers to widespread adoption, particularly in resource-constrained contexts. These findings are consistent with prior research, underscoring systemic obstacles that must be addressed to integrate NBS into urban planning.

To overcome these challenges, several key actions are necessary. The development of user-friendly software that automates data integration and simplifies hydrological modeling would make these tools more accessible to practitioners. Improved availability of detailed and updated environmental datasets would enhance the accuracy of NBS simulations while fostering interdisciplinary collaboration through training and policy support would help bridge the gap between research and implementation.

This study reaffirms the critical role of NBS as an effective, sustainable solution for managing urban stormwater and reducing flood risks. By addressing the operational and technical barriers identified, policymakers and urban planners can unlock the full potential of NBS, advancing climate resilience and sustainable urban development. Future research should expand on this work, focusing on the long-term impacts of NBS on water quality, pollutant removal, and urban ecosystem health, ensuring their benefits are fully realized in diverse contexts.

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Ethics approval

Not applicable.

Conflict of interest

The authors declare that there is no competing interest.

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