

## Hydrological and Urban Criteria for Locating Nature-Based Solutions in Highly Densely Built-Up areas: The Case of Tondo Gioeni (Catania, Italy)

Critères hydrologiques et urbains pour l'implantation de solutions fondées sur la nature dans des zones fortement urbanisées : le cas de Tondo Gioeni (Catane, Italie)

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### RÉSUMÉ

Cette étude propose une méthodologie intégrée visant à identifier et hiérarchiser les zones adaptées à l'implantation de Solutions fondées sur la Nature (SfN) dans des contextes méditerranéens fortement urbanisés, en se concentrant sur le bassin du Tondo Gioeni à Catane (Italie). L'approche combine modélisation hydrologique-hydraulique, analyse spatiale et critères issus de la planification urbaine afin de répondre à l'augmentation du risque d'inondation liée aux épisodes pluvieux extrêmes et aux formes urbaines compactes. Les cartes d'aléa et de risque, obtenues grâce à des simulations HEC-RAS pour différents temps de retour, mettent en évidence les secteurs prioritaires pour les interventions. Ces résultats sont croisés avec des données d'occupation du sol, de morphologie et d'environnement afin d'identifier les espaces non bâtis où les SfN peuvent favoriser l'infiltration et réduire les débits de pointe. Des déterminants urbains supplémentaires—tels que les réglementations en vigueur, les outils de planification, la vulnérabilité des populations et le régime foncier—sont intégrés dans un cadre multicritère pour évaluer la faisabilité et la transformabilité des sites. Les résultats préliminaires montrent un potentiel significatif pour la mise en œuvre ciblée des SfN, tout en soulignant les contraintes propres aux environnements urbains très construits. Le cadre proposé soutient la prise de décision en intégrant les dimensions hydrauliques, écologiques et urbanistiques pour une gestion durable des eaux pluviales dans les environnements urbains méditerranéens.

### ABSTRACT

This study presents an integrated methodology for identifying and prioritizing suitable areas for Nature-Based Solutions (NBS) in highly urbanized Mediterranean contexts, focusing on the Tondo Gioeni catchment in Catania (Italy). The approach combines hydrological–hydraulic modelling, spatial analysis, and planning-based criteria to address increasing flood risks driven by extreme rainfall events and compact urban development patterns. Flood hazard and risk maps were produced using HEC-RAS simulations for different return periods, highlighting critical zones requiring intervention. These results were overlaid with land-use, morphological, and environmental datasets to identify unbuilt areas where NBS could effectively mitigate peak flows and enhance infiltration. Additional urban determinants, including zoning regulations, planning frameworks, population vulnerability, and land ownership, were incorporated into a multi-criteria evaluation to assess the feasibility and transformability of each site. Preliminary findings reveal significant opportunities for targeted NBS implementation but also emphasize the constraints associated with highly built-up urban settings. The proposed framework supports decision-making processes that integrate engineering, ecological, and planning perspectives for climate-resilient stormwater management in Mediterranean urban environments.

### KEYWORDS

Flood risk assessment, Hydraulic-Hydrological modelling, Nature-based solutions, Spatial planning, Urban sustainability.

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## 1 INTRODUCTION

The impacts of climate change are particularly acute in the central Mediterranean region, where high-intensity storm events are becoming increasingly frequent, with substantial increases in peak flow rates and runoff volumes, (Abdessamed and Abderrazak, 2019). Urban sprawl significantly alters hydrological processes, intensifying the magnitude of flood events (Sciuto et al., 2024). Sustainable stormwater management strategies are becoming increasingly urgent. A promising approach involves Sustainable Drainage Systems (SuDS), commonly acknowledged among Nature-Based Solutions (NBS) and recognized as “win-win” strategies that both mitigate pluvial flooding and deliver multiple co-benefits (Chen et al., 2024; Landoni et al., 2025). Moreover, the recently adopted EU Nature Restoration Regulation (NRR, 2024/199) becomes a relevant opportunity for boosting the adoption of NBS in urban areas, by integrating ecosystem restoration with climate and disaster risk policies, supporting resilience and ecosystem services.

However, hydrological suitability alone is insufficient for NBS implementation, especially in densely built-up areas, where space limitations, regulatory constraints, and urban morphology might strongly condition feasibility and implementation (La Rosa and Pappalardo, 2021). As a consequence, NBS deployment and prioritization must rely on site-specific constraints and risk profiles, but should also account for careful consideration of urban planning, including legislation in force, local land-use and landscape plans, adopted policy frameworks, and land tenancy. An integrated approach, coupling hydrological evidence with planning and policy concerns, is particularly relevant for compact Mediterranean city cores, where limited space, regulatory barriers often represent the primary obstacles to effective NBS deployment (Zanetti et al., 2024; Ranzato et al., 2023).

The aim of this study is to develop an integrated approach to identify suitable areas for the implementation of NBS and to prioritise them in the catchment of Tondo Gioeni in Catania, taking into account both hydrological-hydraulic and urban-planning elements. The methodology includes: (i) the assessment of flood-risk and runoff dynamics at the catchment scale through hydrological-hydraulic modelling; (ii) the overlay of criteria derived from morphological, planning, and environmental factors; and (iii) the identification of priority areas for NBS implementation based on a multi-criteria evaluation framework.

## 2 CASE STUDY

The study focuses on the Tondo Gioeni catchment, a highly urbanized basin of approximately 110 hectares, in the northern part of the municipality of Catania. A Digital Terrain Model (DTM), is used to delineate the catchment, considering Tondo Gioeni as the basin outlet (Figure 1a). Here a small-scale retrofitting intervention is planned within the CARDIMED project (<https://www.cardimed-project.eu/demo-sites/catania-ferla-urban-resilience-nbs/>). This intervention, involving bioretention systems such as rain gardens, aims to reduce the hydraulic load on the conventional drainage system. However, this measure cannot fully resolve the runoff management of the catchment. The catchment is densely built-up, with limited green spaces, steep slopes, and high traffic loads, which exacerbate stormwater runoff and flooding issues. This is the result of an intense development process that took place mainly after the approval of the city Master Plan (Prg) in 1969. However, the area still comprises some unsealed patches, including a section of the university campus, the Agricultural technical institute and part of Gioeni park (Figure 1b). Effective long-term stormwater control would require interventions distributed throughout the upstream areas to promote infiltration and reduce peak flows across the entire basin.

### 2.1 Hydrological–Hydraulic Modelling for Flood-Risk Area Identification

The hydraulic modelling is carried out through the freeware software HEC-RAS to identify the flood hazard areas and to generate the flood risk maps, with a return period of 2, 5, 10, 50 and 200 years. Risk areas (R) are the result of three factors as shown by the following equation proposed by Sicilian Hydrogeological Risk Management Plan (HRMP):

$$R = H \cdot E \cdot V$$

where  $H$  is the level of hazard within an analysed area associated to a particular probability of occurrence of a flood event;  $E$  represents the receptors at risk (people, infrastructures, economic activities, cultural heritage sites, etc.) located within an analysed area which are exposed to a flood event;  $V$  is the vulnerability, namely the degree of ability or inability of an element or an area to hold up against a flood event. The product  $E \cdot V$  is the potential damage ( $P_D$ ) that is expected to happen to the receptor at risk following a flood event with a particular

probability of occurrence and, in this study is associated to the land use. The flood hazard (H) areas are identified by combining the runoff depth and the flow velocity maps generated for each return period time analyzed through the following flood hazard rating equation (ISPRA, 2012):

$$H = h \cdot (v + 0.5) + DF$$

where  $h$  (m) and  $v$  ( $m \cdot s^{-1}$ ) are respectively the runoff depth and the flow velocity at a specific location of the catchment, DF is the debris factor. Finally, the risk factor is classified in 4 classes from R1 to R4 as suggested by Sicilian HRMP.

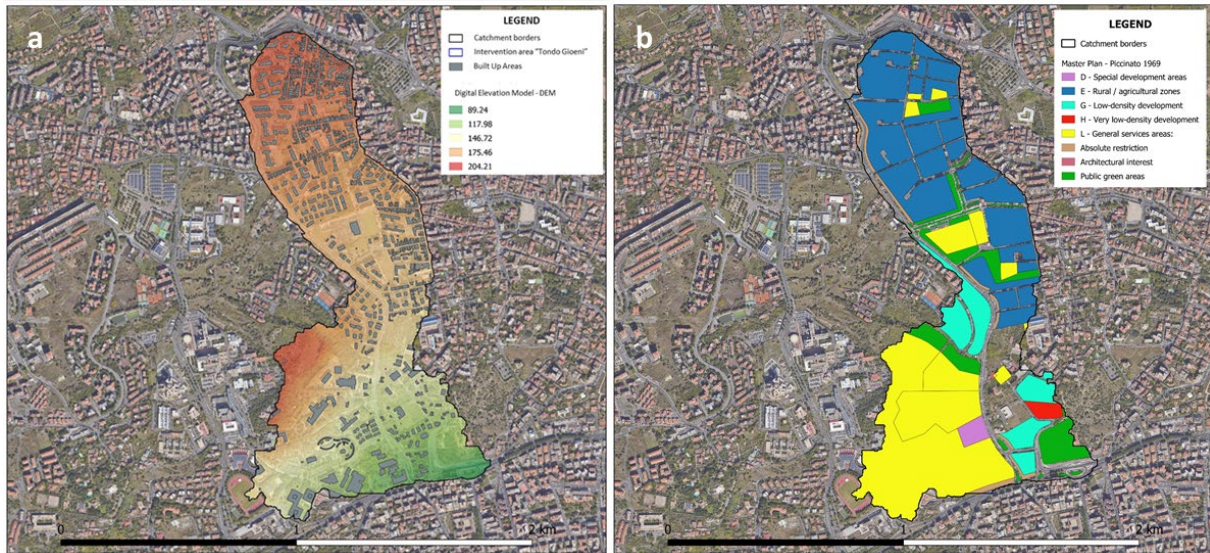


Figure 1 – a) Localization of the Tondo Gioeni basin (Catania, Sicily) with ground elevations; b) Overlay of the masterplan zoning and the Tondo Gioeni basin

## 2.2 NBS suitability

According to the vision of NRR, which protects green spaces, NBS implementation is primarily investigated in unbuilt areas (UAs) within the urban catchment. UAs areas are identified and categorized according to available land cover, land use maps, and the tree cover density and type maps (Urban Atlas Land Cover/Land Use - 2018; Tree Cover Density - 2023. European Union's Copernicus Land Monitoring Service information). The method addresses the improvement of sustainable urban drainage while enhancing the overall quality of the built environment through an overlay analysis of UAs and the distribution of flood-prone areas. By overlapping these layers, the approach identifies potential interface zones where nature-based solutions can occur, thus exploring the potential for UAs to contribute to urban flood mitigation. NBS types to be potentially located in identified areas are pre-selected based on their capacity to deliver the desired hydrologic and hydraulic performance. To assess the suitability of identified NBS the study combines criteria of size, shape, and other land-use and physical site constraints, which might limit the viability of certain NBS types to the specific sites.

To refine the analysis, the study adds some further critical aspects to be carefully considered in order to check if the NBS location aligns with the planning framework and policy opportunities windows.

Determinants are mainly related to masterplan zoning and urban regulations in force, landscape planning provisions, spatial identification of urban vulnerabilities (distribution of population and vulnerable groups, public buildings), and land tenancy/landownership (Table 1).

Table 1 - Multicriteria evaluation framework including the urban determinants.

Urban determinants	Description
Site-specific physical constraints	Size; Shape; Compatible land uses/land cover transition; Drainage area; Soil, Slope; Underground/surface infrastructure
Policy & planning contexts	Local norms; Landscape/environment prescriptions; Masterplans prescriptions and regulations; Upgraded policy tools (transfer of development rights, seizing of property; etc.)
Urban drivers	Urban patterns and morphologies; Green area density; Population density and vulnerability profiles; Land ownership

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The investigation of urban determinants facilitates a mixed-methods analysis of the transformability of the different UAs into specific NBS for flood mitigation.

Specifically, transformability is evaluated based on the potential for Urban Areas (UAs) to be effectively re-designed to enhance their flood mitigation performance, considering their existing layouts and land cover characteristics. These variables, along with key urban determinants, define a transformability matrix (Privitera et al., 2018).

### 3 PRELIMINARY RESULTS

Flood risk map emphasize the most critical areas (in terms of hydraulic risk), within the Tondo Gioeni catchment, that require prioritization for NBS implementation. In details, the area affected by each Italian risk factor category R1, R2, R3 and R4 covers approximately 2,775 m<sup>2</sup>, 15,584 m<sup>2</sup>, 14,858 m<sup>2</sup> and 20,518 m<sup>2</sup>, respectively. In the current scenario, the estimated peak flow values at the basin outlet were 2.1 m<sup>3</sup>/s, 10.2 m<sup>3</sup>/s, 16.9 m<sup>3</sup>/s, 32 m<sup>3</sup>/s, and 45.3 m<sup>3</sup>/s for return periods of 2, 5, 10, 50, and 200 years, respectively.

In order to mitigate peak flows and related flood prone areas, a set of NBS are pre-selected based on their hydraulic performance capabilities.

According to available datasets, UAs included in the Tondo Gioeni catchment that are more suitable for NBS are the following: unsealed soil 33.11 ha (30.3%), with total tree canopy 22.07 ha (22.85%); landscape protected areas 29.9 ha (27.4%), areas zoned for public services 33 ha (30.6%), zoned for parks and green areas 8.6 ha (7.9%), zoned for roads 21.8 ha (19.9 %).

### 4 CONCLUSION AND FUTURE DEVELOPMENTS

Bridging hydrological modelling with urban spatial analysis, allows to overcome the divide between engineering-driven stormwater planning and district-scale urban planning and design. This approach can lead to more resilient and sustainable actions in urban planning and development. Moreover, it offers a transferable approach for Mediterranean cities seeking climate-resilient and spatially feasible strategies for managing stormwater in densely urbanised environments. Future developments of the research will focus further NBS opportunities within urban patterns, allowing for an overall assessment of the transformability level of the urban catchment towards more sustainable flood management.

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