Urban Climate Adaptation in Naples: An Integrated Framework for Flood Risk, Urban Heat Island, and Nature-Based Intervention Planning

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Abstract. In densely built cities, the progressive replacement of permeable surfaces with impervious, heat-retaining materials simultaneously reduces infiltration capacity, amplifying urban flood risk and limits evapotranspiration, thus intensifying the Urban Heat Island (UHI) effect. These two climate-related hazards share a common structural driver and are particularly severe in compact, socially heterogeneous urban neighbourhoods where green infrastructures are scarce and drainage systems are ageing. This paper proposes an integrated methodology for urban climate adaptation applied to three Naples districts (Fuorigrotta, Ponticelli, Soccavo), combining: (i) flood risk mapping through coupled EPA SWMM+FLO-2D hydraulic modelling and CubiST machine learning vulnerability assessment; (ii) open space microclimate simulation via ENVI-met to quantify thermal co-benefits of greening scenarios; and (iii) spatially explicit Low-Impact Development-Best Management Practices (LID-BMP) and greening siting based on compound risk overlay. For flood risk (R), the formulation $R = H \times E \times V$ allows integrating the hydraulic hazard (H) with socio-economic vulnerability (V) and exposure (E) into a composite index suitable for spatial planning. For UHI, where no analogous probabilistic risk framework is established in the literature, thermal performance is assessed through ENVI-met simulations comparing the baseline scenario with design ones including post-greening open space configurations. Cooling co-benefits through PET and outdoor air temperature are also quantified. Results show that nature-based interventions in open spaces generate compound reductions in both flood risk and thermal stress, providing local decision-makers with a physically grounded, spatially explicit evidence base for urban renewal investment.

Keywords: Urban flood risk · Urban Heat Island · Low-Impact Development-Best Management Practices · ENVI-met · EPA SWMM · Nature-Based Solutions · Naples · Climate adaptation · Open spaces

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1 Introduction

Urban flooding and the Urban Heat Island (UHI) effect are two of the most pressing climate-related challenges for contemporary cities. According to the IPCC Sixth Assessment Report, coastal and inland cities deal with substantially higher exposure to extreme precipitation and rising mean temperatures [1], with UHI intensities in European cities typically ranging 2–6 °C and peaking above 8 °C during heat waves [2]. These two impacts share a structural driver: the progressive replacement of permeable, vegetated surfaces with impervious, heat-retaining fabrics that simultaneously reduces infiltration capacity and suppresses evapotranspiration – the primary cooling mechanism in urban environments [3].

The two phenomena nevertheless call for partially different assessment approaches. Flood risk is a composite, probabilistic quantity that can be formally expressed as $R = H \times E \times V$ [4], where hazard probability (H), exposed elements (E), and vulnerability (V) are independently quantifiable and can be spatially combined into a risk index that directly assists in emergency planning and building regulation. For UHI and thermal stress, no analogous consolidated probabilistic risk framework exists in the literature: thermal conditions vary continuously, are highly sensitive to local morphology, and their health and comfort consequences depend on individual physiological parameters. The proper assessment approach is thus scenario-based simulation, modelling how spatial interventions affect thermal comfort indices (PET, UTCI) under representative summer conditions – rather than probabilistic risk mapping. This methodological difference, embedded in Modules 1 and 2 of the proposed framework, reflects the current state of practice and the different nature of the two phenomena. Their integration in Module 3 thus allows both outputs to inform a unified spatial intervention strategy.

Nature-based interventions restoring permeability and vegetation in open spaces generate a distinctive double dividend: they reduce runoff and drainage stress while simultaneously lowering surface temperatures and improving thermal comfort [5, 6]. This paper proposes and tests an integrated framework applied to three morphologically contrasting Naples (Italy) districts of Fuorigrotta, Ponticelli, and Soccavo selected for their documented flood history, different urban morphologies, and distinct socio-economic features. The framework couples physically based hydraulic modelling (EPA SWMM+FLO-2D), CubiST machine learning vulnerability weighting, and ENVI-met microclimate simulation within a unified GIS workflow. Open spaces, squares, courtyards, parking areas, are the primary spatial units of analysis and intervention, as their surface characteristics jointly affect both hydrological performance and thermal regulation [7, 8].

The scientific contribution is threefold: (i) CubiST provides objective vulnerability weighting; (ii) EPA SWMM+FLO-2D coupled with ENVI-met enables simultaneous flood and UHI co-benefit quantification from the same interventions; (iii) the cross-neighbourhood comparison gives evidence on how urban structure and open space configuration shape compound climate vulnerability. The paper is structured as follows: Sect. 2 reviews the literature; Sect. 3 presents the methodology; Sect. 4 reports results; Sect. 5 draws conclusions.

2 Background and State of the Art

2.1 Shared Drivers and Integrated Approaches

In densely built urban environments, the gradual replacement of natural, permeable surfaces with impervious covers, roads, rooftops, paved squares, car parks, and the concurrent removal of trees and vegetation trigger two interconnected processes. On one hand, reduced infiltration and increased runoff speed overload urban drainage systems, thus intensifying flood hazard; on the other, the significant lowering of evapotranspiration and the thermal mass of built materials relies on the rising of surface temperatures compared to those of surrounding rural areas, then entailing the so-called UHI effect [3]. This shared physical driver is especially pronounced in compact, high-density districts where building coverage is high, open spaces are scarce, and the legacy of rapid, often unregulated post-war urbanisation has left behind ageing grey infrastructure with limited adaptive capacity [7, 9]. Open spaces, which surface features jointly determine hydrological capacity and thermal performance, are the natural focus for integrated adaptation strategies [7, 8].

2.2 Urban Flood Risk Assessment

Methodological approaches to flood risk assessment span three families: indicator-based (AHP, vulnerability indices) [10], physically based coupled 1D-2D hydrodynamic models (EPA SWMM+FLO-2D, HEC-RAS 2D) [11, 12], and machine learning ensemble methods (Random Forest, XGBoost, CatBoost) [1, 13]. Nevertheless, key gaps exist: vulnerability and hazard are typically assessed separately, ML-based vulnerability weighting is underused in Southern European contexts, and district-scale LID-BMP siting combining flood and UHI evidence remains largely unexplored.

2.3 UHI Simulation and Open Space Thermal Performance

ENVI-met is the most widely adopted tool for district-scale microclimate simulation, validated extensively in Mediterranean contexts [14]. Remote sensing-based Land Surface Temperature mapping provides the spatial thermal baseline, while ENVI-met assesses scenario-based cooling effectiveness through PET and UTCI [8, 9, 15, 16]. Research for the Naples metropolitan area has specifically confirmed ENVI-met's suitability for characterising Southern Italian urban fabrics and evaluating greening interventions [17, 18]. The complementarity between these two approaches is a key methodological asset of the present study.

2.4 Lid-BMPs and Nature-Based Solutions: Co-benefits

Nature-based Solutions (NbS) and Low Impact Development-Best Management Practices (LID-BMP) generate a distinctive double dividend: they address urban flooding by enhancing infiltration, retention, and evapotranspiration at source; and simultaneously mitigate the UHI effect by cooling the urban surface through evapotranspiration, shading, and increased albedo [6, 7, 19]. Among others, green roofs, bioretention cells, rain

gardens, detention ponds, permeable pavements, and trees were extensively investigated [8, 20]. Consistently, researchers proposed the combination of open space tree planting and permeable paving to reduce stormwater runoff while cooling the city in Mediterranean cities [15, 21]. In compact historic fabrics, researchers demonstrated that cooling and greening strategies significantly lower the energy needed for cooling by 31% and increase comfort hours by 27%, and a stormwater management model (EPA SWMM) based evaluation shows that LID measures can reduce stormwater runoff by 20–40% where the total LID area is 10–30% of the entire catchment [22, 23]. Recent works specifically addressing the Naples urban context further confirmed that greening transformations in small open spaces within dense historical fabrics can generate significant UHI mitigation effects at the district scale [9, 24, 25].

However, the systematic identification of open spaces where LID-BMP and greening interventions can generate maximum integrated benefits while remaining technically and economically feasible is a key methodological challenge. Space availability, structural loading capacity, competing land uses, and morphological variability across urban fabric types all impose context-specific constraints requiring site-by-site spatial analysis rather than generic prescriptions [8, 20].

2.5 Regulatory and Policy Context

Urban flood risk management and UHI mitigation are embedded within a multi-level governance architecture. At the global level, the Sendai Framework for Disaster Risk Reduction (2015–2030) calls for multi-hazard urban adaptation strategies, the Paris Agreement (2015) commits signatories to resilience-oriented planning, and the SDG Agenda 2030 contextualises urban climate adaptation within Goals 6, 11, and 13 [26], respectively. They train a contemporary triad of global alliances that convey a joint policy mandate for solutions to flooding and thermal risk [27]. Namely, the Floods Directive (2007/60/EC) refers to National Preliminary Flood Risk Assessments, Flood Hazard and Risk Maps, and Flood Risk Management Plans for three specified return periods [28]. The EU Climate Adaptation Strategy (2022–2024) directly promotes NbS and the use of integrated green and grey infrastructures as key strategies to deal with both flooding and thermal stress [29].

In Italy, Legislative Decree 49/2010 transposes the EU Floods Directive through eight, District Hydrographic Authorities, with hazard and risk classes categorized as H1– H3 and R1–R4; the national hazard maps are not yet high-resolution enough for a district-scale applications, and UHI is not considered in Flood Risk Management Plans yet. At the city-scale, China's Sponge City programme has promoted permeable pavements, bioretention, and green corridors in more than 30 pilot cities since 2015, with clear co-benefits for flood and urban cooling [23]. In Singapore, the ABC Waters Programme provides exemplary references for integrated management of water bodies using green infrastructures for flood and thermal benefits. Barcelona's urban greening plan, Rotterdam's Water Square concept, and Vienna's Cool Streets initiative all show examples of combined solutions for flood management and heat reduction. References are also found in the Flood Risk Management Policy (2014) of the Tokyo Metropolitan Government (TMG, 2014).

Against this background, this study contributes to the practice by testing the robustness of linked EPA SWMM+FLO-2D coupled with ENVI-met, and Machine Learning-based vulnerability analysis in an overall GIS workflow in addressing both flood risk and UHI mitigation. Applying the framework to a real-world Mediterranean city allows drawing out comparative results across three morphologically diverse districts of Naples municipality.

3 Methodology

The methodology is structured as an integrated three-module framework developed within a GIS environment (QGIS) on a 30 m × 30 m grid (Fig. 1). Module 1 returns flood risk maps through coupled hydraulic modelling and machine learning vulnerability assessment. Module 2 investigates open spaces thermally and simulates UHI mitigation through ENVI-met greening scenarios. Module 3 integrates both outputs to site and assess LID-BMPs and greening interventions. The two approaches differ by design: Module 1 adopts the probabilistic risk formulation $R = H \times E \times V$, which is well established in flood management regulation and allows composite spatial mapping of hazard and vulnerability. Module 2 does not produce a risk index, because no equivalent probabilistic framework for UHI is consolidated in the literature; instead, ENVI-met simulations compare current open space configurations (baseline scenario) with post-greening configurations (design scenarios) to assess the thermal improvement achievable by specific interventions – expressed through PET and outdoor air temperature – under representative summer conditions. Module 3 overlays flood risk maps with thermal priority zones to identify open spaces generating maximum compound benefit (Figs. 2, 3, 4, 5).

3.1 Module 1: Flood Vulnerability Assessment and Hazard Mapping

3.1.1 Vulnerability Parameters and Machine Learning Weighting

Flood vulnerability was assessed through a Vulnerability Index (IV) combining exposure and vulnerability on the 30 m grid. Following a review of 24 scientific case studies, 72 candidate parameters were filtered to 19 effective variables according to contextual coherence, data availability, and demonstrated explanatory power [10]. Data sources include ISTAT census data, Italian Ministry of Economy and Finance income data, Geofabrik road and transport network, and Urban Atlas land use layers. As a training dataset for machine learning, the output was used from the reference IV produced in the experimental task of the CO-FRAME_NA project on a total of 23,588 cells. Two learning algorithms were employed and compared, namely: (i) Random Forest (RF), (ii) CubiST (https://CRAN.R-project.org/package=CubiST accessed on 1 April 2023). The CubiST algorithm returns statistical trees based on a recursive partitioning approach commonly used in decision trees combined with linear regression models used at each terminal node of the tree. It is commonly applied to contexts when many observations but few predictor variables are available, notably a condition that often affects some phases of the vulnerability mapping process at the district scale [45,46].

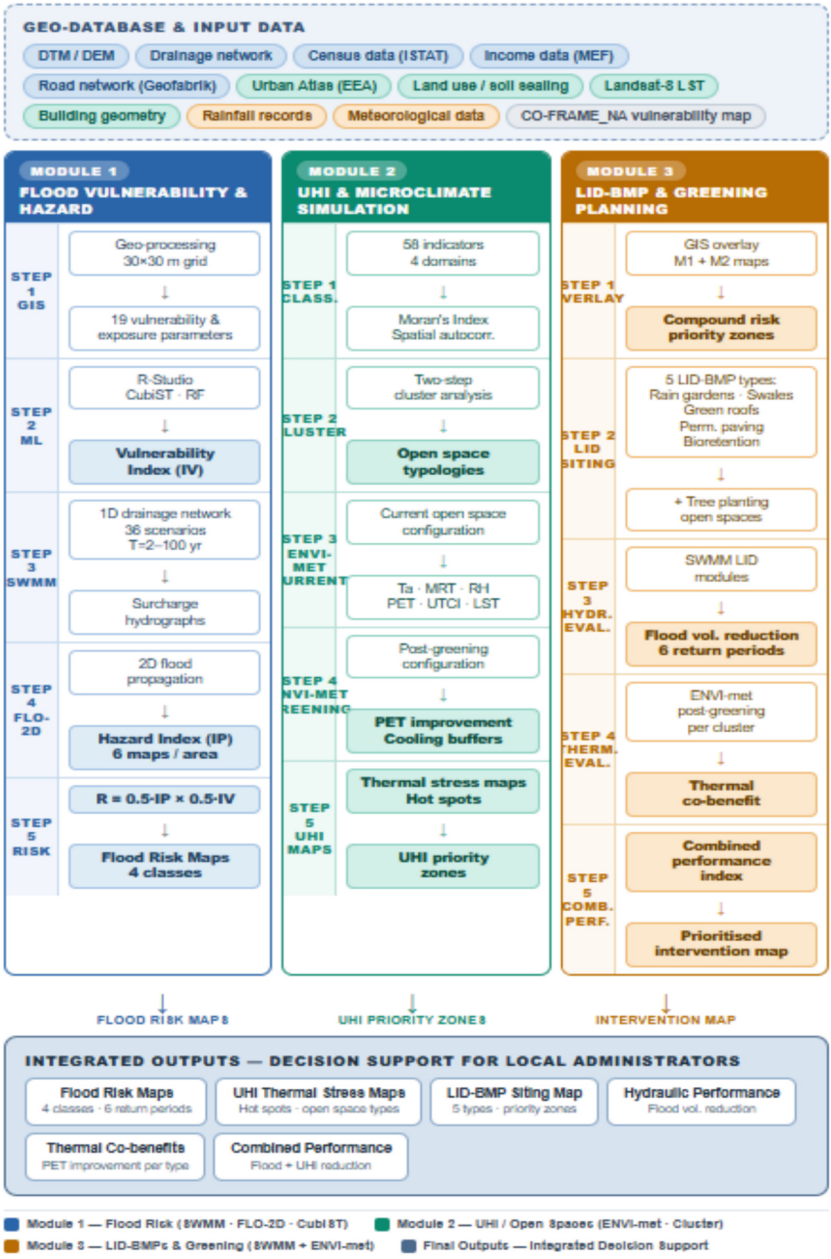

Fig. 1. Integrated Methodology Framework. All modules operate within a GIS environment, 30 m × 30 m grid.

A comparative assessment of the results of the two learning algorithms using R^2 and Mean Squared Error (MSE) indicators enabled the selection of the best-fitting model,

CubiST, which reports the accuracy of approximately 60% for this kind of application, which is an acceptable value considering the approximated nature of the reference output variable. The resulting parameter weights were applied to compute IV for each cell as the weighted sum of normalised parameter values.

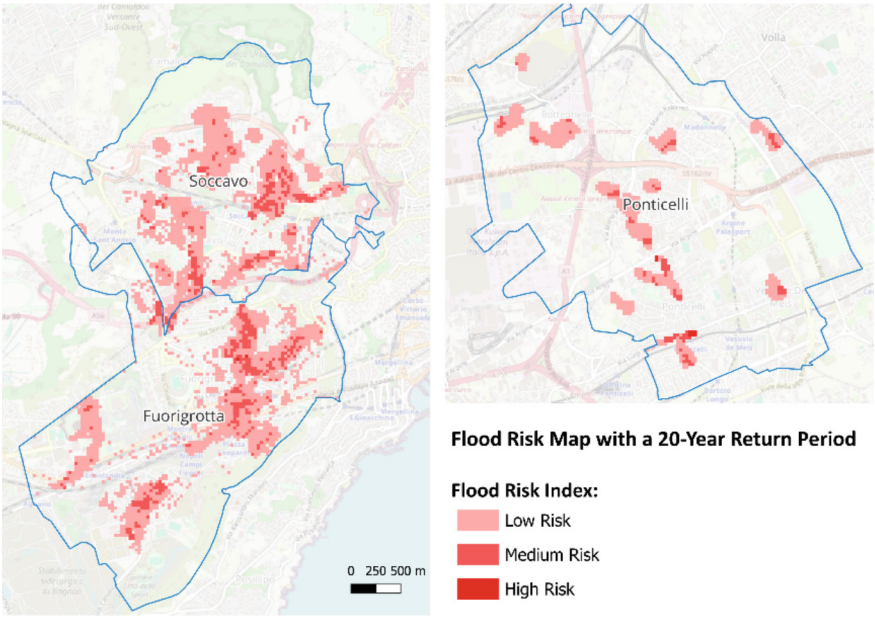

Fig. 2 Flood Risk Map for T = 20-year (Fuorigrotta, Ponticelli, Soccavo).

3.1.2 Hydraulic Hazard Modelling: EPA SWMM and FLO-2D

Following the modelling in EPA SWMM environment available in [30, 31], the drainage systems of the investigated districts were implemented and tested, by simulating different design rainfall events according to the regional frequency curve $h(t,T) = K^t \cdot a \cdot t^n$ (Naples Capodimonte station, 2000–2020) for six return periods (T = 2, 5, 10, 20, 50, 100 years) and five durations ($t \in [0.2, 6]$ hours). Dynamic Wave routing was set for simulations to account for both unsteady flows and pressurized occurrences of the system. Overall, 36 scenarios were yielded per district, then deriving the flooding hydrographs at critical nodes which allowed implementing the FLO-2D two-dimensional flood propagation and thus generating maps of the normalised Hydraulic Hazard Index (IP), given the maximum flood depth and velocity.

3.1.3 Flood Risk Mapping

Risk maps were computed as $R = 0.5 \cdot IP \times 0.5 \cdot IV$ (equal weighting, MATTM 2014 and IPCC framework [4]), classified into four levels (null, low, medium, high) for each of the

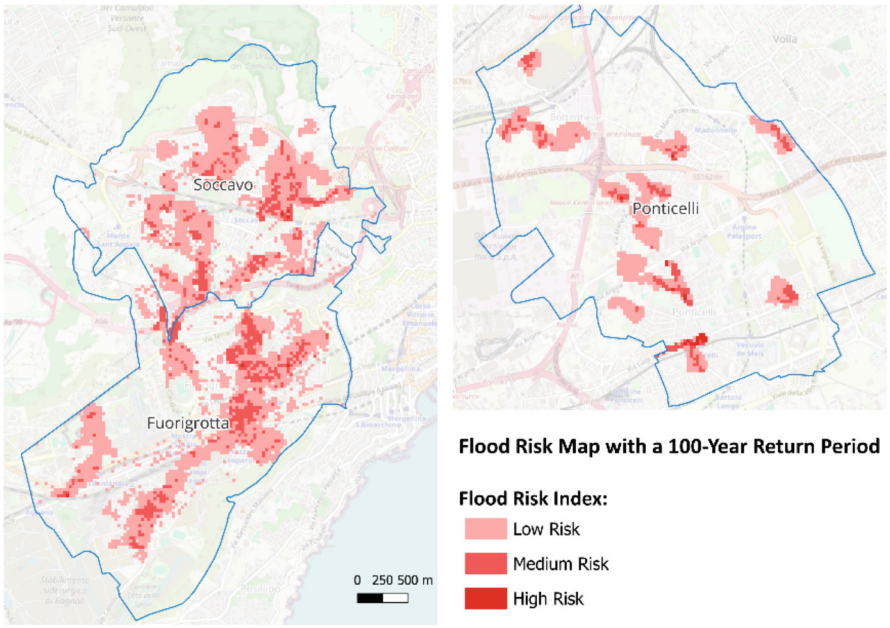

Fig. 3 Flood Risk Map for T = 100-year (Fuorigrotta, Ponticelli, Soccavo).

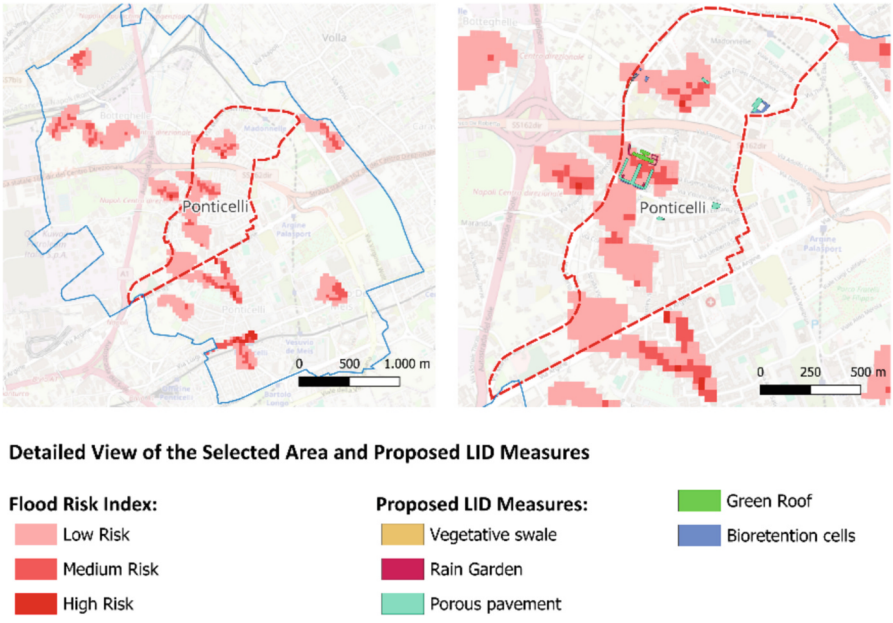

Fig. 4. Detailed View of the Selected Area and Proposed LID Measures in Ponticelli district.

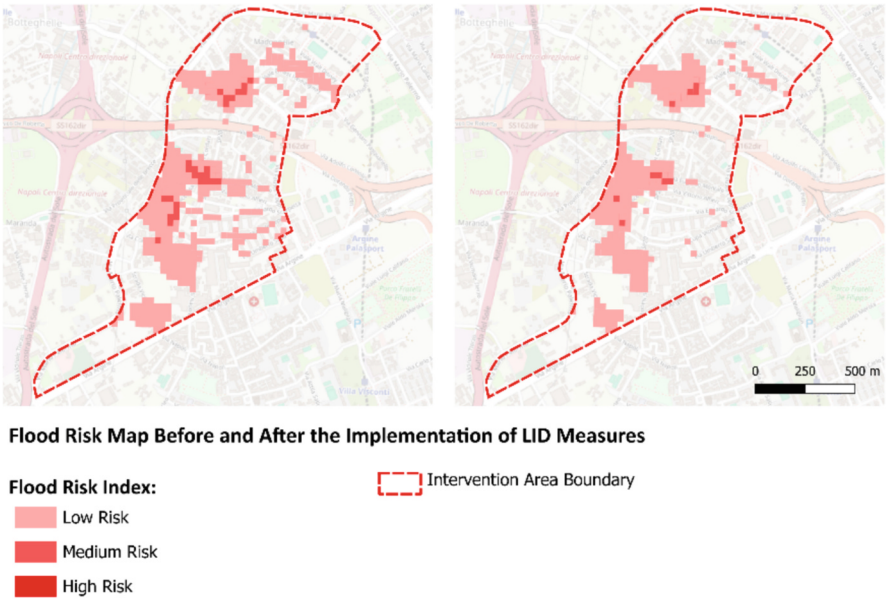

Fig. 5 Pre- and Post-Intervention Flood Risk Map Based on LID Measures.

six simulated return periods. The mapping entailed the spatial foundation for LID-BMP siting in Module 3.

3.2 Module 2: Open Space Classification and ENVI-Met Simulation

Open spaces were classified using a 58-indicator framework across four domains: open space features (permeability, vegetation cover), urban context (soil sealing, building materials), microclimatic and geomorphological characteristics (LST from Landsat-8, solar access, MRT), and socio-economic indicators [17, 18].

ENVI-met (v. 5.x) simulations were performed by comparing current open space conditions (baseline scenario) with post-greening configurations (design scenarios). The post-greening configuration relies on tree planting and permeable surface replacement, maintaining identical meteorological boundary conditions (clear-sky July design day). Among the possible outputs, the PET ones are provided as they can be considered representative of the potential benefits of reforestation solutions [8, 15].

3.3 Module 3: Integrated LID-BMP and Greening Siting

GIS overlay of flood risk maps (Module 1) with UHI thermal priority zones (Module 2) identifies open spaces where both stresses simultaneously exceed threshold values. Five LID-BMP were mapped against eligible surfaces: rain gardens and bioretention cells (green areas), vegetated swales (road shoulders), green roofs (flat rooftops), permeable pavements (parking areas), and bioretention cells with drainage layer. Urban tree planting was additionally allocated to all eligible hard-surface open spaces [8, 15]. Hydraulic

performance was re-simulated in EPA SWMM with modified subcatchment parameters; thermal performance was then evaluated through ENVI-met post-greening simulations.

4 Results

The integrated framework was applied to the three study districts, producing spatially differentiated outputs across all three modules. Results are discussed by linking quantitative values to the specific morphological and socio-economic features of each district.

4.1 Flood Vulnerability and Risk Mapping

The CubiST vulnerability weights reveal a structure closely tied to each neighbourhood's urban history. The income index (12.98%) carries the highest weight, followed by commercial buildings (10.22%), non-national residents (9.53%), young population (8.98%), structurally vulnerable buildings pre-1970 stock (8.56%), and residential density (8.43%). Road network parameters account for approximately 12% collectively, reflecting functional exposure of mobility infrastructure.

Fuorigrotta's planned twentieth-century development shows a heterogeneous vulnerability pattern, with high values concentrated in the commercial central strip and lower values around the university campus and Mostra d'Oltremare complex. Ponticelli – with the highest residential density in the Campania region, the largest share of pre-1970 building stock, and the lowest income levels among the three study areas – exhibits the most extensive high-vulnerability surface. Soccavo, morphologically characterised by hillside terrain, concentrates high vulnerability along the valley floor and in the oldest residential blocks, while medium vulnerability extends widely across the hillside fabric.

EPA SWMM simulations ($n = 0.1995$; $a = 25.97$–26.13 mm/h per district) reveal strongly differentiated drainage behaviour. Fuorigrotta's 1950 network (catchment 1.89 km^2) mainly fails at only two nodes, responding worse to short high-intensity events. Ponticelli's complex multi-municipality system (Sbauzone and Cuozzo-Reale channels; basin 20 km^2) shows more diversified crisis patterns across scenarios. Soccavo's 26 ha northern subcatchment, subdivided into four subcatchments (1.97–15.55 ha), has a structurally deficient drainage system – downstream pipes are smaller than upstream ones – producing failure at 3–4 nodes even at low return periods. FLO-2D propagation maps confirm that in Fuorigrotta flooding conveys toward the Agnano plain; in Ponticelli the flat Sebeto plain morphology produces extensive shallow inundation already at $T =$ 20-year; in Soccavo flooding is concentrated in hillside depressions.

Combining IP and IV yields six risk maps per district. In Fuorigrotta, high-risk cells at $T = 100$-year align with the commercial strip and the two EPA SWMM critical nodes. In Ponticelli, high-risk zones at $T = 100$-year overlay much of the densely urbanised central area – a compounding of flat drainage, old building stock, and social deprivation. In Soccavo, high-risk areas are more spatially contained but medium-risk cells extend broadly, thus defining a diffuse medium-priority intervention landscape.

4.2 LID-BMP Siting and Hydrological Performance

The spatial overlay of risk maps with land use identified eligible LID-BMP surfaces across all three districts, distributed as high-priority (high/medium-high risk) and low-priority (low risk) sites.

The hydraulic performance evaluation, conducted on a Ponticelli sub-area offering receptivity to all five LID types simultaneously, shows that LID-BMP are most effective at low return periods ($T \leq 5$ years), producing measurable reductions in peak runoff at critical nodes. At $T = 5$–100-year, relative flooded volume reduction decreases, confirming that LID-BMPs primarily act as source-control complements for frequent events, while structural measures are more effective for extreme ones. The urban planning implication is direct: LID strategies are the appropriate primary tool for managing the high-frequency, moderate-intensity events responsible for the majority of cumulative annual flood disruption in dense Southern Italian neighbourhoods.

4.3 Open Space Typologies and Greening Intervention Map

Three open space clusters were identified across the three districts: (i) large structured green spaces (parks, sports fields), with high vegetation cover and good baseline thermal performance; (ii) hard-surface open spaces (squares, parking areas, courtyards), with high imperviousness and elevated thermal stress; and (iii) residual interstitial open spaces (road shoulders, degraded courtyard edges), with intermediate permeability. Clusters (ii) and (iii) dominate in Ponticelli and Soccavo districts, reflecting decades of speculative densification that progressively expunged vegetated areas. Fuorigrotta's planned fabric concentrates cluster-(i) spaces around the Mostra d'Oltremare and University campus.

Greening interventions were allocated to clusters (ii) and (iii) in high and medium flood-risk zones, producing the combined siting map shown in Fig. 6. The spatial distribution reveals concentration in the historical central cores of Fuorigrotta and Ponticelli, where hard-surface inner courtyards and tree-free squares create co-located hydrological and thermal hotspots. In Ponticelli, the number and accessibility of hard-surface courtyards within the dense residential fabric represents a significant and spatially precise intervention potential that is invisible at the city scale [8, 15].

4.4 UHI Mitigation: ENVI-Met Simulation Results

ENVI-met simulations confirm that greening interventions generate measurable and spatially differentiated thermal co-benefits. Tree planting reduces outdoor air temperature by 1–3 °C near canopy during peak summer afternoon hours in the post-greening configuration, with magnitude modulated by canopy geometry, street aspect ratio, and pre-existing surface albedo [8, 9, 15].

As shown in Fig. 7, the PET improvement following greening is strongly differentiated by open space morphology. Inner courtyards in Ponticelli and Fuorigrotta show the highest thermal gains (PET reductions of 11–18 °C), because enclosed geometries amplify mean radiant temperature under current conditions and canopy shading intervenes precisely on this mechanism. Public squares and parking areas show intermediate

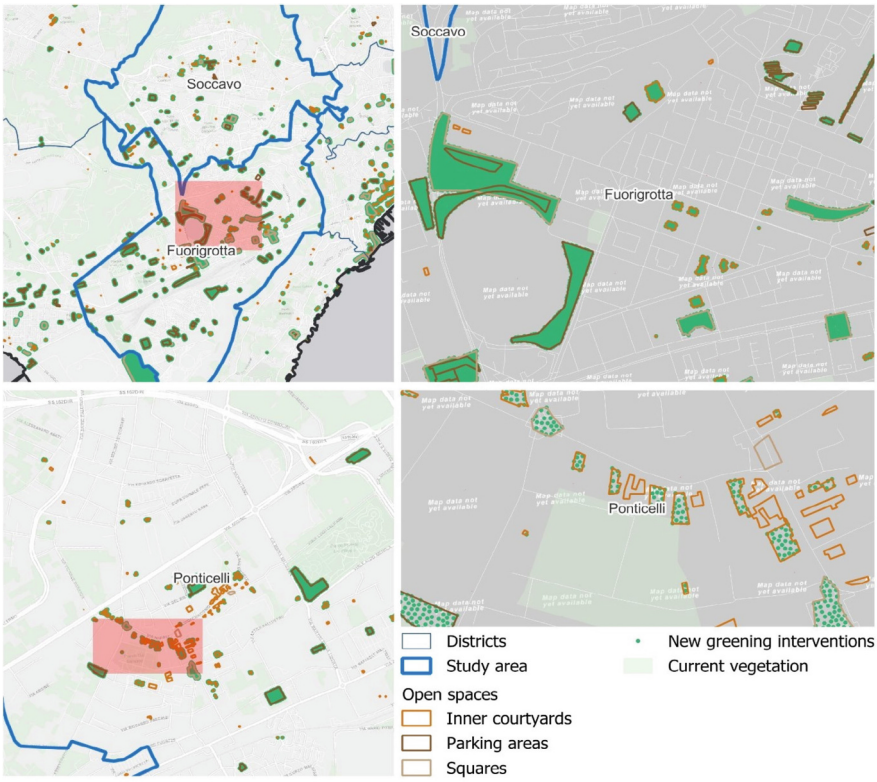

Fig. 6. Spatial distribution of greening intervention sites (Fuorigrotta, Ponticelli, Soccavo).

thermal improvement (PET reductions of 2–10 °C), concentrated within tree shadow zones and diminishing rapidly beyond the cooling buffer [8, 15].

The urbanistic reading is direct: the compact, poorly planned morphology of Ponticelli and Soccavo – narrow canyons, enclosed courtyards, minimal existing greenery – simultaneously produces the highest current thermal stress and the greatest thermal improvement potential from targeted greening. Fuorigrotta's planned layout shows lower current PET values but also lower marginal gain from additional tree planting. This confirms the planning principle that UHI mitigation investments should prioritise the most morphologically compact and thermally stressed portions of the urban fabric [16–18].

Critically, the highest-priority LID-BMP sites in Ponticelli and Soccavo – high flood-risk cells – are simultaneously the spaces with the greatest thermal improvement potential. This spatial convergence validates the integrated framework's core hypothesis: compound climate risk and compound nature-based response can be identified and prioritised within a single consistent GIS workflow, without separate planning processes for flooding and thermal stress [15, 33].

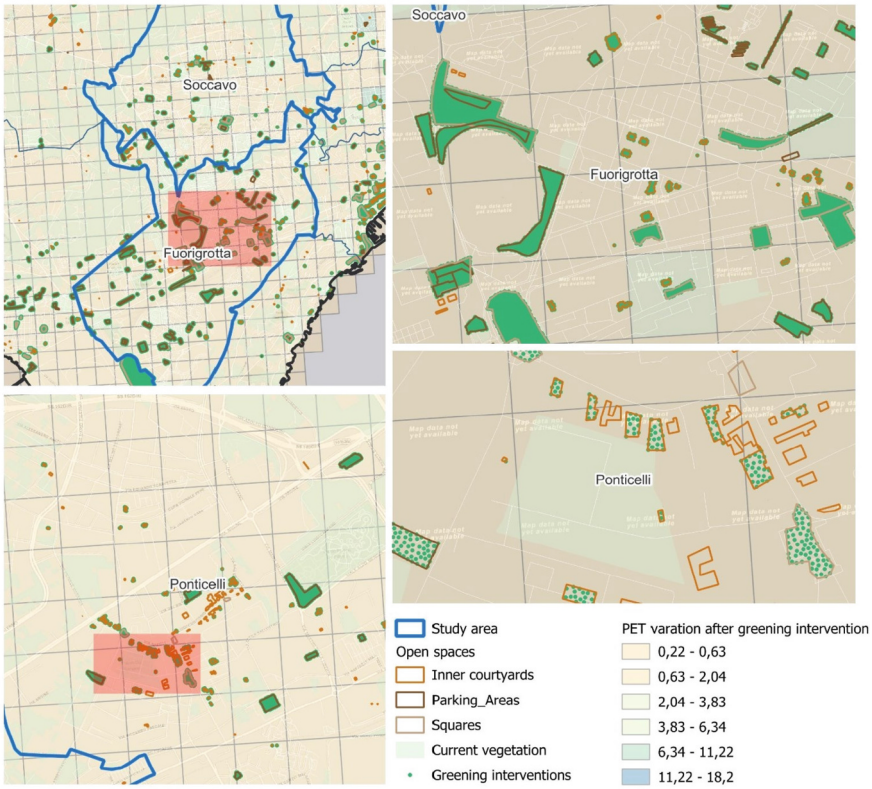

Fig. 7. PET improvement (°C) in open spaces of Fuorigrotta and Ponticelli, following greening interventions. Classes range from 0.22–0.63 °C (large open squares) to 11.22–18.2 °C (enclosed inner courtyards).

5 Conclusions

Urban flooding and the UHI effect are not two independent challenges: they are two displays of the same urban transformation process, and thus they should be addressed through integrated approaches, aimed at enhancing the resilience improvement. This study demonstrates that such integration is operationally feasible at the district scale through the coupling of established hydraulic and microclimate simulation tools within a GIS-based framework.

The application to Fuorigrotta, Ponticelli, and Soccavo (Naples, Italy) shows that compound vulnerability to flooding and thermal stress concentrates in the densest, most socio-economically fragile, and most morphologically unplanned portions of the urban fabric: the post-war spontaneous settlements where sealing is most extensive and green infrastructure most lacking. In these areas, LID-BMPs and urban greening in open spaces can simultaneously limit flooded volumes at low-to-moderate return periods and produce thermal comfort improvements of 2–18 °C PET. Both effects are delimited in the same

priority locations such as hard-surface inner courtyards, treeless squares, parking areas within high flood-risk perimeters.

The methodological contributions are threefold. First, CubiST ML weighting provides objective, reproducible vulnerability assessment overcoming the subjectivity of indicator weighting methods. Second, the 58-indicator open space classification with cluster analysis enables identification of thermally critical urban space typologies at a spatial resolution essential for effective intervention design. Third, the explicit coupling of EPA SWMM+FLO-2D with ENVI-met, demonstrated here in the Naples metropolitan context, transforms two disciplinary traditions into a jointly interpretable planning evidence base. The key asymmetry between the two modules – probabilistic risk mapping for flooding versus scenario-based comfort assessment for UHI – reflects the different state of practice and the fundamentally different nature of the two phenomena and is explicitly preserved in Module 3's spatial overlay logic.

The urgency of integrated approaches is reinforced by climate projections for Mediterranean cities: both extreme rainfall frequency and summer heat stress are projected to increase substantially under RCP4.5 and RCP8.5 scenarios. Cities that continue addressing these risks through separate sectoral processes, flood risk management plans blind to thermal consequences, and greening strategies oblivious to hydrological performance, will increasingly implement redundant or counterproductive investments. The framework proposed here, anchored in open space transformation as the shared spatial logic, offers a decision-support architecture through which local authorities can consistently identify and prioritise the nature-based interventions most likely to generate compound resilience gains [8, 9, 15, 16, 20].

Future work will extend ENVI-met simulation to full neighbourhood coverage, integrate building energy performance data, develop IPCC-scenario risk projections for Naples, and embed the framework within participatory planning processes. The methodology relies exclusively on open-source data and tools and is directly transferable to comparable Southern European urban contexts.

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Disclosure of Interests. The authors have no competing interests to declare.

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