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# Prioritising nature-based solutions for urban flood mitigation in public and private spaces: A study in Trento, Italy

Chiara Parretta [a], Chiara Cortinovis [a], Giuseppe Formetta [b], Davide Geneletti [a,*]

[a] *Planning for Ecosystem Services and Urban Sustainability Lab, Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano 77, 38123, Trento, Italy*

[b] *Department of Civil, Environmental and Mechanical Engineering, University of Trento, via Mesiano 77, 38123, Trento, Italy*

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ABSTRACT

Urban flooding is a hydrologic–hydraulic phenomenon influenced by climate change and driven by intense urbanization. Nature-Based Solutions (NBS) can help mitigate this phenomenon by providing water-regulating ecosystem services. NBS spatial prioritisation is increasingly used to identify which interventions should be implemented and where. However, most existing approaches are based on simple hydrologic analyses of surface runoff that overlook hydraulic pressure within the sewer system. Moreover, opportunities for NBS implementation are often assessed without distinguishing between public and private spaces, thus missing key information for decision-making. This study develops and tests a spatially explicit method at the subcatchment level that combines three hazard-contributing indicators (Runoff Coefficient, Flooding Ratio and Surcharging Ratio), with suitability analysis for different NBS types in both public and private spaces. The testing application in Trento, Italy, shows that green roofs, rain gardens, and permeable pavements generate distinct priority patterns, and that the three indicators capture complementary and spatially heterogeneous hazard contributions at the subcatchment level. Results also highlight that private areas suitable for NBS implementation recur more often in subcatchments classified as high priority under multiple hazard-contributing indicators, whereas suitable public areas are fewer and predominantly associated with a single indicator. By combining hydrologic and hydraulic hazard contribution with public and private suitability for NBS implementation, the study provides a spatially-explicit prioritisation tool for urban planning, translating hazard contributions into spatial priorities to identify where different NBS types should be most appropriately targeted within the urban fabric.

## 1. Introduction

Urban flooding is a hydrologic-hydraulic phenomenon occurring when runoff from impervious surfaces exceeds the sewer system's capacity (Yazdanfar & Sharma, 2015). This phenomenon is influenced by changes in rainfall patterns associated with climate change, and is strongly driven by the expansion of impervious areas due to intense urbanization (e.g. Mahmoud & Gan, 2018; Miller & Hutchins, 2017; Skougaard Kaspersen et al., 2017; Zhou et al., 2019). As runoff volumes increase, conventional grey infrastructures may be inefficient in conveying flows and managing peak discharges, creating urban flood hazard conditions that lead to sewer system overload and surface flooding (Chen et al., 2021; Mailhot & Duchesne, 2010). Moreover, projected increases in rainfall intensity are expected to further load the urban sewer systems, challenging their long-term resilience (Ye et al., 2025). In response, integrated approaches that combine conventional grey infrastructures with green solutions are largely being explored to mitigate urban flooding (Dąbrowska et al., 2023; John & Bhagyanathan, 2024; Pour et al., 2020; Wang et al., 2025; Zhang et al., 2023).

Within this context, Nature-Based Solutions (NBS), defined as actions that protect, restore, and sustainably manage ecosystems while simultaneously delivering multiple benefits (United Nations Environment Programme, 2022), have gained increasing attention over the last decade (Castellar et al., 2021; Ferrario et al., 2024; Raymond et al., 2017). In cities, NBS contribute to urban flood hazard mitigation by providing water-regulating ecosystem services such as the reduction of peak flows (Lähde et al., 2023), the regulation of runoff and base flows (Chen and Chen, 2021), and the reduction of floods and drought impacts (Haines-Young, 2023; Miller et al., 2023; Oral et al., 2020).

To mainstream NBS into planning and increase urban flood

* Corresponding author.
*E-mail address:* davide.geneletti@unitn.it (D. Geneletti).

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resilience, cities need to identify what typology of NBS should be implemented, and where (Li et al., 2020; Sarabi et al., 2022). Green roofs, rain gardens, and permeable pavements are among the most frequently implemented and empirically tested interventions (Alves et al., 2024; Esraz-Ul-Zannat et al., 2024), and evidence shows that they can reduce runoff volumes and peak discharges in a range of 30–75%, depending on context and event magnitude (Esraz-Ul-Zannat et al., 2024). These typologies are characterised by different physical requirements (Castellar et al., 2021), making them suitable for different urban contexts. Green roofs can be installed on existing buildings, offering solutions in dense urban areas where open space is limited (Cortinovis et al., 2022). Rain gardens require dedicated green spaces, such as parks. Permeable pavements can replace impervious surfaces such as parking lots, without requiring land-use conversion, making them suitable in areas with limited land availability (Nature4Cities, 2018; World Bank, 2021). Determining where these NBS can be implemented requires assessing whether local physical conditions meet the requirements of each typology. In this context, suitability refers to the physical conditions that determine whether a specific NBS can be implemented in a given area (Alves et al., 2024; Li et al., 2020).

Identifying where NBS should be prioritised requires not only understanding where implementation is physically feasible, but also how different parts of the city contribute to urban flood hazard. Urban flood hazard assessment mostly relies on models that quantify runoff dynamics (Azadgar et al., 2024). For example, hydrologic models such as the InVEST Urban Flood Risk Mitigation model, based on the Curve Number (CN) method, provide estimates of runoff generation and retention capacity from land cover and soil characteristics (Azadgar et al., 2025; Leta & Adugna, 2024; Veisi Nabikandi et al., 2025), but they do not capture the hydraulic behaviour of runoff once conveyed through the sewer system. For this reason, cities are increasingly adopting coupled hydrologic–hydraulic models to analyse networks response under extreme rainfall events (Kumar et al., 2024). Among these, the Storm Water Management Model (SWMM) is a widely-used tool for simulating urban stormwater dynamics and supporting sewer system design and planning (Nanda et al., 2025; Zhou, 2014). It includes a dynamic hydrological rainfall-runoff model representing runoff generation from subcatchments, and a hydraulic model which simulates flow routing through conduits, junctions, and outfalls (Ferrans et al., 2022; Rossman, 2015; Rossman & Simon, 2022). SWMM outputs are typically reported at the level of individual conduits or nodes, such as conduit degree of filling, flow velocity thresholds, conduit surcharge, or node flooding volumes (e.g. Koc et al., 2021; Kourtis et al., 2021; Lähde et al., 2023). These outputs are useful for diagnosing local hydraulic behaviour, but not for prioritising spatial units where NBS should be implemented, thus limiting their direct applicability for planning purposes.

Only few studies have translated SWMM hydrologic and hydraulic outputs into spatially-explicit indicators at subcatchment level. La Rosa and Pappalardo (2020) derive a conduit-level local hydraulic pressure indicator based on the maximum product of flow depth and velocity, and then spatially transfer this value to land-use polygons by assigning each polygon the highest hazard value among the adjacent street segments. Pelorosso et al. (2018a) aggregate runoff and flooding metrics into a composite resilience index at the subcatchment scale. However, these approaches remain focused on local hydraulic pressure and do not capture how hydrologic and hydraulic effects propagate across the sewer system. As a result, there is still no systematic approach to simplify coupled hydrologic–hydraulic model outputs into spatially explicit indicators that can guide the prioritisation of subcatchments for NBS implementation, explicitly accounting for upstream hydrologic units that influence downstream hydraulic pressures.

Among the areas for NBS implementation in cities, public spaces are widely targeted due to institutional control, regulatory feasibility, and alignment with municipal policy objectives (Op de Beeck et al., 2024). In contrast, despite representing a substantial percentage of urban areas (Colding et al., 2006; Dewaelheyns et al., 2014; Gaston et al., 2005; Loram et al., 2007; Mathieu et al., 2007), private spaces are often overlooked (Lähde et al., 2023; Schmidt & Walz, 2021), primarily due to ownership constraints and the lack of policy tools to guide interventions (Dhakal & Chevalier, 2017; Ronchi et al., 2020). Yet evidence shows that in dense urban areas, with limited public space availability, private spaces can substantially increase pervious surfaces and local water-flow regulation (Cavan et al., 2021; Pugliese et al., 2022). Recent methodological approaches therefore emphasise the need to distinguish public and private spaces when assessing greening interventions or NBS potential (Privitera & Jelo, 2025). However, despite this growing evidence, private spaces remain marginally integrated into planning strategies for NBS uptake (Carter & Fowler, 2008; Lähde et al., 2023; Teerlinck et al., 2024).

The present study aims to develop and test a spatially explicit method that combines three hazard-contributing indicators (Runoff Coefficient, Flooding Ratio and Surcharging Ratio) with suitability analysis for different NBS types, identifying opportunities for NBS implementation offered by public and private spaces. Specifically, the study addresses two main research questions: (1) How can urban subcatchments be prioritised for the implementation of different NBS types, considering both hydrologic and hydraulic contributions? (2) How do priorities vary when considering opportunities offered by public and private spaces? In doing so, the study provides a spatially-explicit prioritisation tool that translates hydrologic–hydraulic pressures into actionable priorities at the subcatchment scale, thereby identifying where NBS interventions should be targeted within the urban fabric.

## 2. Materials and methods

The methodology is structured into three main steps (Fig. 1):

- *Computing hazard-contributing indicators* (Section 2.1). This step involves setting up and running a hydrological–hydraulic model forced by extreme rainfall events over the study area. The model outputs are then summarised into three spatially-explicit hazard-contributing indicators, which defines how subcatchments contribute to hydrologic processes (runoff generation) and hydraulic pressure (flooding and surcharging) within the drainage system;
- *Identifying areas suitable for NBS implementation* (Section 2.2). The suitability for different NBS types is assessed using specific criteria. Suitable areas are classified into public and private spaces, and aggregated at the subcatchment scale.
- *Prioritising subcatchments for NBS implementation* (Section 2.3). The outputs of the previous two steps are combined, generating distinct prioritisation outputs for each NBS type and each hazard-contributing dimension (i.e. hydrological and 1D-hydraulic).

### 2.1. Computing hazard-contributing indicators

To characterise the hydrologic–hydraulic conditions of the case study area, we simulate the response to an extreme rainfall event using SWMM (version 5.2.4). A single-event simulation approach is adopted to model stormwater quantity, employing two modelling techniques: (i) the SCS-CN method (U.S. Department of Agriculture, 1986) to simulate spatially variable infiltration and runoff generation, and (ii) dynamic wave routing to model flow movement through the drainage system. The SCS-CN method accounts for variations in soil type and land use/-land cover (LULC). The dynamic wave routing method captures complex hydraulic phenomena such as pressurised flow, channel storage, flow reversal, backwater effects, and entrance/exit losses (Rossman, 2015). The hydraulic component refers to the 1D conveyance capacity of the sewer network as represented in SWMM; in this application we do not couple the SWMM model with 2D shallow-water or surface-flow models. However, the presented framework is general enough to be extended for

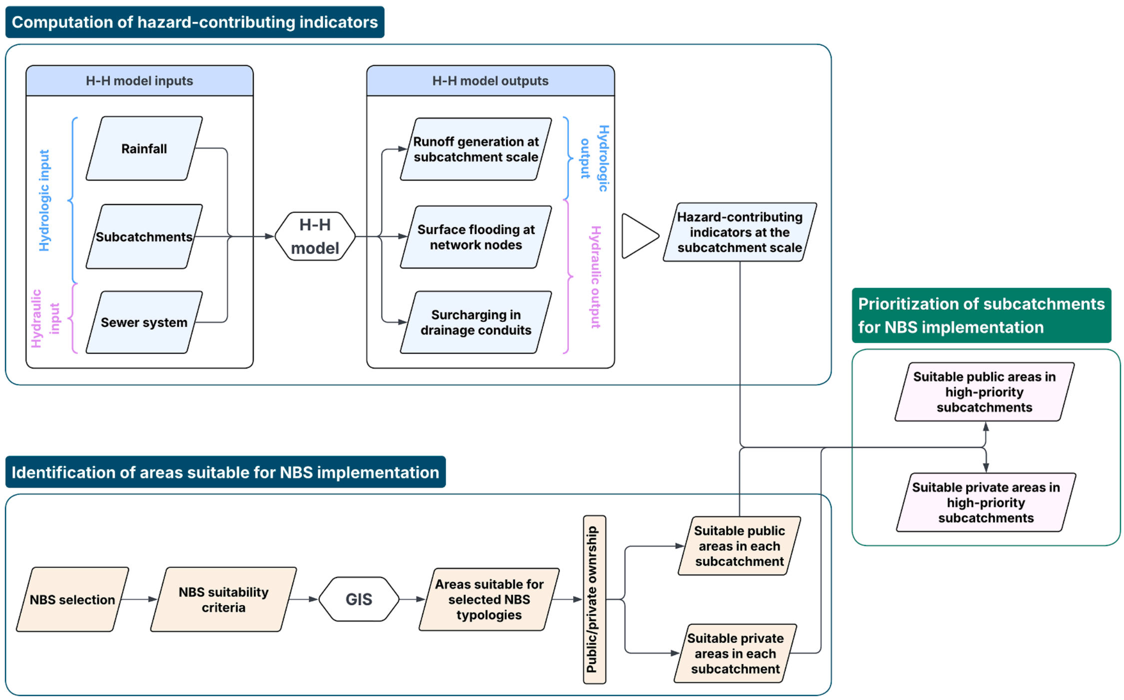


**Fig. 1.** Methodological steps to compute hazard-contribution, identify areas suitable for NBS implementation, and prioritise subcatchments.

such applications. Consequently, the indicators presented in the methodology quantify hazard-contribution within the scope of SWMM model (i.e. hydrological and hydraulic, in the sense of 1-dimensional flow in the urban drainage system), rather than providing a full representation of surface-flood hydraulics. In this study, SWMM is used to derive spatially explicit hazard-contributing indicators that support the prioritisation of subcatchments for potential NBS implementation.

To this end, SWMM model outputs were synthesised into three subcatchment-level indicators: the Runoff Coefficient (RC), the Flooding Ratio (FR) and the Surcharging Ratio (SR).

The Runoff Coefficient (RC) is a widely used indicator reflecting the hydrological contribution of each subcatchment to the simulated rainfall event. It is a direct SWMM output calculated as the fraction of total precipitation that becomes runoff at the subcatchment scale (Eq. (1)).

$$RC_i = V_{\text{runoff},\ i} / V_{\text{precip},\ i} \qquad [0,1] \tag{1}$$

where $RC_i$ is the Runoff Coefficient of subcatchment $i$, $V_{runoff,\ i}$ is the total runoff volume generated by subcatchment $i$, and $V_{precip,\ i}$ is the total volume of precipitation over the subcatchment $i$. Low values indicate subcatchments where only a small fraction of rainfall becomes runoff due to higher infiltration or storage capacity, whereas values approaching 1 reflect highly impervious areas where most precipitation is rapidly converted into surface runoff and afterwards to the conduits.

The Flooding Ratio (FR) and the Surcharging Ratio (SR) are two novel hazard-contributing indices proposed in this study, and are derived through a post-processing of SWMM outputs.

The Flooding Ratio (FR) quantifies the contribution of each subcatchment to flooding within the sewer system. It is defined as the fraction of a subcatchment's runoff that contributes to flooding at one or more downstream nodes along the conduits that link the subcatchment to its respective outfall (Eq. (2)). FR was computed through a post-processing procedure that reconstructs how runoff generated in each subcatchment propagates through the drainage network. The network was represented as a directed graph based on conduit connectivity, and runoff contributions were propagated downstream using a directed topological traversal of the network. At each node, the inflow attributable to each upstream subcatchment was reconstructed by proportionally distributing the incoming runoff among downstream conduits according to their connectivity. Flood volumes recorded at each node were then allocated back to upstream subcatchments in proportion to their reconstructed inflow contributions.

$$FR_i = \sum_{j=1}^{n} V_{\text{flood},\ i,j} \Big/ \sum_{j=1}^{n} V_{\text{flood},\ j} \qquad [0,1] \tag{2}$$

where $FR_i$ is the Flooding Ratio of subcatchment $i$, $n$ is the number of nodes in the branch linking subcatchment $i$ to its respective outfall, $V_{flood,\ j}$ is the total flood volume at node $j$, and $V_{flood,\ i,j}$ is the share of flood volume at node $j$ attributed to subcatchment $i$. Values close to zero reveal subcatchments whose runoff contributes minimally to downstream flooding, whereas values approaching 1 identify subcatchments that account for a large amount of the total flood volume within their drainage network.

The Surcharging Ratio (SR), quantifies the contribution of each subcatchment to hydraulic pressure within the sewer system. SR quantifies the fraction of a subcatchment's runoff that contributes to conduits' critical state, i.e. with a degree of filling exceeding 80% (Eq. (3)). This threshold is commonly adopted in safety standards as the maximum allowable filling percentage and has been used in previous studies (e.g., Ercolani et al., 2018), reflecting the design degree of filling adopted in the hydraulic sizing of the network. SR was derived using the same reconstructed inflow contributions previously described, and conduits whose upstream or downstream node experienced flooding were excluded to avoid double counting of volumes already attributed to FR. For each surcharged conduit, the inflow volume attributable to each upstream subcatchment was used as a proxy for its contribution to hydraulic pressure. Summing these contributions across all surcharged conduits yielded the total surcharging volume attributable to each subcatchment. Unlike flooding, surcharging does not represent a loss of water from the sewer system but indicates a pre–failure condition close to or beyond the design capacity.

$$SR_i = \sum_{k=1}^{m} V_{\text{surch},\ i,k} \Big/ \sum_{k=1}^{m} V_{\text{surch},\ k} \qquad [0,1] \tag{3}$$

where $SR_i$ is the Surcharging Ratio of subcatchment *i, m* is the number of surcharged conduits within the outfall domain linked to subcatchment *i*, $V_{surch,\ k}$ is the total inflow volume in surcharged conduit *k*, and $V_{surch,\ i,k}$ is the share inflow volume in conduit *k* attributable to subcatchment *i*. High values show areas whose runoff strongly contributes to pushing conduits toward, or beyond, their hydraulic capacity, while values near zero correspond to subcatchments that exert only a marginal influence on surcharging within the network.

Further methodological details on the indicators are provided in the Supplementary material (Section S1.1).

### 2.2. Identifying areas suitable for NBS implementation

The assessment identifies areas suitable for NBS implementation, based on land cover characteristics and physical conditions within the urban fabric. For each NBS type, suitability was assessed within the corresponding land-cover categories: building footprints for green roofs (GR), low-vegetation and bare soil areas for rain gardens (RG), and impervious surfaces for permeable pavements (PP).

Suitability criteria for each NBS are derived from existing literature and are summarised in Table 1. Areas meeting all criteria were mapped, and the resulting polygons were aggregated at the subcatchment scale to compute the total suitable area per NBS type. Subcatchments represent the functional spatial units of the hydrologic–hydraulic model and are adopted as the spatial unit for identifying suitable areas, ensuring comparability across analyses. Municipal ownership data were used to distinguish between suitable public areas and suitable private areas within each subcatchment.

A detailed spatial analysis to identify areas suitable for GR, RG, and PP is provided in the Supplementary material (Section S1.2).

### 2.3. Prioritizing subcatchments for NBS implementation

Urban hazard-contribution and NBS suitability data are combined to prioritise subcatchments through a bivariate hazard-contributing and suitability matrix. For each hazard-contributing indicator (RC, FR, SR), a separate map is produced, and subcatchments with indicator values greater than zero are classified into four quantile-based hazard-contributing classes (H1, H2, H3, H4). Quartiles are used as they provide a transparent and non-arbitrary way to select a fixed proportion of higher-priority subcatchments for each hazard-contributing indicator, regardless of the underlying value distribution. Suitability for each NBS type (GR, RG, PP) is similarly classified into four quantiles (S1, S2, S3, S4), considering only subcatchments with a non-zero suitable area. A bivariate class is assigned only where both hazard-contribution and suitability are strictly greater than zero, producing 16 classes (H1–S1 to H4–S4) for each NBS type and hazard-contributing indicator. Each NBS type is treated as a separate intervention, producing three independent sets of maps. To synthesise these results, subcatchments falling within the high-priority classes (H3–S3, H3–S4, H4–S3, H4–S4) are identified for each hazard-contributing indicator. These high-priority subcatchments are then aggregated by counting how many indicators classify them as high-priority, resulting in a priority level ranging from 0 (no indicator) to 3 (all indicators). This aggregation is performed separately for suitable public areas and suitable private areas. The resulting maps therefore report, for each NBS type, subcatchments that reach each priority level within suitable public and private areas, and the priority level (0–3) associated with them.

### 2.4. Study area and input data

The methodology was applied to the valley floor of Trento, a medium-sized alpine city in northern Italy with approximately 120,000 inhabitants. The study area corresponds to an urban catchment located along the Adige River valley floor, which hosts the most densely built-up portion of the city (Fig. 2). The land cover is dominated by impervious surfaces (40.5%) and buildings (22.0%), followed by low vegetation (16.2%), tree cover (10.9%), agricultural areas (6.1%), bare soils (3.69%), and water bodies (0.57%). Impervious surfaces and buildings dominate the central and southern zones, while the northern part transitions into *peri*-urban areas characterised by more vegetation and agricultural land (Supplementary material – Fig. S5). Due to its topography and the high proportion of sealed surfaces, the area is particularly prone to urban flooding.

The analyses of urban flood hazard and areas suitable for NBS implementation relied on a high-resolution land cover and vegetation map derived from Pléiades-Neo satellite imagery (30 cm, June 2022) and municipal land-use data. The satellite image was processed through an object-based classification analysis to distinguish impervious surfaces, vegetation types, buildings, agricultural areas, and water bodies. Public and private areas were identified using ownership data provided by the municipality.

To define the hydrological units of the assessment, the study area was subdivided into urban subcatchments representing the elementary units of the drainage system that produces runoff. Each subcatchment was characterised by hydrological parameters (% of Imperviousness and Curve Number (CN)) derived from the high-resolution land-cover and vegetation classification. The subcatchments were connected to a detailed representation of the urban drainage network, including junctions, conduits, and outfalls discharging into the Adige, Fersina, and Lavisotto rivers, as well as secondary canals (Supplementary material – Fig. S6). The reconstructed drainage network was qualitatively assessed by comparing the spatial distribution of simulated flooding and surcharge locations with historical records of flood-prone areas mapped by the Municipality of Trento, including mapped zones of inundation and water stagnation and areas identified as having specific hydraulic problems (Municipality of Trento, 1976). Moreover, the network was built using real topography, land-use and land-cover data, observed rainfall, and standard hydraulic design practices, ensuring that the model structure is as close as possible to the real drainage system.

Design rainfall inputs were derived from a statistical analysis of extreme precipitation (i.e. annual maxima for durations that span from 15 min to one day) using long-term records available from the local authority database (Meteo, 2024). The Trento-Laste meteorological station was selected as the reference gauge because it is the closest active station to the study area and provides the longest and most complete

**Table 1**
Suitability criteria for the three NBS types selected.

| NBS type | Land cover | Land use | Slope (°) | Water table depth (m) | Area ($m^2$) | Distance to building foundations (m) | Refs. |
|---|---|---|---|---|---|---|---|
| Green roof | Buildings | Any | < 20 | - | ≥ 40 | - | (Cortinovis et al., 2022; Grunwald et al., 2017) |
| Rain garden | Low vegetation, bare soils | Green areas (parks, gardens, yards, …), abandoned areas or degraded soils | < 3 | > 1.8 | ≥ 20 | > 6 | (Ariza et al., 2019; Ávila et al., 2016; Shoemaker et al., 2009) |
| Permeable pavement | Impervious | Parking lots and other sealed areas (excluding buildings, roads, railways, sports facilities, cemeteries) | < 1 | > 3 | - | > 6 | (Ariza et al., 2019; Shoemaker et al., 2009; Yang et al., 2022) |

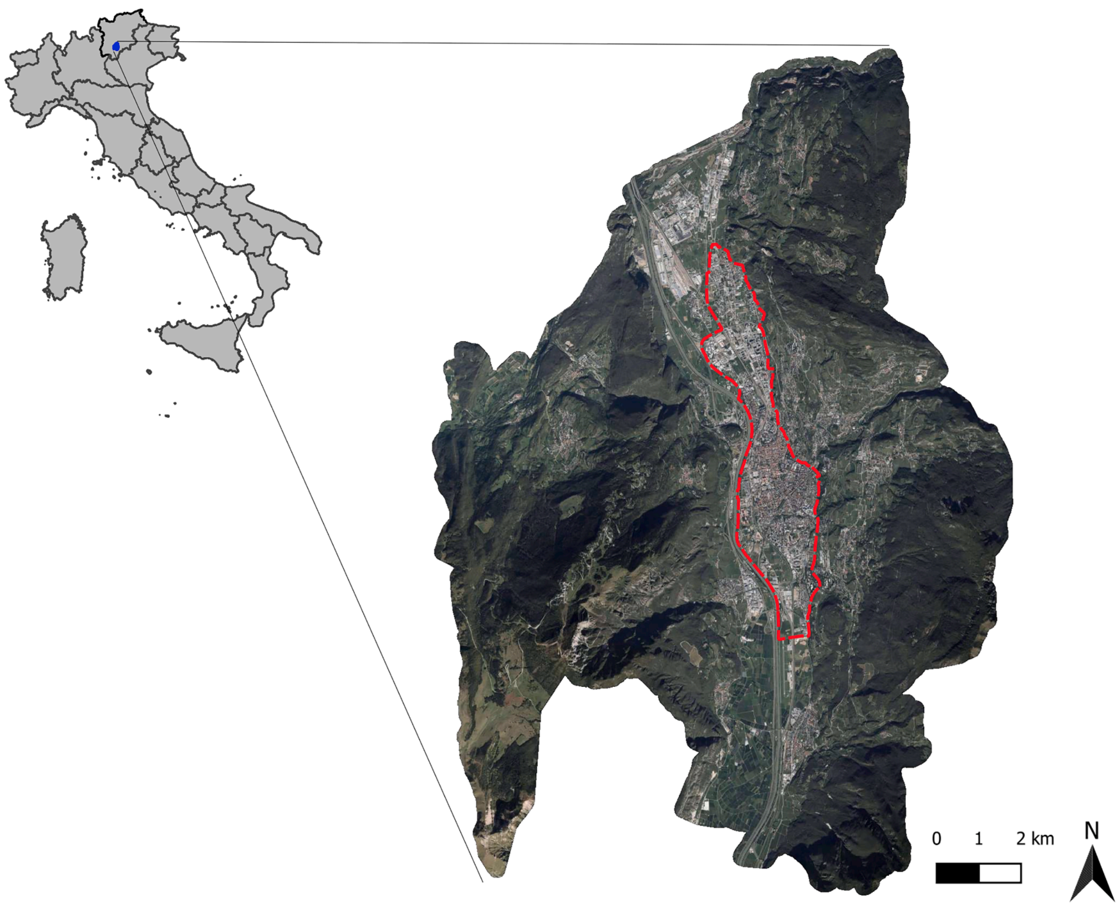


**Fig. 2.** Location of the city of Trento in Italy (left) and aerial photograph with the study area highlighted in red (right).

precipitation time series. The original hydraulic design of the drainage network was based on the 15-min, 10-year return period rainfall event. For the simulations presented in this study, a 15-min rainfall event with a 30-year return period was used.

Full methodological details on land-cover classification, subcatchment delineation, parameter values, and drainage network design are provided in the Supplementary Material (Sections S1.3–S1.4).

## 3. Results

### 3.1. Urban hazard-contribution patterns across subcatchments

The definition of the hydrological units within the study area resulted in 948 subcatchments with an average area of 1.13 ha (min: 0.03 ha; max: 5.11 ha; SD: 1.00 ha; IQR: 0.40–1.59 ha), consistent with the maximum target area of approximately 5 ha adopted in the delineation procedure.

The simulated rainfall event resulted in flooding at 75 out of 848 junctions (9%). Surcharging conditions (conduits' degree of filling > 80%) were recorded in 710 out of 848 conduits (84%) (Supplementary material – Fig. S7). These hazard-contributing patterns should be interpreted as scenario-specific, as they reflect the drainage system response to the selected 15-min, 30-year return period rainfall event. Fig. 3 shows the spatial distribution of the three hazard-contributing indicators derived from SWMM model outputs: Runoff Coefficient (RC), Flooding Ratio (FR), and Surcharging Ratio (SR). All three indicators (RC, FR, SR) are expressed as dimensionless ratios that inherently normalise for subcatchment area, ensuring that differences in hazard contribution reflect hydrologic behaviour rather than differences in subcatchment size. For each indicator, values range from 0 to 1 and are classified into four quantile-based classes, considering only subcatchments with non-zero values. RC values exhibit a mean of 0.75, with elevated values concentrated in central and northern subcatchments. FR values have a mean of 0.02 and SR values a mean of 0.04, both showing heterogeneous spatial patterns. Several subcatchments with moderate RC values display non-zero FR or SR values, while others with high RC show limited hydraulic contribution.

Additional statistical analyses confirmed that RC, FR and SR are not redundant and capture complementary hazard-contributing behaviours, as indicated by low cross-correlations (Pearson:0.02 to 0.22; Spearman:0.22 to 0.16) and distinct spatial association patterns (Moran's I: 0.154–0.255) (Supplementary material – Section S1.1).

### 3.2. Areas suitable for NBS implementation across subcatchments

The suitability assessment revealed that approximately 93 hectares are suitable for green roofs (GR) implementation. This corresponds to 38% of the total building rooftop surface mapped in the study area. For rain gardens (RG) implementation, the total suitable area amounts to 63 hectares, representing 30% of the combined extent of low-vegetation and bare-soil land-cover classes. Nearly 115 hectares are suitable for conversion into permeable pavements (PP), corresponding to 45% of the total mapped impervious surfaces (Supplementary material – Fig. S4). The spatial distribution of areas suitable for NBS implementation across subcatchments is shown in Fig. 4, while Table 2 summarises the proportion of subcatchments that present suitable areas and the percentage of those areas within public or private spaces for each NBS type.

GR show limited suitability across the study area. Suitable rooftops are primarily located in the northern and southern zones, while the central urban part of the study area presents fewer opportunities. Only

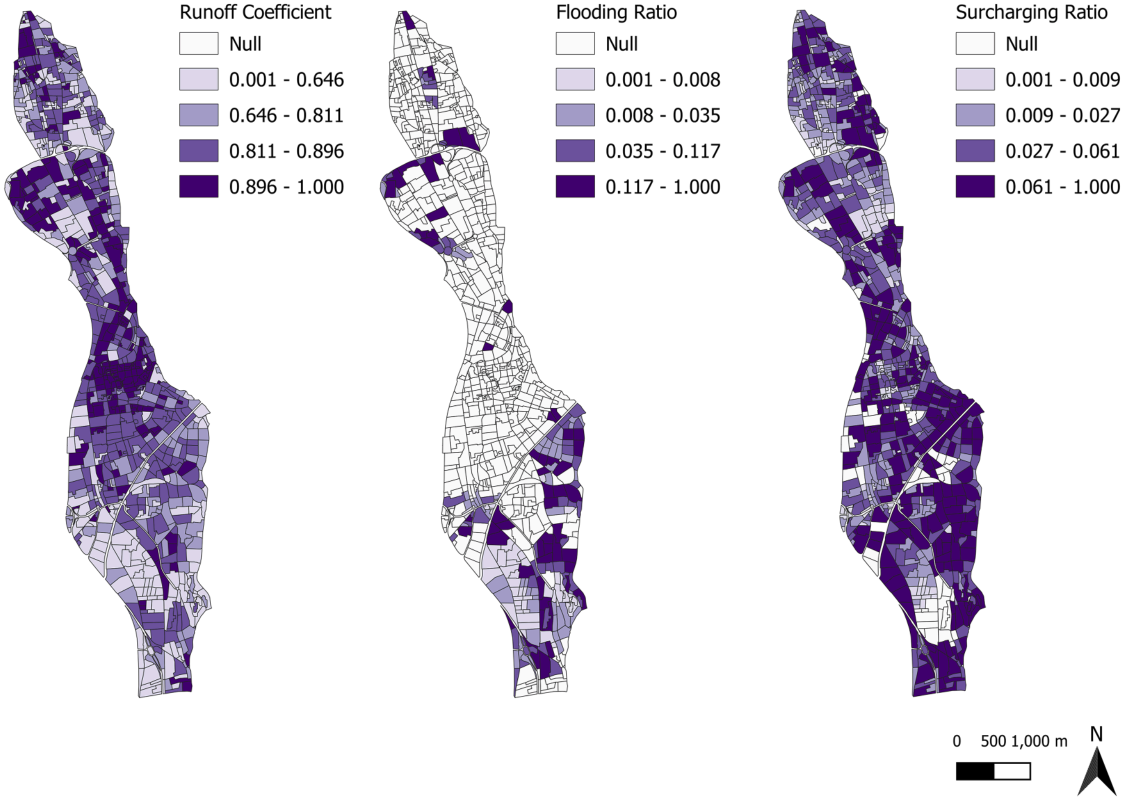


**Fig. 3.** Spatial distribution of the three hazard-contributing indicators for a 15-min, 30-year return period rainfall event: Runoff Coefficient (RC), Flooding Ratio (FR), and Surcharging Ratio (SR).

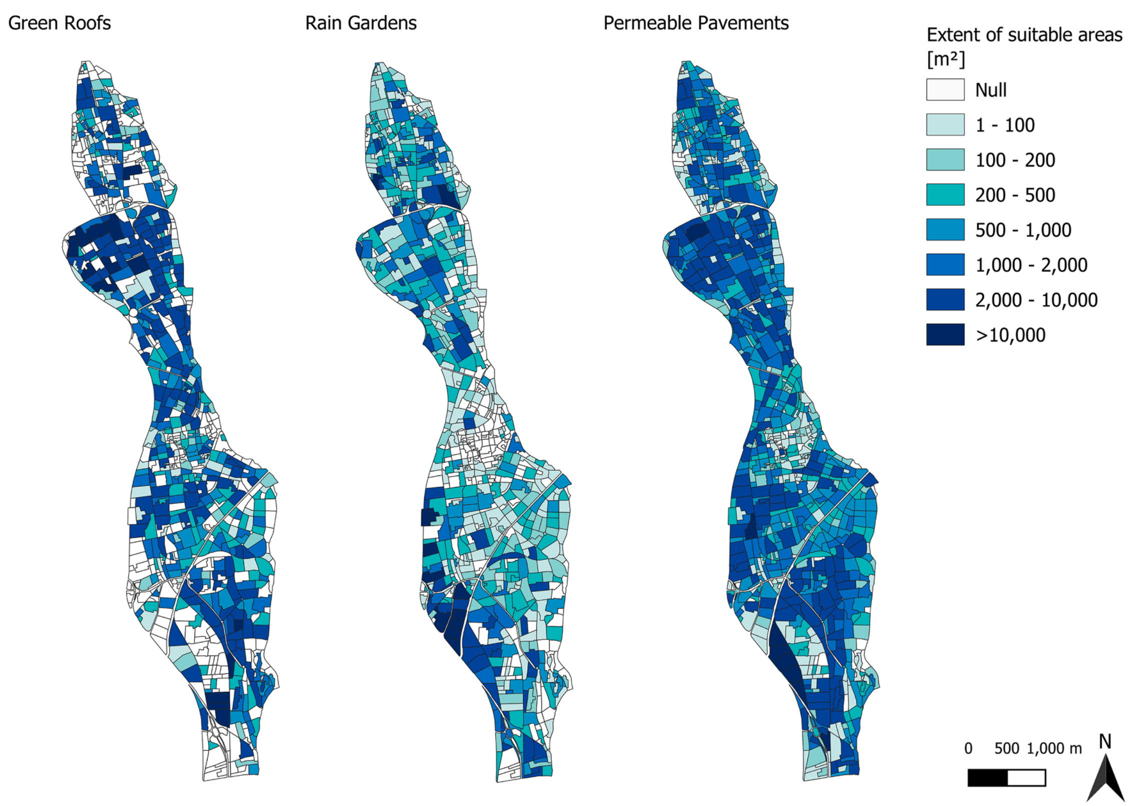


**Fig. 4.** Extent of suitable areas for the three NBS types: Green Roofs (GR), Rain Gardens (RG), and Permeable Pavements (PP), within each subcatchment.

about half of the subcatchments (52.5%) include suitable rooftop surfaces. Among these, 85.1% of suitable rooftop area is located on

**Table 2**
Subcatchment suitability and public–private distribution of suitable areas for each NBS type.

| NBS type | Subcatchments with suitable areas (%) | Total suitable area within the subcatchments (%) | |
|---|---|---|---|
| | | Public | Private |
| Green Roofs (GR) | 52.5 | 14.9 | 85.1 |
| Rain Gardens (RG) | 72.6 | 24.7 | 75.3 |
| Permeable Pavements (PP) | 92.4 | 32.9 | 67.1 |

private buildings.

RG show broader suitability across subcatchments. The spatial distribution is relatively uniform, with a slight concentration in the southern part of the study area. Approximately 72.6% of subcatchments contain suitable areas, indicating a more widespread distribution compared to GR. Suitable areas are predominantly located in private spaces, with only 24.7% occurring in public spaces.

PP show the highest suitability among the three NBS types across the study area. The spatial distribution is homogeneous throughout the territory. Suitable impervious surfaces are found in 92.4% of subcatchments, suggesting that this option is feasible almost everywhere in the study area. The distribution between suitable public areas and suitable private areas is more balanced than for GR and RG, with 32.9% located in public spaces and 67.1% in private ones.

The relative contribution of suitable public areas and suitable private areas within each subcatchment is further illustrated in the Supplementary material (Fig. S8).

### *3.3. Priority subcatchments based on the combination of hazard contribution and NBS suitability in public and private spaces*

The three NBS types exhibit different priority patterns when hazard contribution and suitability are combined. These priority patterns are inherently event-dependent, as they are derived from the selected 15-min, 30-year rainfall event. Fig. 5 shows, for each NBS type (GR, RG, PP) and each hazard-contributing indicator (RC, FR, SR), how subcatchments distribute across the 16 hazard-contribution and suitability classes (H1–S1 to H4–S4). Subcatchments with no suitable areas and/or no hazard contribution appear blank, while coloured subcatchments indicate the presence of suitable areas and their associated hazard-contribution level. Light colours represent low hazard contribution and/or low suitability, intermediate colours represent mixed conditions, and dark colours identify subcatchments where high hazard- contribution levels coincide with high suitability.

The maps reveal that for GR, priority is limited, with only a small number of subcatchments that fall into intermediate or high hazard-contribution and suitability classes, reflecting the restricted availability of suitable rooftops. High classes (H3–S3 to H4–S4) are rare and spatially scattered, resulting in relatively few high-priority subcatchments: 183 under RC (10%), 41 under FR (2%), and 173 under SR (9%). RG displays a slightly more diffuse spatial pattern, with high and intermediate hazard-contribution and suitability classes that appear in both central and peripheral areas, consistent with the broader distribution of vegetated and bare soil surfaces. High-priority subcatchments emerge only where these suitable areas overlap with high hazard-contribution levels, resulting in 94 under RC (5%), 60 under FR (3%), and 193 under SR (10%). PP, instead, generates the most extensive and continuous pattern of high hazard-contribution and suitability classes, especially under RC and SR. This reflects the widespread presence of convertible impervious surfaces across the study area. Consequently, PP present the highest number of high-priority subcatchments across all indicators: 301 under RC (16%), 84 under FR (4%), and 315 under SR (17%).

Fig. 6 summarises, for each NBS type, the number of hazard-contributing indicators (RC, FR, SR) for which each subcatchment is classified as high priority (H3–S3, H3–S4, H4–S3, H4–S4). Values range from 0 (the subcatchment is not classified as high priority under any indicator) to 3 (the subcatchment is high priority under all three indicators). The analysis is shown separately for suitable public areas (a, c, e) and suitable private areas (b, d, f). The combined priority levels shown in Fig. 6 should therefore be interpreted within the context of this specific scenario. Table 3 complements the maps by reporting, for each NBS type, both the number of high-priority subcatchments and the extent of suitable areas within them, separately for public and private spaces.

Across all NBS types, private spaces offer greater opportunities for NBS implementation in high-priority subcatchments. Suitable private areas are more frequently located in subcatchments classified as high priority under multiple hazard-contributing indicators and provide larger intervention surfaces. Suitable public areas, by contrast, tend to fall within subcatchments classified as high priority under only one indicator and generally contribute with smaller extent. For GR, the contrast between suitable public areas and suitable private areas is particularly pronounced (Fig. 6a–b). Although private areas suitable for GR fall within fewer subcatchments classified as high priority under one, two and three hazard-contributing indicators (72, 103, 17, respectively) than those for PP, they offer more extensive suitable areas across all numbers of hazard-contributing indicators (243,587 $m^2$, 355,503 $m^2$ and 109,537 $m^2$, respectively). Public areas suitable for GR are comparatively limited and mostly associated with subcatchments classified as high priority under only one hazard-contributing indicator. RG shows a similar pattern (Fig. 6c-d). Suitable private areas are present in 170 subcatchments classified as high priority under at least one hazard-contributing indicator (72%), but the extent of suitable area is substantially smaller than for GR and PP, especially under three indicators, with only 8,209 $m^2$. Public areas suitable for RG are even more limited, with only 981 $m^2$ in subcatchments classified as high priority under three indicators (1.3%), the lowest among all NBS types. They remain predominantly associated with subcatchments classified as high priority under only one indicator (71%), corresponding to 44,544 $m^2$. For PP, differences between suitable public areas and suitable private areas are less evident, with a more balanced distribution compared to GR and RG (Fig. 6e-f). PP suitable areas are distributed across the largest number of subcatchments classified as high priority under one, two and three hazard-contributing indicators, in both public and private spaces. Suitable private areas occur most notably in subcatchments classified as high priority under two hazard-contributing indicators (138), although the corresponding areas remain smaller than those of GR. Suitable public areas reach their maximum extent in subcatchments classified as high priority under only one indicator (143,625 $m^2$).

## 4. Discussion

### *4.1. Combining hazard contribution with public and private suitability to support urban planning*

This study developed and tested a spatially explicit method that combines three hazard-contributing indicators with suitability analysis for different NBS types, prioritising subcatchments and showing how these priorities vary according to the opportunities offered by public and private spaces. The method is designed as a planning-oriented tool that translates coupled model outputs into subcatchment-level information to support the identification of spatial opportunities for NBS implementation. As a result, the framework provides a spatial targeting approach that identifies where NBS interventions should be prioritised within the urban fabric, supporting planning decisions by translating hydrologic–hydraulic pressures into spatial priorities at the subcatchment scale.

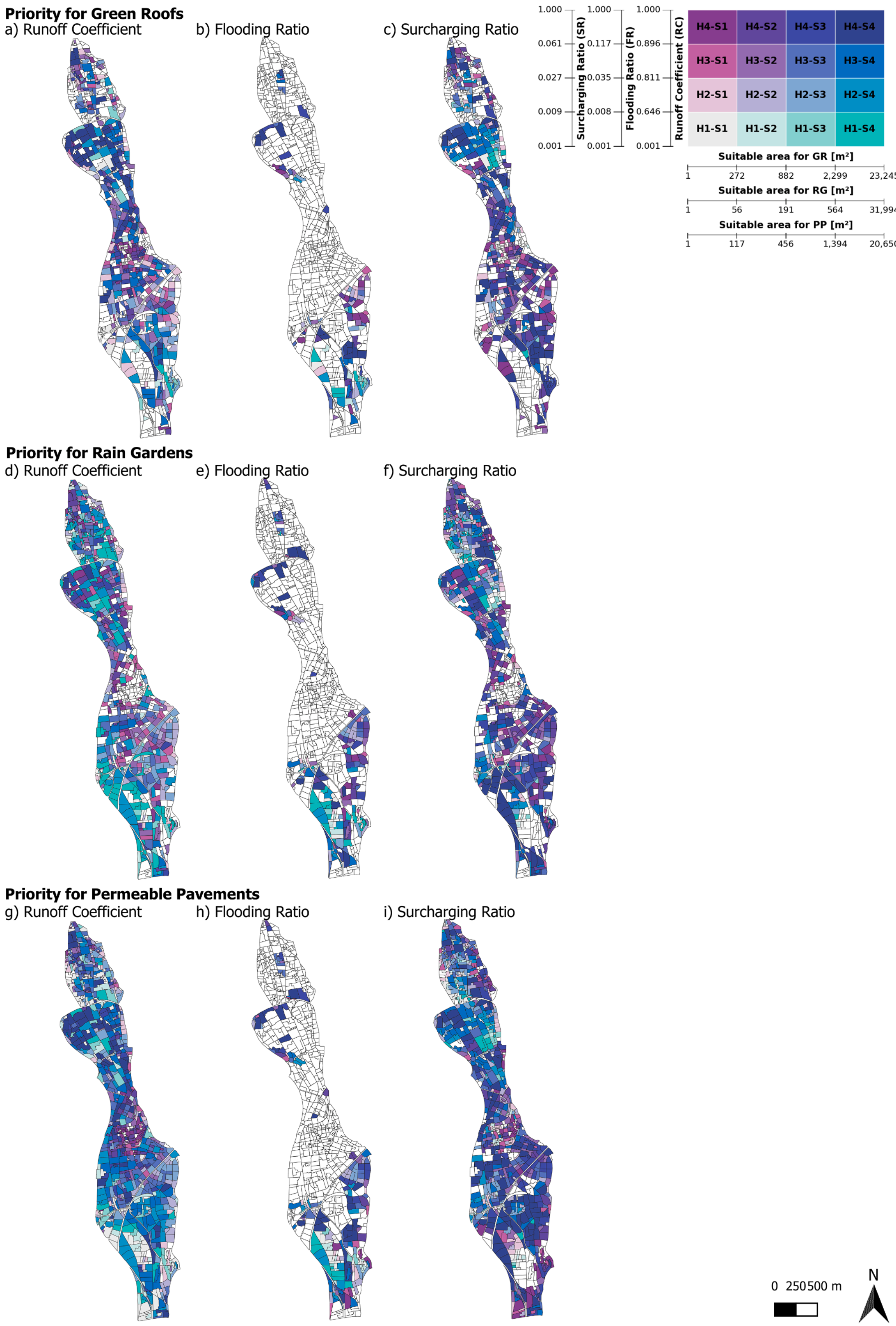


**Fig. 5.** Level of priority of subcatchments for the implementation of Green Roofs (GR), Rain Gardens (RG), and Permeable Pavements (PP), derived by combining hazard contribution for a 15-min, 30-year return period rainfall event with the area suitable for each NBS type. The 16 bivariate classes are based on quartiles.

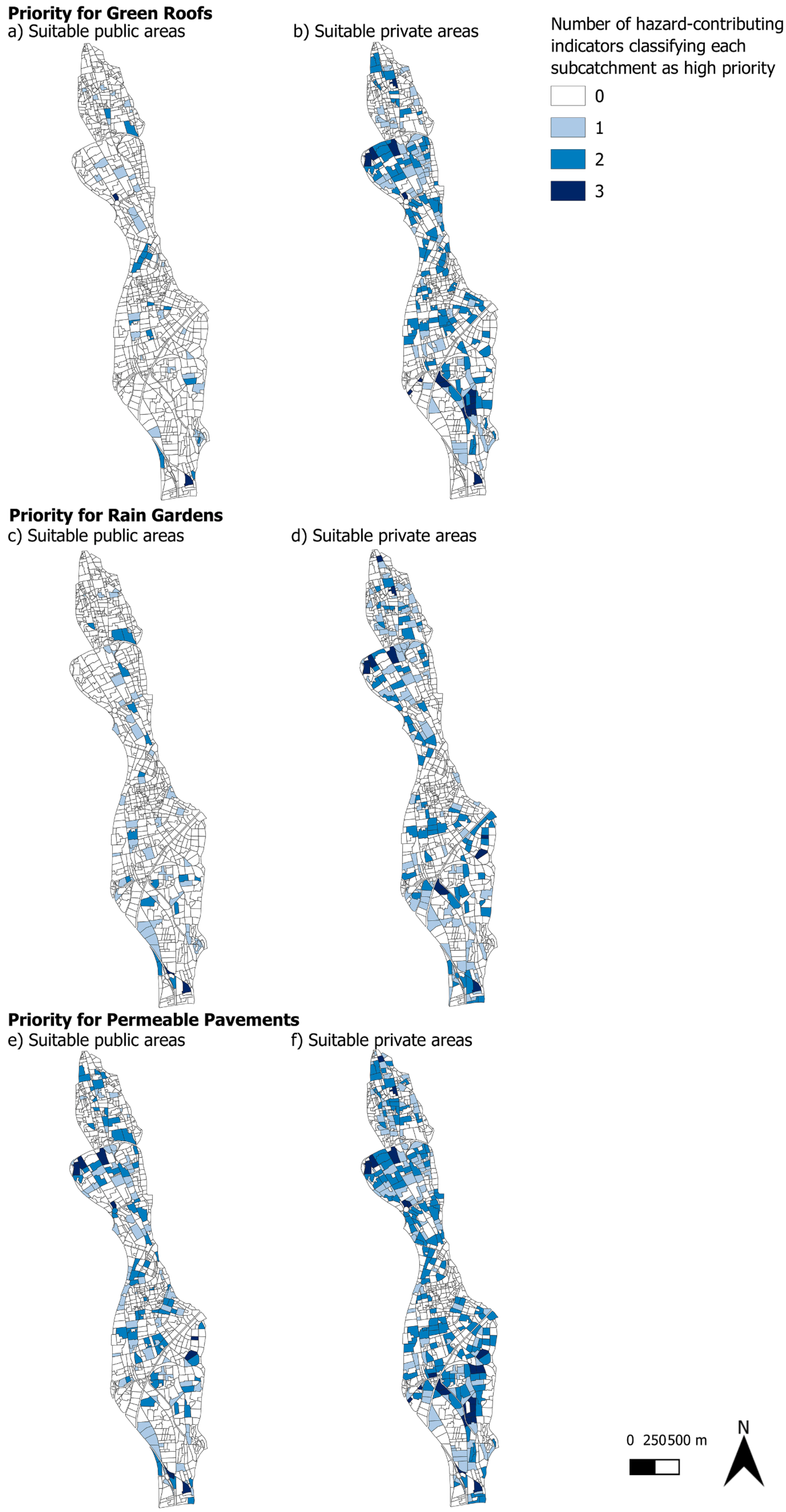


**Fig. 6.** Number of hazard-contributing indicators for which each subcatchment is classified as high priority, considering Runoff Coefficient (RC), Flooding Ratio (FR), and Surcharging Ratio (SR) for a 15-min, 30-year return period rainfall event. Results are shown separately for public (a, c, e) and private (b, d, f) areas suitable for Green Roofs (GR), Rain Gardens (RG), and Permeable Pavements (PP).

**Table 3**
Subcatchments classified as high priority under 1–3 hazard-contributing indicators (RC, FR, SR) for a 15-min, 30-year return period rainfall event, and corresponding areas suitable for each NBS type, across public and private spaces. GR stands for green roofs, RG for rain gardens, and PP for permeable pavements.

| NBS type | Space | Number of hazard-contributing indicators (1–3) | Subcatchments classified as high priority (n°) | Subcatchments classified as high priority (%) | Suitable area in high-priority subcatchments (m$^2$) | Suitable area in high-priority subcatchments (%) |
|---|---|---|---|---|---|---|
| **GR** | **Public** | 1 | 30 | 62.5 | 60,821 | 59.7 |
| | | 2 | 16 | 33.3 | 35,173 | 34.5 |
| | | 3 | 2 | 4.2 | 5,960 | 5.8 |
| | **Private** | 1 | 72 | 37.5 | 243,587 | 34.4 |
| | | 2 | 103 | 53.6 | 355,503 | 50.2 |
| | | 3 | 17 | 8.9 | 109,537 | 15.5 |
| **RG** | **Public** | 1 | 46 | 70.8 | 44,544 | 58.5 |
| | | 2 | 17 | 26.2 | 30,629 | 40.2 |
| | | 3 | 2 | 3.1 | 981 | 1.3 |
| | **Private** | 1 | 89 | 52.4 | 157,454 | 62.7 |
| | | 2 | 71 | 41.8 | 85,573 | 34.1 |
| | | 3 | 10 | 5.9 | 8,209 | 3.3 |
| **PP** | **Public** | 1 | 77 | 49.7 | 143,625 | 59.1 |
| | | 2 | 69 | 44.5 | 86,287 | 35.5 |
| | | 3 | 9 | 5.8 | 13,142 | 5.4 |
| | **Private** | 1 | 110 | 40.4 | 233,958 | 36.9 |
| | | 2 | 138 | 50.7 | 336,507 | 53.0 |
| | | 3 | 24 | 8.8 | 64,022 | 10.1 |

The three developed indicators (Runoff Coefficient, Flooding Ratio and Surcharging Ratio) capture complementary dimensions (i.e. hydrological and 1D-hydraulic) of hazard-contribution. This represents a shift from existing applications, which either rely on node-based pressurisation metrics (La Rosa & Pappalardo, 2020), or composite indicators that aggregate multiple SWMM outputs into a single value (Pelorosso et al., 2018a, 2018b). The spatial mismatch observed among the three indicators shows that high runoff does not necessarily translate into high downstream hydraulic pressure, highlighting the central role of internal network dynamics in shaping where hydrologic–hydraulic pressure emerges (Park et al., 2024). As already noted in previous studies, relying solely on hydrologic indicators would therefore provide only a partial basis for prioritisation, which reinforces the need for spatially explicit hydraulic indicators (Pelorosso et al., 2021). By keeping the indicators separate, the approach preserves this multidimensionality and provides planners with a more complete understanding of how different parts of the city contribute to flooding and surcharging.

In parallel, the suitability assessment clarifies how the physical structure of the built environment constrains or enables the implementation of different NBS types. The observed differences in the extent and distribution of areas suitable for green roofs, rain gardens and permeable pavements reflect the heterogeneity of urban form and confirm the importance of suitability information as a basis for integrating NBS into planning processes (Ronchi et al., 2020). Across all NBS types, suitable areas are predominantly located within private spaces, a result consistent with previous studies showing that opportunities for urban greening often lie on privately owned land and that public space availability can be limited (Poupelin et al., 2025; Privitera et al., 2018). This finding highlights the relevant role of private spaces in shaping the suitability of NBS and confirms the importance of considering both public and private opportunities when assessing where interventions can realistically be implemented. The analysis further shows that suitable private areas tend to coincide more frequently with subcatchments classified as high priority under multiple hazard-contributing indicators, suggesting that many of the locations where NBS could most effectively mitigate hydrologic–hydraulic pressures fall within private domains (Fonseca Alves et al., 2022; Pappalardo et al., 2017). While ownership provides an important first distinction for identifying where NBS could be implemented, it represents only one dimension of feasibility. Implementation is also shaped by institutional, legal, regulatory, social and economic factors, including governance constraints, stakeholder willingness, and financial barriers, which are widely recognised as key challenges to NBS uptake (Martin et al., 2025).

The spatial attribution introduced by the urban flood hazard-contributing indicators links hydraulic pressure to the subcatchments that contribute to it rather than to the nodes or conduits where exceedances are observed. This perspective enables a targeted prioritisation of interventions, as it identifies which upstream subcatchments contribute most to hydrologic–hydraulic pressures, clarifying where NBS should be targeted, and informing how resources can be allocated across the urban fabric to address the areas that exert the greatest pressure. By expressing hydraulic stress on areal units, this approach aligns the hazard information with the spatial scale at which NBS suitability and land-use decisions are made, thereby making the prioritisation directly actionable for urban planning (Mori et al., 2021). Moreover, the concentration of suitable areas within private land, combined with the result that these areas are more frequently located in subcatchments classified as high priority under multiple indicators, indicates that many of the locations where NBS could most effectively mitigate hydrologic–hydraulic pressures fall within private domains. Consequently, planning instruments aimed at supporting NBS uptake must explicitly address the role of private spaces. Policy tools such as incentive schemes, co financing mechanisms, regulatory obligations, and voluntary agreements can help prioritise these areas for NBS implementation and integrate them into broader urban resilience strategies (Croci et al., 2022; Longato et al., 2024; Scheuer et al., 2024). Urban planning strategies must therefore integrate private actors, mobilise private investment and recognise the contribution of private spaces to NBS implementation (Liberalesso et al., 2020; Neumann & Hack, 2020; Privitera et al., 2024). Mainstreaming these contributions requires multi actor governance arrangements capable of coordinating public authorities with private owners (Tran et al., 2024). Although suitable public areas represent fewer opportunities and are mostly associated with subcatchments prioritised under a single hazard-contributing indicator, they still provide localised possibilities for NBS implementation in areas where public land intersects with elevated hydrologic–hydraulic pressures (Poupelin et al., 2025). These opportunities are more limited in extent but remain strategically relevant for targeted interventions.

### 4.2. *Limitations and future directions*

One limitation of this study concerns the partial availability of input data for the hydrologic–hydraulic model. Detailed information on the drainage system (such as the exact location, geometry, and connectivity of pipes, the presence and operation of pumping stations, pressurised flow regimes, manholes, and discharge structures) was only partially available. As a result, the entire SWMM network had to be reconstructed from scratch using real topography, land-use and land-cover data, observed rainfall, and standard hydraulic design practices, to ensure that the model structure is as close as possible to the real drainage system. Although this data gap inevitably limits the level of detail with which local hydraulic processes can be reproduced, the plausibility of the reconstructed network was qualitatively assessed by comparing the spatial distribution of simulated flooded nodes and surcharged conduits with historical flood-prone areas mapped by the Municipality of Trento (1976). Although the map is historical, many of the drainage pathways and morphological constraints that generate hydraulic problems change only gradually over time, meaning that long-standing critical areas often remain indicative of locations where the system is structurally more vulnerable. The comparison reveals that several of these historically critical locations spatially overlap with model-identified hydraulic stress areas, providing qualitative support for the credibility of the reconstructed network topology. The absence of complete hydraulic attributes (e.g., pumping dynamics, detailed conduit geometry, operational settings) may also inevitably affect the accuracy with which local hydraulic processes can be reproduced, particularly in systems where pumping, backwater effects, or pressurisation play a major role. In a planning context, these data gaps may reduce the level of detail with which local hydraulic processes can be represented, but the reconstructed network was sufficient to support the development of the hazard-contributing indicators and the resulting prioritisation analysis. The limitation nonetheless highlights the value of more complete and integrated hydraulic datasets, which would allow future applications of the method to capture a wider range of hydraulic behaviours and further strengthen the evidence base for planning. At the same time, many cities increasingly rely on advanced hydrologic–hydraulic models in their drainage network management, meaning that the required datasets are already available in several contexts and are expected to become progressively more accessible in the future.

A second limitation concerns the derivation of the Flooding Ratio (FR) and Surcharging Ratio (SR). These indicators build upon existing planning-oriented volumetric metrics derived from SWMM outputs (e.g., La Rosa & Pappalardo, 2020; Pelorosso et al., 2018a), extending them by introducing a proportional allocation of flood and surcharge volumes to upstream subcatchments. This methodological step allows exceedances occurring at nodes and along conduits to be translated into subcatchment-level contributions, effectively spatialising hydraulic stress on areal units. As a result, FR and SR quantify how much each subcatchment contributes to flooding or surcharging within the sewer system, enabling a consistent prioritisation approach that combines hazard contribution with NBS suitability, both expressed at the subcatchment scale where interventions can be implemented. The proportional allocation relies on a volume-based attribution procedure, which assumes that the fraction of inflow volume contributed by a subcatchment to a node can be used to proportionally allocate the node's flood or surcharge volume back to upstream areas. This assumption applies only to the volumetric partitioning step and does not attempt to reproduce the non-linear hydraulic dynamics simulated by SWMM (e.g., peak timing, local storage, pressurised waves). However, the approach is fully consistent with the cumulative volumetric outputs of SWMM, since flood volumes are subtracted before downstream propagation and leftover inflows are conserved along the network. FR and SR should therefore be interpreted as indicators of volumetric contribution within the sewer system, as they quantify how much each subcatchment contributes to flooding or surcharging, rather than reconstructing detailed hydraulic processes that produces those exceedances. More broadly, the hazard-contributing indicators used in this study should be interpreted as relative measures of how strongly each subcatchment contributes to flooding or hydraulic pressure, rather than as physical hydraulic quantities.

The numerical values of the hazard-contributing indicators reflect the empirical distribution of model outputs for the case study and are therefore inherently site-specific. As highlighted in hydrologic–hydraulic modelling studies, SWMM outputs vary depending on storm characteristics, parameterisation and drainage configuration (Xu et al., 2019), meaning that the spatial patterns of FR and SR may be sensitive to model assumptions. In addition, the 80% degree-of-filling threshold used to identify surcharged conduits reflects a methodological choice based on previous studies, and future applications may explore how alternative thresholds or local design standards influence the identification of critical hydraulic conditions through sensitivity analyses. Further applications of the indicators in contexts where empirical flood records or monitoring data are available would enable more detailed calibration and validation.

Urban hydrologic–hydraulic responses are inherently event dependent, as storm duration, intensity, temporal rainfall patterns strongly influence runoff generation and hydraulic pressures (Miller et al., 2023). Although a multiple-scenario assessment is beyond the scope of this work, this aspect requires further consideration for interpreting the prioritisation results. First, the choice of a design-level event is consistent with standard drainage planning practice, as urban sewer networks are typically dimensioned on specific return periods (Egger & Maurer, 2015; Ghodsi et al., 2023; Peng et al., 2015). Considering substantially more extreme events would lead to widespread system exceedance (Lee et al., 2025; Rahmoun et al., 2022), reducing the ability to differentiate among subcatchments and limiting the usefulness of hazard-contributing indicators for prioritisation. In such conditions, most of the network would simultaneously exceed capacity (e.g., Neumann et al., 2024), making it difficult to identify meaningful spatial differences in hazard-contribution across the catchment. Second, the effectiveness of NBS varies substantially with storm characteristics (Beceiro et al., 2022). Permeable pavements perform best during mid-peak events, while green roofs perform best during late-peak storm events (Qin et al., 2013). Moreover, green roofs tend to behave similarly to conventional roofs under extreme conditions and are most effective for attenuating storms with return periods up to two years (Woods Ballard et al., 2015). NBS therefore provide their strongest mitigation potential under moderate to design-level rainfall conditions, where their capacity to reduce runoff and attenuate hydraulic pressures is greatest. The use of a single 15 min, 30-year event therefore represents a specific hydrologic-hydraulic scenario, and different rainfall patterns would produce different responses and could therefore change the spatial configuration of of hazard-contribution across subcatchments (Sciuto et al., 2025). This has direct implications for planning decisions, as the prioritisation produced in this study reflects the hazard-contribution associated with this specific event. As a consequence, the resulting priority areas are event-specific and should be interpreted within that rainfall context. For these reasons, future applications may also explore how the spatial distribution of hazard-contribution varies under different storm scenarios, to investigate how alternative rainfall conditions could influence the prioritisation of NBS intervention areas.

## 5. Conclusions

This study developed and tested a spatially explicit method that integrates three hazard-contributing indicators, Runoff Coefficient (RC), Flooding Ratio (FR) and Surcharging Ratio (SR), with suitability analysis for different NBS types, showing how subcatchments can be prioritised for implementation and how these priorities differ across public and private spaces. The method addresses a key gap by combining hydrologic and hydraulic information with NBS suitability within a unified prioritisation approach.

Results highlight two main messages. First, the three NBS types generate distinct priority patterns when hazard contribution and suitability are combined, reflecting both the complementary behaviour of RC, FR and SR and the influence of urban morphology. GR show the most limited suitability (52.5% of subcatchments, with 85.1% of suitable rooftop area on private buildings), whereas RG display broader but less extensive suitability (72.6% of subcatchments, predominantly private). PP are suitable in 92.4% of subcatchments and show a more balanced public–private distribution. Consistently with these patterns, PP generate the highest number of high-priority subcatchments across all three indicators, whereas GR and RG produce fewer and more spatially scattered high-priority areas.

Second, opportunities for NBS implementation differ markedly between public and private spaces. Across all NBS types, suitable private areas are more frequently located within subcatchments classified as high priority under multiple hazard-contributing indicators and generally provide larger intervention surfaces. Suitable public areas, by contrast, are comparatively limited and mostly associated with subcatchments classified as high priority under only one indicator. These contrasts are most evident for GR and RG, where public areas are largely concentrated in subcatchments prioritised under only one indicator and contribute very small surfaces under three indicators, while private areas span multiple indicators and cover substantially larger areas. For PP, the distribution is more balanced between subcatchments prioritised under one and multiple indicators, particularly in private spaces.

Taken together, these findings clarify how hazard contribution and NBS suitability jointly shape the spatial distribution of priority areas, and how these priorities differ across public and private spaces. By bringing these dimensions into a single spatially explicit assessment, the study provides an evidence-based method for urban planning that translates hydrologic–hydraulic pressures into spatial priorities, identifying where different NBS types can be most appropriately prioritised within the urban fabric. Further applications of the indicators in contexts where empirical flood records or monitoring data are available would enable more detailed calibration and validation. Moreover, applying the framework under multiple storm scenarios would allow exploring how priority patterns vary across different hazard conditions.

## Declaration of generative AI use

During the preparation of this manuscript, the author CP used Microsoft Copilot to support language refinement, improve clarity, and assist in the organisation of selected sections. The authors reviewed, edited, and validated all content produced with the assistance of this tool and take full responsibility for the final version of the manuscript.

## CRediT authorship contribution statement

**Chiara Parretta:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chiara Cortinovis:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Giuseppe Formetta:** Writing – review & editing, Software, Methodology, Investigation. **Davide Geneletti:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization.

## Declaration of competing interest

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

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2026.107904.

## Data availability

Data will be made available on request.

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