Università degli studi di Milano-Bicocca

Data Science Lab on Smart Cities

Final Essay

Nature-Based Solutions for Urban Flooding: Milan Case Study

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Abstract

Urban flooding, exacerbated by climate change and urbanization, poses a significant challenge for cities like Milan. This study develops a comprehensive risk assessment tool, the Pluvial Flood Index (PFI), integrating geomorphological and socioeconomic factors to identify flood-prone areas and prioritize interventions. By analyzing soil impermeability, slope, soil types, proximity to rivers, and social vulnerability indicators, the PFI identifies the most vulnerable areas in Milan. The study proposes nature-based solutions (NBS) such as filter strips, vegetative swales, and bioretention areas as effective, localized interventions to mitigate flood risk while enhancing urban livability. These NBS offer co-benefits like improved air quality, reduced urban heat island effect, and increased biodiversity. The research underscores the importance of a multi-faceted approach to urban flood management, combining scientific analysis with nature-based solutions for a more resilient and sustainable urban future.

1 Problem Description and Indicators

Climate change is one of the most pressing challenges of our time, with significant impacts on atmospheric indicators and society as a whole. According to the IPCC [1], the global average temperature has risen by about 1.1°C compared to pre-industrial levels, and this increase is already causing an intensification of extreme weather phenomena, including floods, whose economic damage alone in Europe has been estimated at more than 280 billion euros between 1980 and 2022 [2]. These occur when precipitation cannot be absorbed by the ground and instead flows over the surface, crossing urban areas before reaching drainage systems or waterways. It is an alarming trend that is also reflected in Italy, and particularly in Lombardy, where the phenomenon of flash floods has become increasingly frequent and is of particular concern considering that urban areas are the most vulnerable to the impacts of flooding, as demonstrated by research by Guerreiro et al. [3], which examined climate risks for 571 European cities. In this context, the city of Milan, with its 1.4 million inhabitants and a territorial urbanization index (percentage ratio of urbanized area to land area) of 72 % [4], is in a particularly critical position, with 6.5% of the resident population living in areas of medium to high hydraulic risk [5]. Over the years, the city has undergone a process of soil sealing, which has led to a significant increase in surface water runoff. Over a period of 15 years (from 2000 to 2015), the urban expansion of Milan has increased the impermeable surface area by almost 20% [6][7] with direct consequences on the absorption capacity of the soil. The city's location in the Po Valley and its high building density are factors that make it further vulnerable to flood events, as evidenced by the recurrent flooding of the Seveso River, with 120 episodes recorded between 1976 and 2023 [8].

Figure 1: October 31, 2023 - Heavy flooding led to overflow of Seveso river. Sources: Nova News & CNN

In the face of these challenges, Nature-based Solutions (NBS) emerge as a promising strategy to mitigate the effects of urban flooding. Defined by the European Commission [9] as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience", NBSs have gained increasing attention through EU-funded research [10]. These solutions are divided into small-scale and large-scale, offering a wide range of interventions adaptable to different urban contexts, and not only mitigate stormwater runoff, reducing the risk of flooding, but also offer numerous co-benefits, including improving air quality, reducing the urban heat island effect, and increasing biodiversity [11].

Figure 2: Examples of small-scale green solutions. Source: European Commission

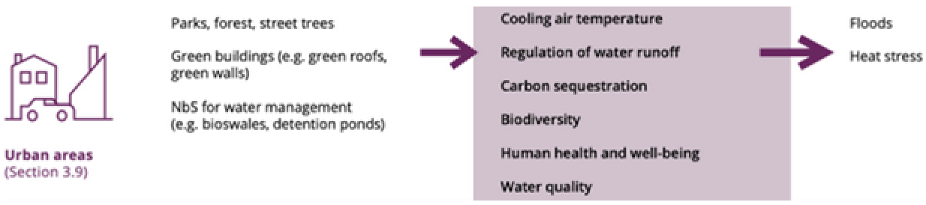


Figure 3: Multiple benefits of nature-based solutions for addressing climate hazards in urban areas. Source: European Environment Agency

Despite demonstrated benefits, widespread adoption of NBS still faces significant obstacles, such as lack of adequate funding, limited political awareness, and lack of quantitative data on long-term performance [12]. As pointed out by Nature Based Solutions Institute co-director Cecil Konijnendijk, accurately quantifying the benefits of NBS compared to traditional solutions remains an area of ongoing research. However, Milan is making strides in this direction with the Piano di Governo del Territorio 2030, approved in 2019, which aligns with the United Nations Sustainable Development Goals and the Paris Climate Agreement, proposing ambitious goals such as promoting zero-emission buildings and increasing green areas, including ”the development of a map of areas in the city that are intended to be de-paved, planted or forested” [13]. To overcome the challenges in implementing NBS, it is crucial to develop robust methodologies to identify the critical areas that could benefit the most. The approach proposed by Kuller et al. [14], who developed a framework for multi-criteria assessment of NBS feasibility in urban settings by integrating spatial and socioeconomic data, is an important step in this direction. In parallel, the creation of new institutions dedicated to the management and monitoring of NBSs proves crucial to ensure their long-term effectiveness. Frantzeskaki [15] highlighted the importance of collaboration between different local stakeholders, including public agencies, private companies, and communities, for the success of NBS initiatives, a participatory approach that not only improves the social acceptance of interventions, but also helps to build a more resilient and livable city for all its inhabitants.

Inspired by the innovative approach of Kuller et al. [14], a tool was devised to quantify the impact of extreme weather events on the urban and social context, as well as to effectively assess and manage related risks. This tool takes the form of a composite risk index for pluvial flooding in the Milan metropolis, called the Pluvial Flood Index (PFI). This allows a hierarchy of priority areas to be established, thus providing useful support for risk mitigation and resilient urban planning strategies.

The peculiarity of the index lies in its bipartite nature, which seeks to integrate geomorphological and hydrological aspects with socioeconomic factors. This dual perspective allows us to consider a more complete picture not only of the geographical conformation of the city, but also of the characteristics of the population that inhabits it. For the selection of variables, we were inspired mainly by the study conducted in Florence [16], adapting it to the Milanese context.

1.1 Geomorphological component

The geomorphological component of the index incorporates a number of crucial variables, including:

- The soil imperviousness index, which provides precise spatial mapping of areas characterized by permeable or impermeable soils.
- The slope of the land, which highlights geological peaks and troughs that, due to their conformation, are particularly vulnerable to flooding because of the difficulty of water runoff.
- The types of soils analyzed in terms of material composition, recognizing that different substrates, such as sand and gravel, have different water retention capacities; some soil types, in fact, are more prone to runoff due to their reduced and slow absorption capacity.
- The proximity to surface watercourses, a factor of primary importance since Milan is surrounded by numerous bodies of water that, over the years, have undergone multiple modifications to accommodate urban expansion.

This set of parameters provides us with an in-depth, multifaceted understanding of the physical characteristics of the urban area, allowing us to more accurately assess its susceptibility to flooding.

1.2 Socioeconomic component

While the geomorphological component can provide us with extremely relevant information for assessing risk, it must be recognized that vulnerability to disaster events is not solely determined by environmental factors. The second component of the PFI is therefore a Social Vulnerability Index (SVI). Vulnerability refers to the characteristics of an area that can amplify or reduce the potential immediate damage caused by an exceptional event [17]. This concept is related to that of resilience, which is a measure of a territory's ability to absorb impact, adapt and reorganize over the long term. The goal that a good risk management system must have is precisely to understand vulnerability and improve resilience. E. Fischer [18] reminds us, in fact, that the decision to incorporate an SVI into models is based on a growing body of scientific evidence that underscores the critical importance of social factors in determining the impacts of natural disasters. This approach recognizes that the consequences of events such as pluvial flooding are not uniformly distributed within the population, but are significantly modulated by socioeconomic and demographic variables.

For this reason, it is of utmost importance to understand the components of social vulnerability and to recognize that the SVI, although it has its limitations, has several points in its favor: its practicality in using easily accessible public domain data, the transparency of its construction methodology, its interpretability in translating the complex concept of social vulnerability into an easily communicable number, and its relevance in providing a solid basis for understanding a community's social vulnerabilities.

The measurement of social vulnerability, while having factors widely recognized by the scientific community, is subject to uncertainty and debate regarding the selection of the most reliable indicators. The choice of indicators is closely related to the theoretical framework and functional relationship between variables, or a combination of both. This process often involves a subjective component, known as "expert judgment," in which experts decide which indicators are most relevant to the overall vulnerability model [19][20]. In general, the construction of the index is accomplished by considering broader aspects that often occur in the circumstance of risky events (low income, a poor level of infrastructure, inadequate public health), others that become evident as a result of specific disasters (state of maintenance of a building, the state of preservation). So, the measurement of social vulnerability remains an evolving field of research to date, and future iterations of our index could benefit from the inclusion of additional indicators.

Based on this premise, in the process of constructing the SVI, mainly objective data were considered and optimized for the specific context of Milan. These indicators include variables such as:

- Resident population ratio under 14 and over 65 - children and the elderly are particularly susceptible to the negative effects of extreme weather events due to factors such as social isolation and pre-existing health conditions
- Education level of the resident population aged 18 and over
- Numerosity of resident households
- Average income of the resident population
- Housing density

- Condition of residential buildings

Socioeconomic factors, such as income, employment, and education level, significantly influence adaptive capacity and resilience, that is, to the posterior management in the medium term of disaster shock. Individuals with limited economic and educational resources often face greater difficulties in responding to and recovering from adverse weather events. Finally, the living and built environment plays a crucial role. Limited accessibility to green space, high building density, and the presence of impervious surfaces amplify vulnerability.

1.3 Analytic Hierarchy Process

The integration of geomorphological data with the Social Vulnerability Index laid the foundation for the development of the Pluvial Flood Index. However, in order to calculate both the SVI and, consequently, the PFI, a crucial step must be addressed: the weighting of the different indicators that comprise them. In both cases, the Analytic Hierarchy Process (AHP) [21] was adopted. This methodological approach is based on the construction of a pairwise comparison matrix, in which values of relative importance are assigned according to a calibrated scale, ranging from 1 to 9. Importantly, although the AHP provides a structured framework for feature weighting, the process retains an inherent degree of subjectivity. Careful consideration was given to the consistency and coherence of the scores, but it is not excluded that they are subject to potential bias. This awareness has prompted a cautious interpretation of the index results, viewing them as a good informational guide rather than absolute truth. The value of the approach lies in its transparency and ability to provide a structured starting point for further discussions and analysis. The integration of weighted socioeconomic factors with geomorphological data has led to the construction of a risk index that, while it has its limitations, provides a more comprehensive view of urban vulnerability to flooding.

1.4 Possible solutions

The synthesis of these elements made it possible to identify the areas of Milan most vulnerable to heavy rainfall, according to the Pluvial Flood Index. The outcome of the analysis is not surprising, given the geographical conformation of the Lombard capital: located in a low-slope plain and subject to intense urbanization. Nevertheless, the Milanese administration is taking proactive measures to enhance the resilience of the urban fabric to extreme weather events, while simultaneously aiming to elevate the quality of life of its citizens. To validate the PFI, past disastrous flood events were geolocated, comparing our index with actual historical data. The results show significant consistency. For example, the municipality with the highest PFI is "Stazione Centrale - Greco - Crescenzago," followed by "Porta Nuova - Bovisa - Niguarda - Fulvio Testi." We note that these municipalities, although not devoid of urban greenery, are not exempt from flood risk, as confirmed by historical evidence. This shows us that even areas apparently with good green endowments can be vulnerable to flooding.

The NBSs we propose, such as filter strips, vegetative swales, bioretention areas, and rain gardens, represent a multifunctional approach that integrates engineering innovations with the importance of urban greenery. These solutions were selected based on criteria reported in the literature [16] and found to be suitable for implementation in public and open spaces such as parking lots, parks, streets, pedestrian and bicycle paths, and traffic islands. Such solutions not only manage stormwater runoff, but also improve air quality and reduce the urban heat island effect.

A key difference from more invasive interventions or comprehensive urban redevelopments is that these solutions can be distributed evenly throughout the city, reducing the risk of creating disparities between neighborhoods. They also require less displacement of residents and businesses, minimizing the risk of gentrification. This approach is inspired by the concept of 'just green enough'[22], which aims to balance environmental benefits with the prevention of gentrification. In line with expert recommendations, the approach taken favors small-scale interventions aimed at preserving the neighborhood's characteristic identity. At the same time, emphasis is placed on integrating policies aimed at safeguarding housing affordability. It is essential to balance the creation of new green spaces with the preservation of existing natural areas and the redevelopment of brownfield spaces, creating multifunctional green spaces that meet the specific needs of current residents. Just as it is essential to consistently monitor socioeconomic impacts to ensure that our interventions promote environmental justice while minimizing the risks of triggering gentrification processes. A good point is to create local economic opportunities by incorporating employment and training opportunities for local residents into green infrastructure projects, thereby contributing to community economic development and fostering a sense of ownership and environmental responsibility.

Despite the many benefits of green solutions, it is crucial to consider the potential downsides. These solutions require regular maintenance, with significant long-term costs. For example, clogging problems and variable performance have been highlighted for bioretention areas [23]. In addition, their effectiveness may vary seasonally, decreasing during winter or during periods of drought. In densely populated urban areas, finding adequate space can be difficult, and drainage problems can arise if not designed properly, leading to stagnant water, and if such stagnant water is not managed properly, there is a risk of mosquito breeding. In polluted areas also, there is a risk of them accumulating contaminants in the soil.

Public acceptance can be a challenge [24] as some people may perceive them as untended areas. Plant selection must be carefully considered to adapt to the local climate, thus avoiding overwatering. Finally, the introduction of new plant species could have negative impacts on local biodiversity. These issues need to be carefully considered at the planning stage to maximize the benefits of green solutions and reduce potential risks.

2 Anthropic and green elements in Milan

In the context of the analysis of Smart Cities and their resilience to climate change, Milan represents an emblematic case study. The city, the economic heart of Italy and among the most densely populated in Europe, is facing significant challenges related to intensive urbanization and its effects on the urban and environmental fabric; in fact, the entire metropolitan area of the city is prone to flood risk, due to the expected increase in the currents of the Olona and Seveso rivers and the spills generated by the impermeable and compact urban structures. The geographic analysis of the city context was possible thanks to data from the Milan topographic database (2020) [25]. A first visualization of the buildings and anthropization (Figure 4a) clearly shows the high building density that characterizes the city, especially in the historic center and surrounding areas, with a gradual decrease toward the suburbs. The above map includes:

- **Buildings**: by which is meant a built body that is seamless, has a single building type, may have multiple use categories, has a given state of preservation, may possibly be underground.
- **Covering elements**: describes one of the various roofing parts of a building, i.e. pitches, terraces, domes, etc.
- **Minor Buildings**: described in this class are those objects that complete the definition of the built-up area but are not real buildings, either because of their unstable nature, size, use etc.

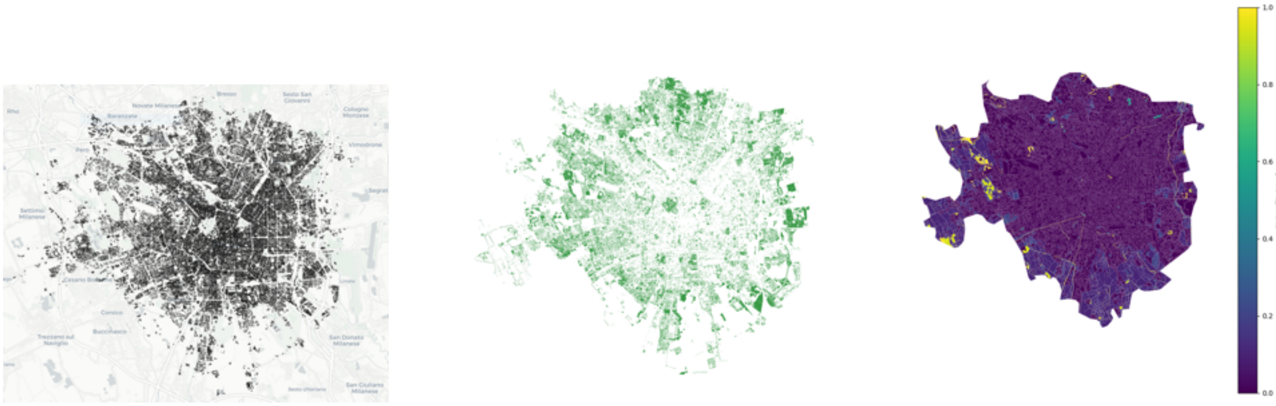
In contrast, urban greenery is depicted in Figure 4b, revealing an uneven distribution of green areas within the city. There is a concentration in suburban areas, particularly evident in the northwest and southeast of the city. As the documentation reports, these elements consist of:

- **Isolated trees**
- **Street of trees**: trees arranged in a line at the edge or dividing line in road areas, or as dividing elements of the farm system.
- **Green areas**: areas used as greenery for ornamental purposes or included in recreational areas. Areas of flower beds, gardens, lawns, tree-lined areas inserted into the urban for public use or even private gardens belong to this class.

The presence of these green areas is crucial for the mitigation of the urban heat island effect and for the management of stormwater runoff, key aspects in planning a climate change resilient city.

The last image (Figure 4c) presents the Naturality Index of Milan. This is an index that places undeveloped land at the center of analysis in order to assess, albeit tentatively, its ecological aspects and the long-term effects that the impacts of dispersed cities may have on the degree of sustainability of anthropocentric land use. Index values close to 1 indicate areas with high naturalistic value determined by limited or no human action on the land, while values close to 0 indicate areas with no naturalistic aspects due to a greater influence of anthropogenic activity [26]. On average, the city of Milan has a Naturality Index of 0.1; in fact, the predominance of highly urbanized areas (in dark purple) with sporadic areas of greater naturalness (in yellow and green) is clear.

Joint analysis of these three maps shows a clear dichotomy between the city center, characterized by high building density and low naturalness, and the peripheral areas, where the greatest opportunities for urban greening interventions are concentrated. In response to these challenges, Milan has adopted the Piano di Governo del Territorio 2030, which includes ambitious goals for increasing green areas and depaving, aiming to create a more resilient and livable city. Among the most innovative initiatives is the ForestaMi project, which aims to plant 3 million trees by 2030, contributing not only to the mitigation of hydrogeological risk but also to improving air quality and reducing the heat island effect. In parallel, the city is investing in blue-green infrastructure, such as the Navigli reopening project, which not only restores a historic element of the urban landscape but also provides opportunities for sustainable stormwater management and increased urban biodiversity.



(a) (b) (c)

Figure 4: Anthropic elements (a), urban green (b) and naturality index (c) in the city of Milan. Source: Comune di Milano

3 Sources and methods

The heterogeneity of sources and formats required a careful harmonization process to ensure the consistency and integrity of the data in the study. Table 1 summarizes the data sources used, specifying the data type, format and resolution.

Table 1: GIS layers and data sources

GIS layer	**Format/Resolution**	**Data source**
Imperviousness	Vector / nominal scale, Multiscale	Città metropolitana di Milano, DECIMETRO [27]
Slope	Raster / 5 m	Regione Lombardia [28]
Global Hydrologic Soil Groups	Raster / 250 m	ORNL DAAC [29]
Hydrographic network	Vector / nominal scale 1:10000	Città Metropolitana di Milano [30]
Children, Elderly, Large families, Education	xlsx	ISTAT [31]
Income	csv	Comune di Milano [32]
Population density	csv	Sistema Statistico Integrato - Comune di Milano [33]
Building status	csv	Sistema Statistico Integrato - Comune di Milano [33]
Milan sub-comunal boundaries	Vector / scale from 1:5,000	ISTAT [34]
Sezioni di censimento	Vector / scale from 1:15,000	ISTAT [31]

- **Imperviousness**: impervious areas prevent stormwater from infiltrating into the ground, increasing surface runoff. By assessing imperviousness, areas at risk of flooding can be identified where stormwater drainage is compromised. The dataset is provided by the DECI.METRO (Decision System of the Metropolitan City of Milan) system, the institutional platform for consulting geographic information about municipalities belonging to the Milan metropolitan territory, and maps the percentage of impermeable surfaces [%]. It was created on November 15, 2018 and updated on November 21, 2023.
- **Slope**: measures the slope of the terrain with respect to the horizontal plane and significantly affects rain-flow transformation. Steeper slopes contribute to more intense flood events, while gentler slopes are more susceptible to flooding. Percent slope is obtained from the Lombardy Region Digital Terrain

Model (DTM) with a spatial resolution of 5 m. The calculation was done using GDAL (Geospatial Data Abstraction Library), an open-source library for processing and manipulating geospatial data.

- **Hydrologic Soil Group**: soil characteristics play a crucial role in the formation of runoff based on the composition of sand, gravel, silt and clay, which determine infiltration capacity. Soils are divided into the following categories:
  - **HSG-A** has the lowest runoff potential (typically contains more than 90% sand and less than 10% clay);
  - **HSG-B** has moderately low runoff potential (typically contains between 10 to 20% clay and 50 to 90% sand);
  - **HSG-C** has moderately high runoff potential (typically contains between 20 to 40% clay and less than 50% sand);
  - **HSG-D** has the highest runoff potential (typically contains more than 40% clay and less than 50% sand);
  - **HSG A/D** indicates soil that would normally be classified as HSG-A, but has a shallow water table and therefore also has the characteristics of HSG-D;
  - **HSG B/D** indicates soil that would normally be classified as HSG-B, but has a shallow water table and therefore also has the characteristics of HSG-D;
  - **HSG C/D** indicates soil that would normally be classified as HSG-C, but has a shallow water table and therefore also has the characteristics of HSG-D;
  - **HSG D/D** indicates soil that would normally be classified as HSG-D, but has a shallow water table.

  In anticipation of subsequent analyses, each soil category was assigned a numerical value: category A was assigned 0, category B was assigned 1, category C was assigned 2, and all other categories were assigned 3. These values were chosen based on the documentation provided by the data provider and represent 1 = very good soil, 3 = very bad soil.

- **Proximity to rivers**: surface rivers have an extremely important impact in cases of flooding caused by heavy rains, due to their "backwaters". The most disastrous events over the years have often occurred right next to rivers, particularly the Seveso and Lambro. Surface rivers were then located and a buffer of 50 meters was calculated, followed by applying a function that assigned a value based on distance from the river. More specifically, the function assigns a value of 1 to the 50x50-meter cells that are in close proximity to the river, and the value decreases by 0.4 every 1000 meters.

- **Social Vulnerability Index (SVI)**: the extent of flood impacts also depends on the vulnerability of the socioeconomic and ecological systems involved. Social vulnerability includes social, cultural, economic, political, and institutional factors that influence people's sensitivity, preparedness, response, coping capacity, and recovery from catastrophic events [18]. Specifically, this study focuses on the analysis of social vulnerability related to flood hazards in Milan. The index was created by grouping eight variables whose weights were identified using the Analytic Hierarchy Process.

3.1 Analysis and description of geomorphological variables

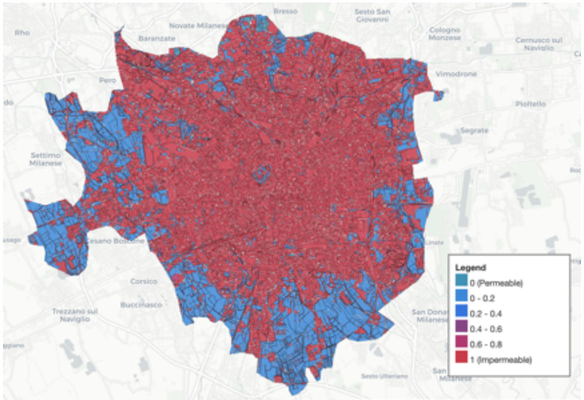
The analysis of geomorphological variables clearly shows how soil impermeability is a widespread problem throughout the city (Figure 5a). The map shows that most areas are impermeable (value close to 1), confirming earlier discussions about the preponderance of gray areas in the city. Permeable areas are mainly located along the perimeter of the city, near large parks or rural and cultivated areas, especially in municipalities 7 (West Milan) and 5 (South Milan). Descriptive statistics confirm this analysis: the average is 0.70, close to the maximum value of 1, suggesting that the land cover in the city is predominantly impermeable.

Regarding slope (Figure 5b), it is evident that the city has a very low slope, less than 2%, with some peaks in the Quarry Park in the Baggio area and on the border between the Mirabello and Gorla neighborhoods, as well as in the Bruzzano area, near the North Park. This terrain conformation is to be expected given that Milan is located in the Po Valley, a predominantly flat area.

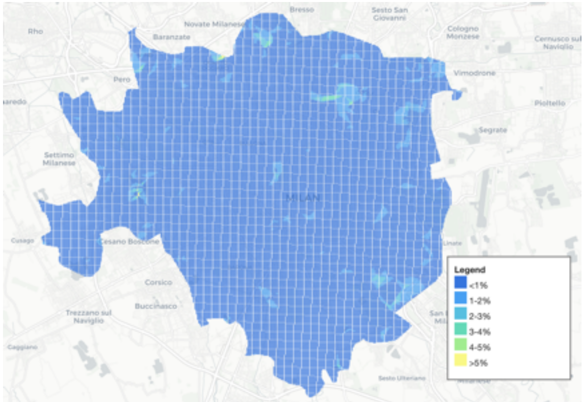
Analyzing the map of soil hydrological groups (Figure 5c), it is observed that Milan has only two soil types: HSG-C and HSG-C/D. These have moderate runoff potential, being typically composed of 20-40% clay and less than 50% sand, or soils classifiable as C but with a surface water table that slightly lowers their quality.

The distribution of these soils does not follow a definite pattern, although the central area seems to have predominantly HSG-C soils.

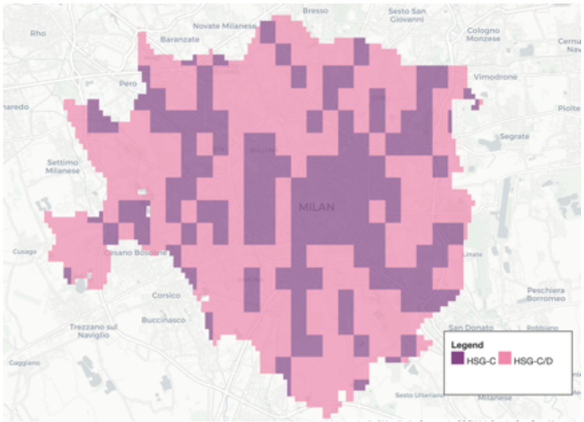
Finally, the grid showing the degree of proximity to surface rivers is shown (Figure 5d). Milan is seen situated between two rivers, the Olona and the Lambro, and is crossed by the Seveso. These rivers represent surface waters, but they have been largely buried or provided with culverted routes to allow them to flow to the Po. It is extremely relevant to consider this aspect as well, since the areas most affected by heavy rains are often those close to these rivers.



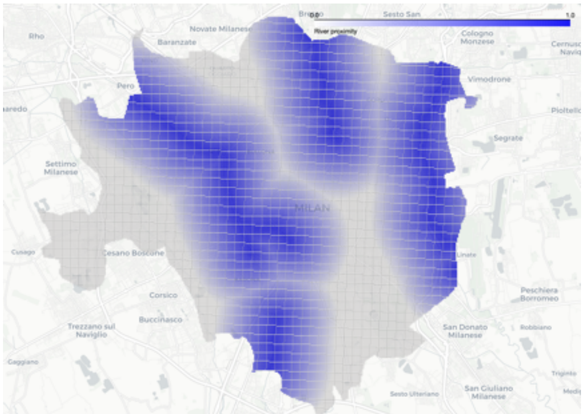
(a) Imperviousness



(b) Slope



(c) HSG



(d) River proximity

Figure 5: Geomorphological components for the city of Milan.

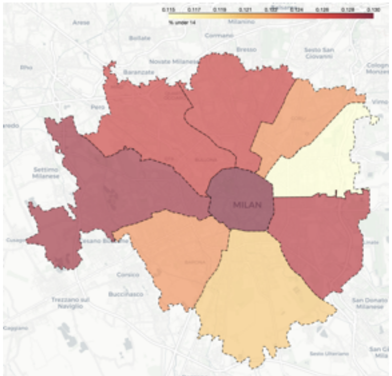
3.2 Analisi e descrizione delle variabili socioeconomiche

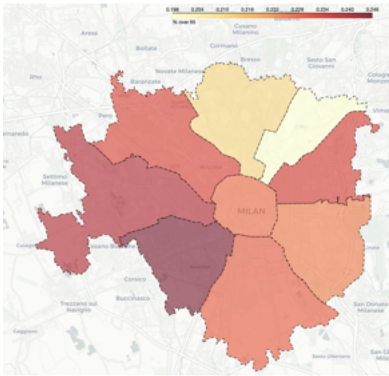
As described above, the SVI was created by considering eight variables:

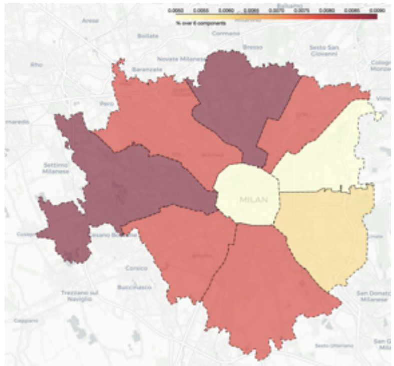
- **Resident population under 14 / Total resident population**
- **Resident population over 65 / Total resident population**
- **Resident population with education $\leq$ middle school diploma / Total resident population over 18**
- **Resident households with $\geq$ 6 members / Total resident households**
- **Average income per CAP**
- **Resident Population / NIL Area**
- **Pre-1970 dwellings / Total dwellings**
- **Housings in poor condition / Total dwellings**

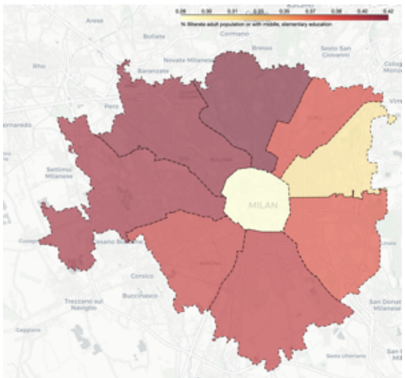
Socioeconomic information was transformed into GeoDataFrame by integrating with reference geometries from official sources:

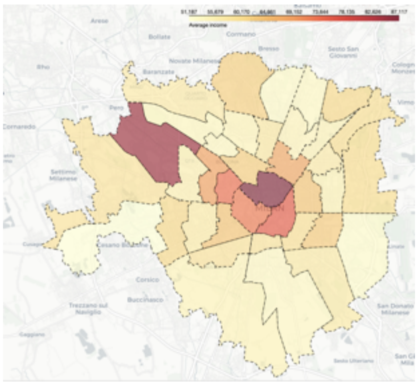
- **Municipality**: Children, Elderly, Large Families, Education
- **Postal Codes (CAP)**: Income
- **Nuclei of Local Identity (NIL)**: Population Density
- **Census areas**: Building Status

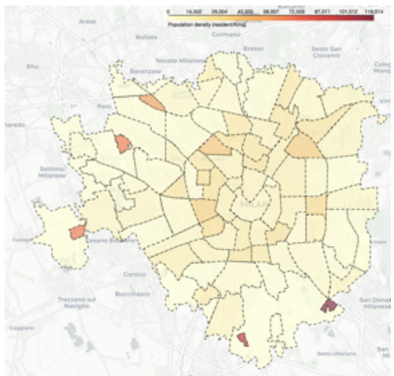

(a) % Under 14 by municipality

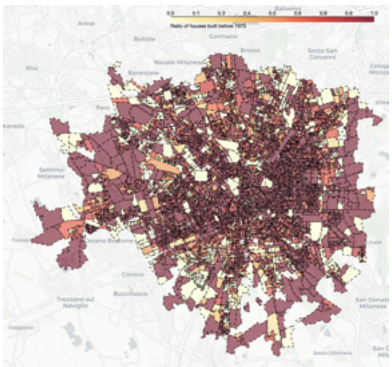

(b) % Over 65 by municipality


(c) % Large families by municipality


(d) % Less than high school education by municipality


(e) Average income by CAP


(f) Population density by NIL


(g) % Dwellings built before 1970

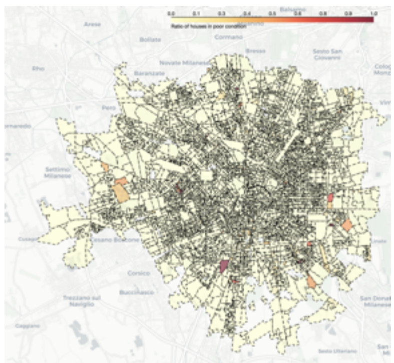

(h) % Dwellings with poor state of conservation

Figure 6: Socioeconomic components for the city of Milan.

When analyzing the distribution of residents aged 14 and under (Figure 6a), it appears that Municipality 1, Old Town, has the highest percentage, while Municipality 3, Porta Venezia-Lambrate-Città Studi, has the lowest percentage. However, the difference between the two municipalities is relatively small, at 11.5% versus 13%. On the other hand, as for the population over 65 years old (Figure 6b), Municipality 6, Porta Genova-Giambellino-Lorenteggio, has the highest percentage with 24.6%, while Municipality 2, Central Station-Greco-Crescenzago, has the lowest percentage with 19.8%. In this case, the difference between the two municipalities is more pronounced with respect to the "under14" variable.

Households with six or more members are a minority in all municipalities (Figure 6c), with percentages ranging from 0.9% in Municipalities 7 (San Siro-Forze Armate-Baggio) and 9 (Porta Nuova-Bovisa-Niguarda-Fulvio Testi) to 0.5% in Municipalities 1 (Centro Storico) and 3 (Porta Venezia-Lambrate-Città Studi).

With regard to education, which in this case considers the percentage of residents aged 18 and over with no education or with a maximum level of elementary or middle school education (Figure 6d), there is a notable difference between 28% in Municipality 1 (Centro Storico) and 41.7% in Municipality 9 (Porta Nuova-Bovisa-Niguarda-Fulvio Testi).

From an economic point of view, income analysis (Figure 6e), carried out by zip code (ZIP code), shows that ZIP codes 20151 and 20121, located in Municipality 8 and Municipality 1, respectively, have a particularly high average income. In general, central areas tend to have higher average incomes than suburban areas.

In terms of housing density (Figure 6f), which represents the ratio of residents to the area of the Local Identity Core (NIL), the cores of Chiaravalle in the southeast of the city and Ronchetto delle Rane in the south particularly stand out for their high density.

The last two variables concern the status of housing (Figure 6g and 6h). The percentage of dwellings built before 1970 is high, reflecting Milan's historical heritage, which is rich in historic buildings both of artistic value and functional to city life, many of which were renovated but originally built before the 1970s. Finally, ISTAT provided data on the condition of housing, allowing calculation of the percentage of housing in poor condition by census area. A small area southwest of Milan appears to consist exclusively of houses reported to be in very poor condition.

3.3 Spatial granularity management and feature scaling

This section outlines the methodologies adopted for the processing and normalization of the variables of interest, a crucial process for ensuring meaningful comparative analysis. The approach adopted involved harmonizing all variables on a uniform 50x50 meter grid, covering the entire area of the city of Milan. It is important to note that the perimeter polygons represent an approximation of this subdivision, adapting to the irregular boundaries of the city.

The processing procedure required differentiated approaches for geomorphological variables in Raster format and for socioeconomic variables in Shapefile format. For the Raster data, reprojection to the new resolution was achieved by averaging the values of the original points falling within each cell of the new grid. Socioeconomic variables, on the other hand, required a more elaborate process: the grid was intersected with the different sub-municipal areas, assigning each cell the attribute of the predominant area in case of overlap.

The assignment of values to the new cells followed two main criteria:

1. In case of perfect intersection between a cell and a subcommunal area, the value was assigned directly.
2. In the presence of multiple overlaps, average of the values of the affected areas was calculated.

The normalization process, which is essential to make variables with different scales and units comparable, took two separate approaches:

1. **Maximum scaling**: applied to the variables *Slope* and *Hydrologic Soil Group*, it scales the values so that the maximum becomes 1, preserving relative proportions:

$$x' = \frac{x}{x_{\max}}$$

   where x is the original value and $x_{\max}$ is the maximum value of the variable

2. **Min-Max scaling**: used for *Population Density* and *Income*, normalizes values in a range between 0 and 1:

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}}$$

where x is the original value, $x_{\min}$ is the minimum value, and $x_{\max}$ is the maximum value of the variable.

3.4 Feature Weighting

After integrating the variables, weights were assigned via AHP to calculate the two indices: the Social Vulnerability Index and the Pluvial Flood Index. The core of this method lies in pairwise comparison of the elements (via a comparison matrix of size $n \times n$) using Saaty's fundamental scale. This scale, which extends from 1 to 9, translates qualitative judgments into numerical quantifications, where 1 denotes equal importance and 9 represents extreme importance.

The robustness of the method is manifested in its ability to test the internal consistency of the judgments made by calculating the Consistency Ratio (CR). This ratio, if less than 0.1, is considered acceptable and ensures the reliability of the ratings. The CR is calculated as:

$$CR = \frac{CI}{RI}$$

where CI is the *Consistency Index*, calculated by the formula:

$$CI = \frac{\lambda_{\max} - n}{n - 1}$$

In this formula:

- $\lambda_{\max}$ represents the maximum eigenvalue of the pairwise comparison matrix.
- n is the number of criteria considered.

The index RI is the *Random Index*, a tabulated value that depends on the size of the matrix.

For the Social Vulnerability Index, the pairwise comparison matrix was constructed reflecting the relative priorities of socioeconomic variables in the Milan urban context. The resulting priority order is as follows:

1. Population density
2. Population under 14
3. Population over 65
4. Income
5. Buildings built before 1970
6. Buildings in poor condition
7. Junior high school or below
8. Households > 6 members

All features have positive correlation with the index, excluding income (inverse effect), and the resulting equation is:

$$\begin{aligned} \text{SVI} = {} & 0.194 \cdot \text{Under14} + 0.194 \cdot \text{Over65} - 0.107 \cdot \text{Income} \\ & + 0.058 \cdot \text{Pre\_1970\_dwellings} + 0.027 \cdot \text{Poor\_state\_dwellings} \\ & + 0.027 \cdot \text{Less\_middle\_education} + 0.367 \cdot \text{Population\_density} \\ & + 0.027 \cdot \text{Large\_families} \end{aligned} \tag{1}$$

As for the Pluvial Flood Index, the pairwise comparison matrix was constructed following the indications of the literature [16], adapting them to the specific context of Milan. The defined order of priority is:

1. Slope

2. IMP (Imperviousness)
3. HSG (Hydrologic Soil Groups)
4. Distance from river
5. SVI (Social Vulnerability Index)

Again, all features contribute positively to the index, with the exception of *Slope* whose associated weight takes on a negative sign. The resulting equation is:

$$\begin{aligned} \text{PFI} = 0.260 \cdot \text{IMP} - 0.503 \cdot \text{Slope} + 0.134 \cdot \text{HSG} \\ + 0.068 \cdot \text{River\_proximity} + 0.035 \cdot \text{SVI} \end{aligned} \tag{2}$$

In both cases, the matrix with subjectively chosen values was consistent, with a CR less than 0.1.

3.5 Social Vulnerability Index

The Social Vulnerability Index, normalized and represented through an interactive color map (Figure 7), provides a detailed view of the spatial distribution of socio-economic vulnerabilities in the Milan urban context.

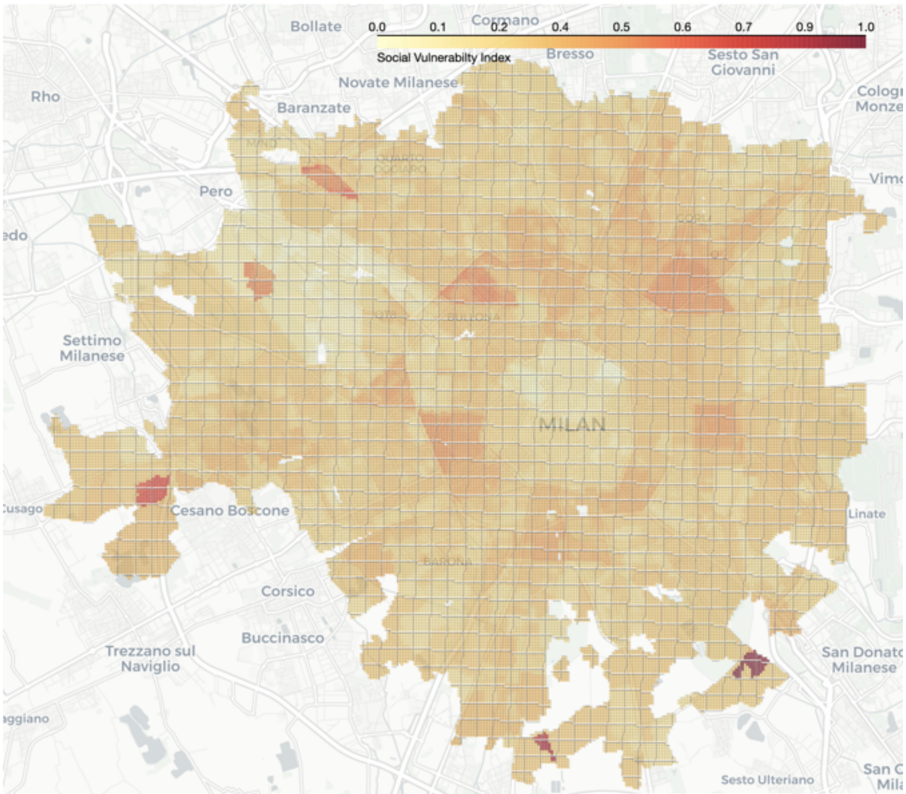


Figure 7: Social Vulnerability Index in the city of Milan (grid of 50x50m)

From the map, several areas of high vulnerability are observed, represented by unevenly distributed areas of brighter red, particularly evident in the southern and western peripheral areas. These "islands" of high vulnerability coexist with "corridors of resilience," characterized by lower vulnerability indices, extending from the center to some peripheral areas. These corridors could correspond to areas of recent urban development or areas benefiting from redevelopment interventions, think of the Gallaratese neighborhood area (Northwest area).

The map also reveals significant intra-neighborhood/municipality heterogeneity, with index variations on relatively small spatial scales. This phenomenon underscores the presence of micro-areas of vulnerability or resilience within larger neighborhoods, highlighting the complexity of urban socio-economic structure at the local level.

4 Pluvial Flood Index – Interpretation and Validation of the results

The map (Figure 8) shows the normalized PFI values for the city of Milan. The color range extends from soft yellow, indicative of low risk, to intense red, signaling high criticality.

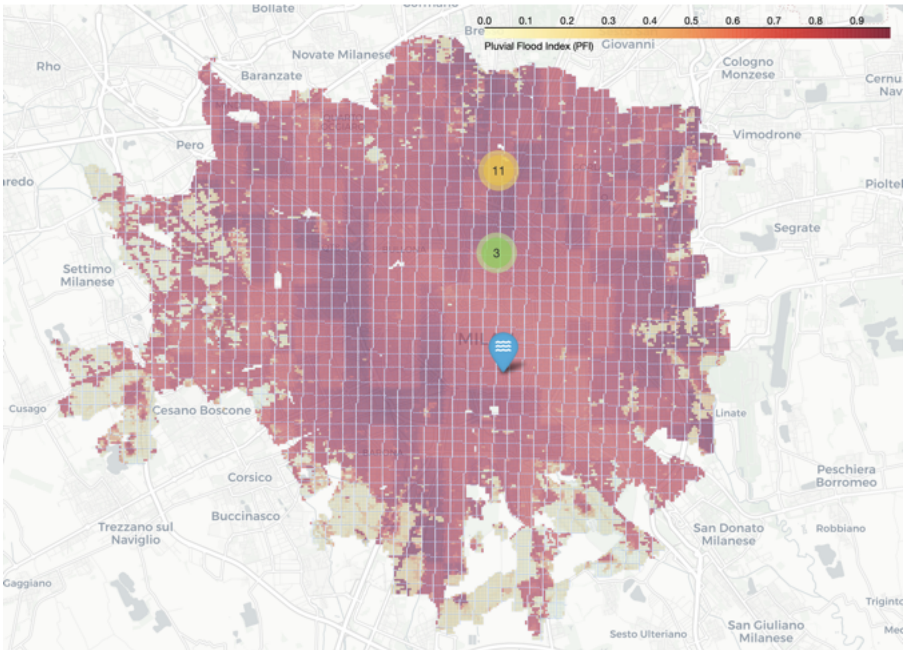


Figure 8: PFI in the city of Milan with historical urban flood hotspots (2010-2020)

Analysis of the risk map shows a predominance of orange and red shades over much of the urban area, indicating a widespread medium to high level of risk. This distribution suggests a generalized vulnerability of the city to pluvial flooding events. Some spatial variation in the level of risk is observed, i.e., outlying areas, mainly those located to the west and south present slightly lighter shades, suggesting a relatively lower, though still significant, risk. The historic center and areas near rivers generally show more intense hues, indicating the highest levels of risk.

To corroborate the results obtained, areas historically prone to pluvial flooding were identified and geolocated. Information on this was taken from the report published by Legambiente in 2020 [35]. Of the 29 reported events from the past 10 years, only a portion of them could be located, as the location information is not completely exhaustive (for example: July 5, 2018 - Seveso flooding). The hotspots were therefore selected by identifying only clearly distinguishable locations and reporting core points, identified through Google Maps, related to streets, avenues, squares or entire neighborhoods.

To identify the priority intervention area, the average PFI for each municipality was calculated. Municipality 2 (Central Station - Greco - Crescenzago) showed the highest PFI (0.83), followed by Municipality 9 (Porta Nuova - Bovisa - Niguarda - Fulvio Testi) with 0.82. Although the historically most affected municipality is not the one with the highest PFI, the minimal difference between the values and the lack of data on drainage infrastructure, groundwater, and sewage capacity-which could influence the analysis- nonetheless support the validity of the index. Therefore, the most critical points in the territory of Municipality 9 were selected and filtered for PFI values above the third quartile of 0.9.

5 Proposed nature-based solutions in high-risk areas

Given the wide range of green solutions (NBS) available, a focused selection process was necessary. This involved identifying a specific area of focus, as mentioned above, and selecting solutions in line with the constraints expressed in the literature [16]. This approach allowed the identification of NBSs that fully met the geomorphological and spatial requirements of Milan, namely:

1. **Filter strips**: are strips of vegetation, usually grass or other plants, designed to intercept and slow stormwater runoff. They function as natural barriers that capture sediment, nutrients and other contaminants, preventing them from reaching water bodies or sensitive areas. These strips not only improve water quality but also help prevent flooding, making them ideal for use in urban areas, along roads and in public open spaces.

2. **Vegetative swales**: are shallow, open, densely planted channels designed to manage and purify stormwater runoff. Their shape and vegetation slow the flow of water, reducing peak flows during heavy rains. They also facilitate the infiltration of water into the ground and the filtration of pollutants. They are particularly suitable for parking lots, traffic islands and areas with moderate slopes.

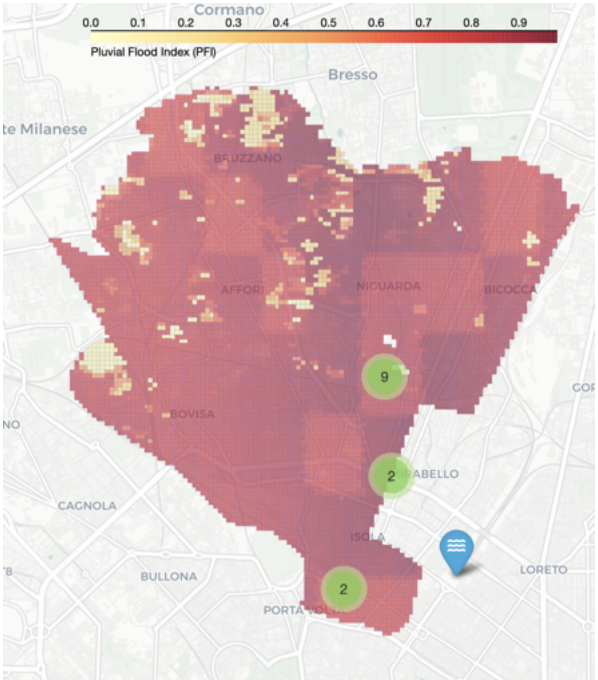
3. **Bioretention areas and rain gardens**: are landscaped depressions specifically designed to capture and treat stormwater. These green spaces are made with a mix of soil, sand and organic matter that supports a variety of plants capable of tolerating intermittent flooding. They work by capturing the first flow of rainwater, usually the most polluted, allowing it to slowly infiltrate into the soil. This natural process filters and cleans the water before it reaches groundwater or surface streams. They can be integrated into parks, plazas, and pedestrian areas, improving not only water management but also urban aesthetics.

Table 2 provides an overview of the selected solutions, including application constraints and potential areas of implementation, thus providing practical guidance for the feasibility of these interventions.

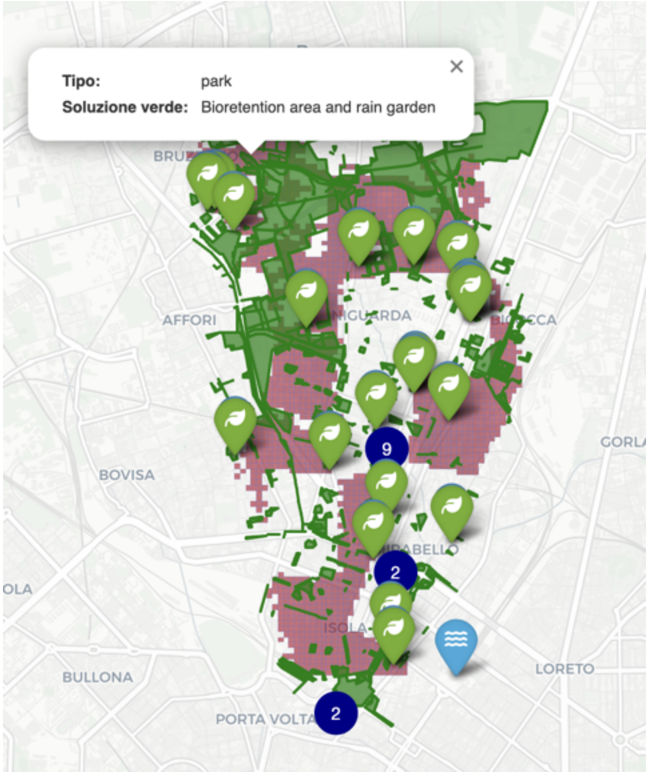
Table 2: Constraints for NBS installation

NBS type	**Area (ha)**	**Slope (%)**	**HSG**	**Suitable public space**
Filter strip	-	<5	-	Public open space, parking lots, paths, streets, pedestrian and cycling areas
Vegetative swale	<2.0	<10	A-D	Parking lots, traffic islands
Bioretention area and rain garden	<0.4	<12	A-D	Parks, square, traffic islands, platforms, pedestrian and cycling areas

The final stage of the process involved the identification, using OpenStreetMap, of the types of public spaces suitable for the implementation of the selected green solutions. The visual analysis consists of two cartographic representations of Milan's Municipality 9:



(a) PFI in Municipality 9 with historical urban flood hotspots (2010-2020)



(b) More risk areas and feasible nature-based solutions by type of space

Figure 9: Confronto tra due grafici.

1. The first map (Figure 9a) provides an overview of the municipal area. The color scale highlights areas according to the associated PFI and is enriched by markers that flag hotspots of past disaster events, providing historical context to current vulnerabilities.
2. The second map (Figure 9b), which is more detailed, focuses on critical areas, showing only areas with a PFI greater than 0.9. Also present are:
   - Blue markers indicating the precise locations of relevant historical events.
   - Green areas representing public spaces potentially suitable for the implementation of green solutions, such as parks, plazas, and pedestrian areas.

This layered representation makes it possible to overlay historical and current hydrological criticalities with opportunities for intervention, thus facilitating a focused and contextualized approach to planning adaptation solutions. Indeed, it can be seen that most of the critical areas where nature-based solutions are adaptable coincide with spaces belonging to the city's North Park, which the analysis suggests should be targeted with a view to optimizing the use of green spaces. This is to benefit both the environmental and social aspects at the same time.

6 Conclusions

Urban flooding is a contemporary challenge, exacerbated by global warming and intensifying urbanization. Milan, the beating heart of the Po Valley and characterized by high soil sealing, stands as an emblematic case of this phenomenon. In recent years, the city has experienced frequent flooding events, resulting in economic repercussions and inconvenience for its citizens.

This study has developed a risk index that integrates geomorphological and social aspects, offering a valuable tool to assess the potential for implementing Nature-Based Solutions (NBS). This index allows for a comprehensive view of the context, considering not only the physical and architectural elements, but also the social fabric that inhabits it and recognizes its intrinsic value.

The proposed methodology is distinguished by its clarity and simplicity, first identifying the areas at greatest risk and then the micro-areas most suitable for the installation of NBS. Importantly, although an overall assessment of the urban context provides interesting insights, the implementation of solutions often occurs on a smaller scale, involving specific neighborhoods, streets, avenues or squares.

In this context, Gill et al. [36] highlighted the crucial role of green infrastructure as policy tools to help cities address climate change, emphasizing the importance of integrating this infrastructure into every stage and level of urban planning, from local implementation to large-scale management.

The analysis revealed that the most vulnerable areas are those adjacent to the Seveso River, mainly in City Hall 9, an area with a history of severe flooding, thus validating the validity of the proposed index. The suggested solutions, while representing only a subset of a broader range of NBSs, share multiple benefits. In addition to mitigating the risk of flooding, these solutions integrate harmoniously into the urban fabric, preserving its identity while enhancing its quality. They also improve air quality and urban microclimate, optimize stormwater management, promote public health, reduce noise pollution, mitigate the effects of climate change, and increase real estate value, supporting the local economy. Ultimately, these solutions help create more livable and resilient cities, promoting social cohesion.

The study verified the physical feasibility of the proposed solutions, although it did not consider any specific spatial constraints, an aspect that could be the subject of further investigation. For future implementations and improvements, financial and political aspects are also suggested to be considered, specifically:

- Expansion of NBSs requires careful evaluation of construction and maintenance costs, including life cycle management, procurement, and public reporting.
- NBSs are not yet widely recognized as a stand-alone tool, so specific legislative frameworks are lacking. There is a need to recognize NBSs as a key element for sustainability and urban resilience by defining them in standard documents and developing local impact assessment techniques.

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