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To cite this article: Yu Chen *et al* 2025 *IOP Conf. Ser.: Earth Environ. Sci.* **1546** 012004

IOP Conf. Series: Earth and Environmental Science **1546** (2025) 012004 doi:10.1088/1755-1315/1546/1/012004

Predicting the impact of Nature-based Solutions on rainwater management through urban analysis

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Abstract. The increasing frequency and severity of rainfall events, driven by rapid urbanization and climate change, are progressively affecting urban environments and communities. In response, Nature-based solutions (NbS) have proven highly effective to address these challenges while delivering multiple co-benefits. The urban fabric forms an essential part of urban systems and represents potential areas for NbS implementation. However, not all areas can be realistically transformed. This paper reports an investigation into different NbS for urban rainwater management and how they can be integrated with the existing urban fabric at the neighborhood scale. The study considers the combination of NbS, maps the urban fabric structure with different layers through urban analysis to develop alternative design scenarios, and uses Bolognina neighborhood, Bologna (Italy), as a test bed to further evaluate and discuss the potential of NbS in real-world urban conditions. The findings offer insights for urban planners, designers, and architects who aim to improve neighborhood resilience for urban rainwater management.

1. Introduction

Rapid urbanization has led to increased land consumption and extensive soil sealing, defined as the permanent coverage of soil with fully or partially impermeable artificial materials (1). In response, the European Commission has set a target to achieve "no net land take" by 2050, as soil sealing increases surface runoff, reduces natural water infiltration, and intensifies the urban heat island (UHI) effect (2). These negative impacts are further exacerbated by climate change, which heightens cities' vulnerability to natural hazards, such as more intense rainfall events (3).

Nature-based Solutions (NbS) have emerged as a promising approach. Wide-scale implementation of NbS—such as green roofs, pervious pavements, and bioretention systems—has proven effective in mitigating urban soil sealing while delivering multiple co-benefits, including improved rainwater management, enhanced environmental quality, and better public well-being and health (4). The urban fabric, defined as the physical characteristics of the city, plays a critical role in determining how cities respond to these challenges.

Despite existing studies already demonstrating NbS potential, the practical implementation at a wider scale in the urban environment is still underexplored. A comprehensive analysis of the relationship between urban fabric and the applicability of NbS, along with an in-depth exploration of its feasibility under real-world urban conditions, is site-specific and therefore necessary for every urban context. Furthermore, there is a gap in methodologies for studying existing cities, particularly in cases of refurbishment, requalification, and regeneration. This study aims to address these gaps by: (i) redefining urban fabric from a new urban analysis perspective, specifically by categorizing the city into two hierarchical domains—ground level and roof level, and (ii) developing balanced and implementable design scenarios that bridge the gap between ideal response and real-world urban conditions.

Using the Bolognina neighborhood in Bologna, Italy, as a test bed, this study evaluates and discusses the potential for integrating NbS at the neighborhood scale under real-world urban conditions. The findings are intended to offer valuable insights for urban planners, designers, and architects seeking to enhance community resilience and improve urban rainwater management.

2. Methodology and materials

2.1Description of the main steps of the methodology

The adopted research methodology is based on the following steps:

1- Define the urban structures into two domains.

Urban morphology adopts a hierarchical perspective, recognizing cities as compositions of common elements—streets, blocks, plots, and buildings—configured uniquely in each urban context (5). Traditional urban morphology offers a 2D perspective, this study introduces a 3D perspective, distinguishing two hierarchical domains: the ground-level domain and the roof-level domain. This 3D perspective is needed because impermeable surfaces exist at both levels—at the ground level (e.g., sidewalks, parking areas, and other paved or unpaved surfaces) and the roof level (e.g., pitched and flat roofs). Furthermore, existing literature on rainwater management solutions often categorizes interventions based on their application within these two domains. Figure 1 presents a classification of urban fabric types across two hierarchical domains and further subdivides the types.

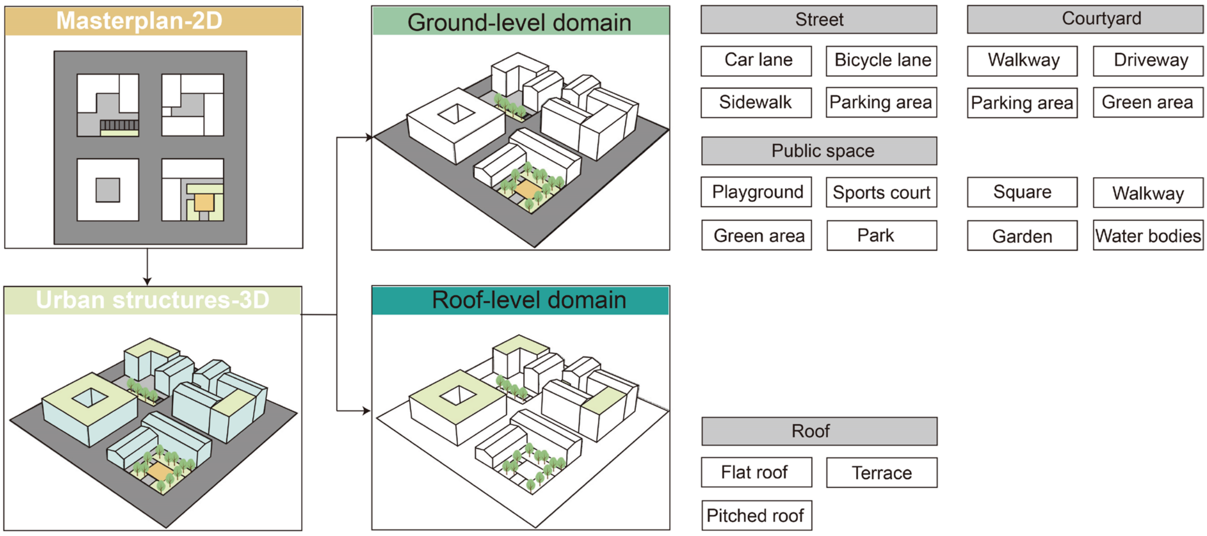

Figure 1. Classification of urban fabric types.

2- Alternative NbS for rainwater management.

It is essential to consider the characteristics of NbS during the early stages of the selection process and their typical applications. Table 1 summarizes the common types of NbS across these two domains that are more suitable to implement in urban areas, along with their variations, performance, applicable conditions, and benefits (6). These NbS are categorized into three groups based on their characteristics: (i) green solutions, which primarily rely on vegetation for rainwater management; (ii) hybrid green-grey solutions, which combine elements of green and grey solutions; and (iii) grey solutions, which predominantly consist of non-vegetative water storage systems.

Table 1. Overview of NbS characteristics.

Ground-level NbS type	Performance	Applicable conditions	Benefits
Bioretention Systems (BS)	The main hydrological function is rain interception. The effectiveness depends on the size of the system relative to its catchment.	BS can be integrated into existing landscape areas, and implemented in small shared public spaces, sidewalks, etc.	Rainwater management (quantity and quality), improve air quality, reduce noise pollution, control microclimate, enhance biodiversity and visual amenity.
Pervious Pavements (PP) 1.Porous Asphalt (PA); 2.Pervious Concrete (PC); 3.Grid Pavement (concrete or plastic pavers) (GP); 4.Permeable Interlocking Concrete Pavement (PICP)	The main hydrological function is infiltration. The permeability coefficient and runoff coefficient describe the performance.	1.PA: car parks, private driveways, lightly trafficked roads, playgrounds, and schools. 2.PC: sidewalks, car parks, access route to parking area and lightly trafficked roads. 3.GP: car parks, private driveways, schools, lightly trafficked roads. 4.PICP: walkways, driveways, car parks, alleys and low-speed roads.	Rainwater management (quantity and quality), reduce traffic noise and mitigate UHI effect.
Tanks	The main hydrological function is water storage. The volume determines the performance.	Tanks can be installed beneath car parks and other public open spaces.	Possible re-use in conjunction with other NbS.
Roof-level NbS type			
Green Roofs (GR) 1.Extensive Green Roof (EGR); 2.Intensive Green Roof (IGR); 3.Semi-intensive Green Roof (SGR)	The main hydrological function is water storage capacity. The runoff coefficient describes the performance.	Suitable for flat or low-sloped roofs.	Rainwater management (quantity and quality), mitigate UHI effect, energy saving, reduce noise pollution, enhance wildlife and biodiversity.
Blue Roofs (BR)	The main hydrological function is water storage. The volume determines the performance.	Suitable for flat or low-sloped roofs.	Rainwater management (quantity), energy saving.

3- Develop a matrix of applicability and design scenarios.

The aforementioned two steps lay the foundation for the development of the applicability matrix, which is designed to help policymakers choose suitable NbS for different urban surface types. The vertical axis of the matrix lists the diverse urban surface types identified within the study area, while the horizontal axis categorizes different NbS types along with their hydrological performance indicators.

Subsequently, matching rules and a scoring system are established. The rules are based on the functional requirements of the urban fabric layers and the applicability of the proposed NbS. The scoring system is divided into four levels: (i) technically impossible to implement, (ii) technically possible but functionally unsuitable, (iii) technically or functionally possible but not preferable, and (iv) preferable to implement. In addition, design criteria are established:

- Prioritize selecting urban surface types with high transformation potential, which is determined by three factors: material (permeable or impermeable), ownership (public, semi-public, or private), and dimension (area and proportion relative to total area). Transformation potential is classified as high, medium, or low.
- Where technically feasible, prioritize selecting NbS with better hydrological performance and measurable, relatively accurate evaluation indicators.
- Beyond hydrological benefits, consider additional environmental, social, and urban quality benefits.

When using the matrix, selecting a cell (highlighted in green) indicates the adoption of a specific NbS for a given urban surface. Notably, each urban fabric type can be assigned only one NbS.

4- Calculation of the hydrological performance.

This study adopts a simplified method intended for the preliminary estimation of annual runoff volume. However, it cannot substitute for detailed urban drainage models that are specifically calibrated for local climatic conditions, particularly given the high sensitivity of hydrological responses to climate variability.

The runoff coefficient (Ψ) is a parameter that is used in surface hydrology to describe the water holding capacity (water retention) in medium-long time (i.e. one season or one year). It is defined as the ratio of the volume superficially drained during rainfall to the total volume of precipitation during a certain period (7). This study employs the following formula to calculate runoff volume (Vr):

$$V_r = A \times P \times \Psi$$

where A is the surface area (m^2) and P is the yearly rainfall (mm).

The surface area is measured using AutoCAD software with a .dwg map file obtained from the municipal government website (8). Yearly rainfall data are sourced from meteorological statistics available in official city weather databases (9). Since this study focuses on improving rainwater management under regular conditions rather than during extreme rain events, the yearly rainfall data are determined based on the average annual precipitation from 2016 to 2023 to ensure greater accuracy in the calculations. The runoff coefficients used in this study are derived from existing literature or technical standards (10,11). The result of this formula represents the total annual runoff volume for a specific surface type, typically expressed in liters (L) or cubic meters (m^3). The total annual runoff volumes for the ground-level domain and the roof-level domain are obtained by summing the results of all individual layers within each domain.

The current state of the study area is used as the reference surface. To quantify the improvement in rainwater management, baseline scenario data (pre-transformation) are compared with design scenario data (post-transformation). The difference value between the two scenarios is the runoff volume improvement, while the improvement percentage is determined by dividing the difference value by the baseline scenario data.

2.2 Case Study of the Bolognina Neighborhood, Bologna, Italy

The described methodology serves as a test-bed site for the Bolognina neighborhood in Bologna, Italy. The 1899 urban plan granted the neighborhood a distinctive grid pattern, characterized by alternating plots of residential buildings, open courtyards, public services, and shops (12).

Figure 2 highlights the selected study area within Bolognina, chosen based on two key factors: (i) Diverse urban surface types – the study area includes a variety of urban surface types, such as flat roofs, pitched roofs, and terraces at the roof level, as well as streets, courtyards, and public spaces at the ground level. This diversity makes it particularly suitable for implementing various NbS. (ii) A representative medium-density neighborhood – the selected area exemplifies a typical medium-density area, characterized by moderate building density and height, along with a layout that integrates green and open spaces. This structural composition enhances its potential for replication in similar urban contexts.

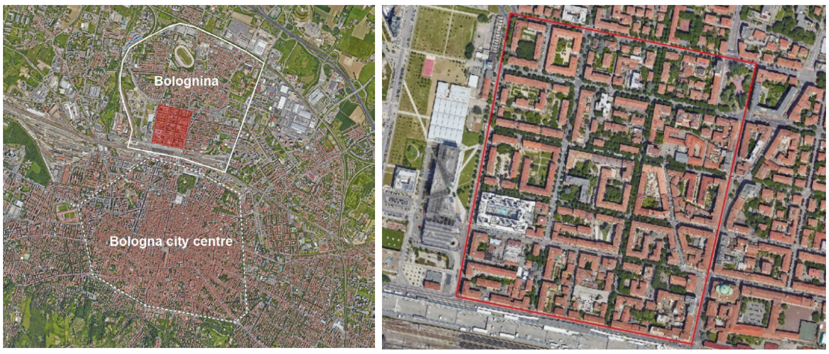

Figure 2. (a) Location of Bolognina neighborhood; (b) Study area in the Bolognina neighborhood.

3. Results and Discussion

3.1Site analysis

The current state of the study area was analyzed and is summarized in Table 2. In the ground-level domain, streets are prioritized for transformation, accounting for 51% of the area, followed by courtyards at 47%. From a practical perspective, within the street group, car lanes occupy the largest area; however, their transformation potential is low due to limited pervious pavement options. In contrast, parking areas have high transformation potential, supported by extensive research on permeable materials for rainwater management and UHI mitigation. The transformation potential for sidewalks is also high, as they represent the second-largest surface area. The bicycle lane transformation potential is theoretically high; however, since most sidewalks and bike lanes in this area are combined, and standalone bike lanes occupy a minimal area. Given the cost-benefit considerations of transformation, this is assessed as medium potential.

Table 2. Current state of the study area.

Group	Type	Material	Ψ	Area (m^2)	Transformation potential
Street (51%)	Car lane	Asphalt	0.90	53451.63	Low
	Parking area	Asphalt	0.90	18855.99	High
	Sidewalk	Concrete	0.85	20630.41	High
	Bicycle lane	Asphalt	0.90	2513.96	Medium
Courtyard (47%)	Parking area	Asphalt	0.90	9674.02	High
	Green area	-	0.10	26998.16	Low
	Driveway	Concrete	0.85	18064.08	Medium
	Walkway	Concrete	0.85	33936.08	High
Public space (2%)	Sports court	Asphalt	0.90	427.41	High
	Square	Interlocking paving	0.70	700.87	High
	Green area	-	0.10	2376.67	Low
	Walkway	Concrete	0.85	779.56	High
Roof (100%)	Flat roof	Waterproofing membrane	0.90	17726.84	High
	Terrace	Tiles	0.85	5189.48	Medium
	Pitched roof	Roof tiles	0.90	84726.75	Not applicable

For the courtyard group, its semi-private nature requires coordination with property owners, but its large share makes it a significant target for improving rainwater performance. Walkways have high transformation potential, similar to sidewalks in the street group. Green areas already offer good permeability, making their transformation a low priority, though they could be integrated with bioretention systems for additional benefits. Courtyard driveways, characterized by lower traffic volumes, have more pervious pavement options compared to car lanes in the street group, giving them medium transformation potential. Parking areas in courtyards also have high transformation potential, for the same reasons as those in the street group, with the added advantage of being less exposed to external factors, allowing for the consideration of aesthetically appealing pervious pavements, such as grass pavers.

Public spaces, although occupying only 2% of the total area, play a crucial role in sustainability and should be designed to maximize their ecological, social, and economic benefits. Green areas follow the same transformation principles as courtyards, while sports courts, squares, and walkways have high transformation potential due to their hard-paved surfaces and the availability of diverse pervious pavement options.

For the roof group, pitched roofs were excluded due to technical challenges, high costs, and the image of Bologna, whereas flat roofs are more viable for rainwater interventions. Terraces occupy a minimal area, so they are evaluated as having medium potential.

Based on these assessments, surfaces are categorized into three priority groups for transformation (see different shades of green in Figure 3). The first phase of transformation targets only the first group, the second phase expands to include both the first and second groups and the third phase encompasses all groups.

3.2 Applicability matrix and design scenarios

Balancing the functional requirements of urban surfaces with the hydrological performance, in particular water retention of NbS, an applicability matrix was developed (Figure 3). Implementation follows a phased approach, corresponding to three priority groups. High potential surfaces come first, PICP was chosen for parking area and sidewalk due to its superior rainwater performance, while GP (grass pavers) was used in courtyards for aesthetics. PA was applied to sports court for functionality, while PICP remained the preferred option for square and walkway. For flat roofs, IGR were implemented for their hydrological and ecological benefits. For medium-potential surfaces, PA was selected for bicycle lanes, and PICP for courtyard driveways, given their low-speed, light-traffic conditions. IGR were also prioritized for terraces. Low-potential surfaces were addressed last. PA was chosen for car lane, suited for traffic loads and good durability. BS was incorporated into green area to reduce runoff, filter rainwater, and enhance biodiversity.

All the layers of ground-level	Group 1-NbS 1 BS	Group 2-NbS 1 PA	Group 2-NbS 2 PC	Group 2-NbS 3 GP	Group 2-NbS 4 PICP	Group 3-NbS 1 Tanks
Related runoff coefficient	0.10	0.85	0.80	0.60	0.50	volume
Street layer-01 car lane		●●	●	●	●●	
Street layer-02 parking area	●●	●●●	●●●	●●	●●●	
Street layer-03 sidewalk	●●●	●	●●●	●	●●●	
Street layer-04 bicycle lane	●	●●●	●●	●	●●	
Courtyard layer-01 parking area	●●	●●●	●●●	●●●	●●●	●●
Courtyard layer-02 green area	●●●					●●
Courtyard layer-03 driveway		●●●	●●●	●●	●●●	
Courtyard layer-04 walkway	●●●	●	●●●	●●	●●●	
Public space layer-01 sports court		●●●	●	●	●	
Public space layer-02 square	●●●	●	●●●	●●	●●●	●●
Public space layer-03 green area	●●●					●●
Public space layer-04 walkway	●●●	●	●●●	●●	●●●	
All the layers of roof-level	Group 1-NbS 2 BR	Group 1-NbS 3 EGR	Group 1-NbS 4 IGR	Group 1-NbS 5 SGR		
Related runoff coefficient	volume	0.60	0.30	0.30-0.60		
Roof layer-01 flat roof	●●	●●●	●●●	●●●		
Roof layer-02 terrace	●	●●	●●●	●●●		
Roof layer-03 pitched roof	●	●	●	●		

Legend

(grey)	Technically impossible to implement	(light green)	First priority group
●	Technically possible but functionally unsuitable	(medium green)	Second priority group
●●	Technically or functionally possible but not preferable	(dark green)	Third priority group
●●●	Preferable to implement		

Figure 3. Applicability matrix and design scenarios.

In the following sections, abbreviations are used to represent different urban fabric layers. For example, S01 denotes the car lane, C01 refers to the parking area, and P01 indicates the sports court, among others.

3.3. Visualization of outcomes and performance evaluation

The transformation process was divided into three phases, resulting in three distinct design scenarios. Figure 4 presents the visual maps between the baseline scenario (current state) and the proposed design scenarios. The performance evaluation and derived benefits of each scenario are outlined below. It is important to note that this study provides only an approximate assessment of the impact of NbS.

- Baseline scenario: The current state of the study area was used as the reference surface. The total annual runoff volume is 95,170,208.29 m^3 at the ground level and 64,638,304.34 m^3 at the roof level.
- Scenario 1: The total annual runoff volume is 75,115,458.68 m^3 at the ground level and 57,522,750.77 m^3 at the roof level. This represents a 21% reduction in runoff at the ground level and an 11% reduction at the roof level compared to the baseline scenario. Beyond runoff reduction, these NbS contributed to water quality improvement.

Implementing PP help reduce traffic noise and mitigate the UHI effect, while IGR provide biodiversity benefits, enhance thermal performance, and reduce building energy costs.

- Scenario 2: The total annual runoff volume is 70,801,622.38 m³ at the ground level and 55,613,281.60 m³ at the roof level. This results in a 26% reduction at the ground level and a 14% reduction at the roof level. The benefits remain consistent with those observed in the scenario 1. Additionally, the integration of IGR on terraces provide easily accessible green spaces for residents, fostering recreational opportunities and enhancing urban quality.
- Scenario 3: The total annual runoff volume is 69,013,665.36 m³ at the ground level and 55,613,281.60 m³ at the roof level. This scenario achieves a 27% reduction in ground-level runoff and a 14% reduction at the roof level. The implementation of multiple NbS also provided a wide range of co-benefits. Environmentally, it regulated the microclimate, enhanced urban quality, and increased biodiversity. Socially, it fostered social interactions and improved health and well-being. Economically, it elevated property values and attracted business and investment.

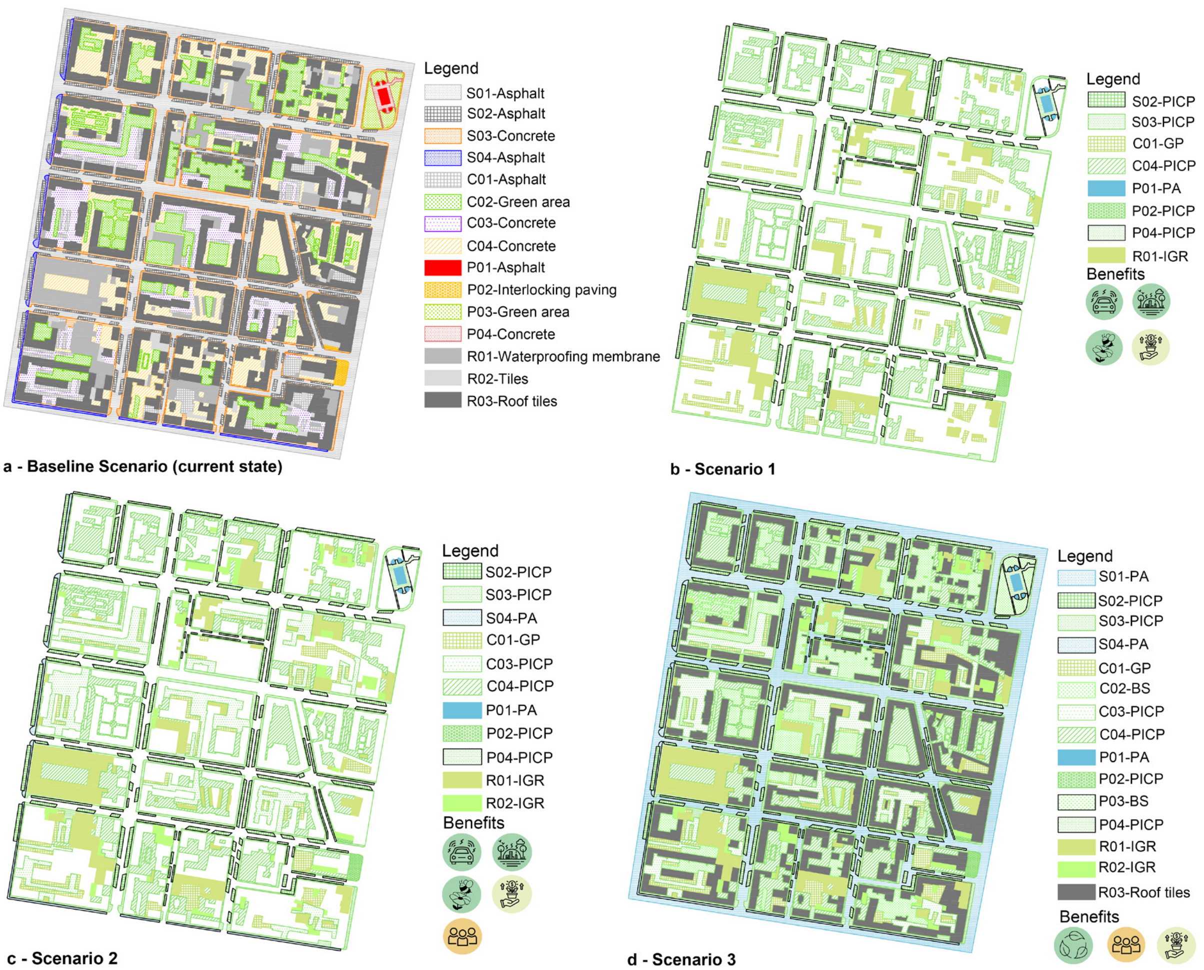

Figure 4. Visual maps of pre-transformation and post-transformation.

The results indicate that even with the maximum transformation of all urban surfaces within the study area, ground-level rainwater management improvement remains below one-third (27%), while roof-level improvement reaches 14%. This highlights the practical constraints of NbS implementation under real-world urban conditions. Rather than contributing solely to rainwater management, NbS further contributes to urban resilience by enhancing environmental quality, social functionality, and potential economic benefits.

4. Conclusion

This paper aims to explore the feasibility of implementing NbS within real-world urban constraints. The hydrological performance, particularly water retention, was evaluated, and the results showed that all design scenarios outperformed the reference surface, demonstrating the effectiveness of transformation. The findings indicate that the design scenarios yield promising results in terms of runoff volume reduction, which is proportional to the amount of de-sealed surface. Nonetheless, the benefits of NbS extend beyond rainwater management, offering multiple co-benefits that are crucial for enhancing neighborhood resilience. In addition, to achieve more effective rainwater management, other strategies are needed in conjunction with NbS.

In conclusion, the findings of this study can serve as a guideline for potential stakeholders during the early stages of considering the implementation of NbS. NbS should be designed as interconnected systems, and it is essential to employ comprehensive tools for predicting rainwater management performance during their evaluation. Future research should expand the analysis to diverse urban contexts with varying densities and land-use patterns, which would help develop a more comprehensive applicability matrix for broader implementation and enhanced urban resilience.

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