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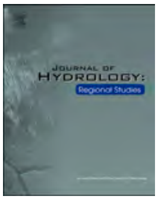

Planning Nature Based Solutions against urban pluvial flooding in heritage cities: A spatial multi criteria approach for the city of Florence (Italy)

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ABSTRACT

Study region: City of Florence, central Italy
Study focus: Aiming at defining a nature-based strategy to mitigate pluvial flood risk, a two-tiered methodology is proposed. Firstly, the areas prone to pluvial flood are identified by a spatial multi-criteria analysis that combines five criteria (imperviousness, slope, hydrologic soil groups, density of sewer system and social vulnerability) to build a Pluvial Flood Index (PFI). The PFI is validated by the comparison with historical pluvial flood events in the city and it is used for the identification of high priority areas for intervention. Then, this information is merged with the analysis of urban planning and NBS design constraints to identify the suitable areas for NBS installation.
New hydrological insights for the region: Results allow the definition of a NBS implementation strategy against pluvial flooding in the city of Florence, identifying for each pluvial flood hotspot the set of measures that can be implemented to solve the problem. The proposed approach represents a flexible assessment technique that can be reproduced in other urban context and provide useful support for NBS adoption in urban flood risk management for heritage cities.

1. Introduction

Urban pluvial floods occur when rainfall intensity locally exceeds infiltration and the conveyance capacity of the sewer system (Rosenzweig et al., 2018, Tanaka et al., 2020; Bulti and Abebe, 2020). They represent a major challenge worldwide (Villordon and Gourbesville, 2014; Schmitt ans Scheid, 2020) both because of their small temporal scale making their prediction complex (Li and Willems, 2020), and due to the extensive damage to property and people they can cause (Yin et al., 2016). Moreover, climate change, ongoing urbanization, reductions in urban green spaces and deteriorating urban water management infrastructures are further increasing pluvial flood risk (Kaykhosravi et al., 2019; O'Donnell and Thorne, 2020; Zölch et al., 2017; Pachauri et al., 2014) and questioning the effectiveness of traditional management approaches (Westra et al., 2014). Indeed, grey infrastructures, or hard engineering solutions - designed only to collect rainwater and convey it away from the city context through sewer systems (Li et al., 2020) - often show their inadequacy to deal with very intense and locally concentrated rainfall events. Moreover, such solutions will not

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provide an adequate response to today and future environmental, economic and social challenges, including climate change (EEA, 2012; Zhou, 2014).

To address these challenges, adaptable and multifunctional solutions are required (Ashley et al., 2007; Woodward et al., 2011; Emami, 2020). In this context, Nature Based Solutions (NBS) represent an interesting approach that involves the use of integrated solutions to manage urban runoff, obtaining simultaneously other benefits. NBS are defined as “solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience” (EEA, 2015). Most frequently, NBS are realized to regulate stormwater in urban areas, creating so-called sustainable urban drainage systems (SuDS). Depending on the context, alternative terminologies can be used to indicate NBS in urban areas, such as Green Infrastructure (GI), Ecosystem-based Adaptation (EbA), Low Impact Development (LID), Water Sensitive Urban Design (WSUD) and Best Management Practices (BMPs) (Fletcher et al., 2015). In this article, the term NBS will be used as it represents the wider set of solutions that encompass all the specific sub definitions (Pauleit et al., 2017).

The great potential of these solutions in urban areas is that they can provide a multitude of ecosystem services (Coutts and Hahn, 2015; Pacetti et al., 2020), in addition to the main benefits for which they are built. For example, NBS can be useful in the management of flooding in terms of retention, managing infiltration and runoff, thus allowing a reduction in the amount of water conveyed into the

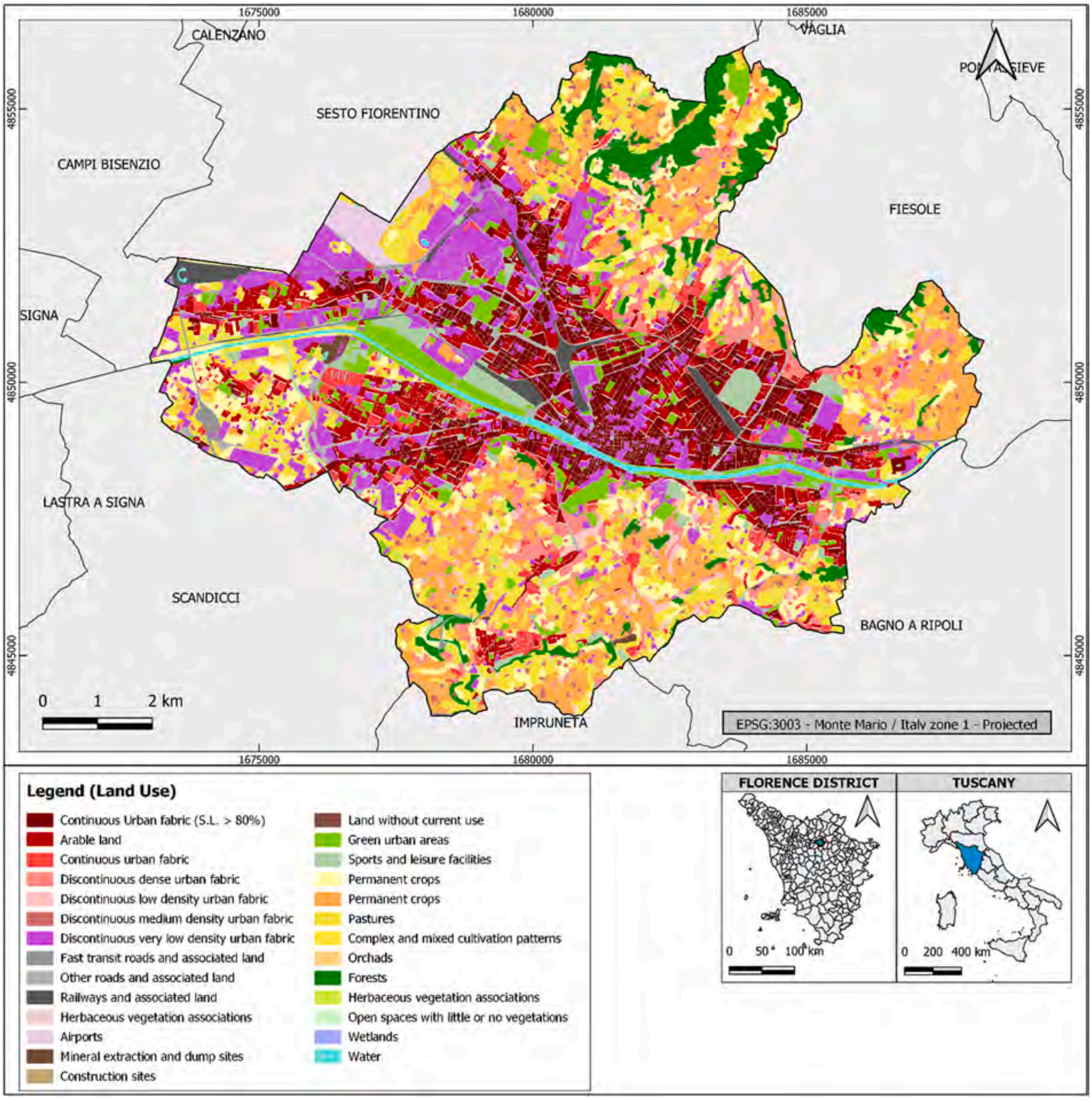

Fig. 1. Location and land use map of the study area.

drainage system. At the same time, thanks to the presence of grass, bushes and trees, NBS contribute to increase water and air quality, biodiversity, amenity of the area (Dagenais et al., 2017; Coutts and Hahn, 2015; Ashley et al., 2013), and to reduce noise level, urban heat island and respiratory diseases (EPA, 2017). NBS can be used alone or in combination with grey infrastructures, favoring cities adaptation to climate change and strengthening the management and utilization of rainwater runoff (Sun et al., 2020). Even though an increasing number of cities have adopted urban planning approaches where nature is seen as an opportunity for adaptation (Kabisch et al., 2017), urban water management is still heavily dominated by gray infrastructures with NBS accounting for less than 5% of the global expenditure in water resources management (WWAP, 2018). The main barriers hindering the investments in NBS are represented by the inadequate financial resources and the lack of incentives, the institutional fragmentation, the lack of political commitment and institutional and technical capabilities, the increasing gentrification, and the limited availability of land due to ownership issues and to urban planning limitations (Ershad Sarabi et al., 2019). In this context, the importance of developing appropriate planning and design tools for the successful NBS uptake is paramount (Ershad Sarabi et al., 2019).

As shown by recent literature, one of the most important aspects is to define the adequate locations for NBS installation, depending on the purpose. Meerow and Newell (2017) developed a Geographical Information System (GIS) based approach to support the spatial planning of multifunctional GI. Li et al. (2020) proposed a multi-criteria evaluation method to identify areas where to realize GI to mitigate urban flood risk. Kaykhosravi et al. (2019) proposed a geospatial framework based on hydrological, hydraulic, economics, social and environmental benefits of LID to identify priority sites. Martin-Mikle et al. (2015) defined a spatial approach to identify priority areas for LID, based on a topographic index, calculated by combining various environmental indicators, and technical suitability.

Aiming at supporting the introduction of NBS to manage stormwater in heritage cities contexts, this study integrates GIS-based and multi-criteria analysis to identify the most suitable areas where implementing NBS against urban pluvial flooding in the city of Florence, Italy. The proposed methodology is divided into two phases: in the first one the Pluvial Flood Index (PFI) of the entire municipality is elaborated to identify the most critical areas during pluvial flood from a combined socio-hydrological perspective. In the second phase the suitability of NBS implementation against pluvial flood is analyzed, focusing on a pilot area.

The City of Florence has special features because it is a historic and art city, with an important architectural, artistic, landscape, scientific and natural heritage that can limit the introduction of NBS (e.g. presence of archeological evidence). Therefore, the urban constraints and technical feasibility constraints of different NBS typologies (i.e. infiltration trenches, filter strips, filter drains, vegetative swales, bioretention areas, tree boxes, permeable pavement, detention basins, ponds) have been analyzed to identify the most suitable areas that allow NBS installation while preserving the city heritage.

The methodology allows the identification of the critical areas that would benefit from NBS implementation and the preliminary assessment of NBS feasibility. The results can support the decision-making process for implementation of NBS for urban flooding

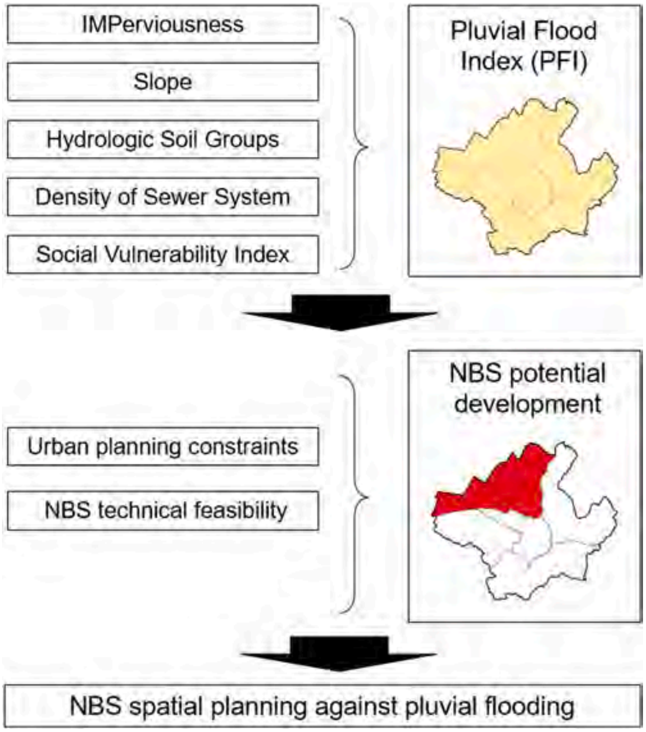

Fig. 2. Flowchart of the proposed methodology. The Pluvial Flood Index is identified for the entire municipality, while the suitable areas for NBS installation are identified at district level including some specific constraints.

mitigation.

2. Study area

Florence (Fig. 1) is the capital city of Tuscany Region, Italy, covering an area of about 102 km^2, with 366.927 inhabitants, according to the 2019 census of the Italian National Statistical Institute (ISTAT). It has a humid temperate climate with an elevation ranging between 83 m and 338 m above sea level. The municipality is crossed by the Arno River that flows in the east-west direction and it is connected to multiple tributaries as well as to some buried rivers, channels, and culverts. The land use in the area is various: on the plain areas along the Arno River, there are residential, commercial, industrial and green urban areas; on hills, agricultural areas including vineyards, orchards and olive groves, and forests are predominant. The sewer system of the city is combined (i.e. no separation between stormwater runoff and wastewater collection) and is mainly based on the infrastructures built in the 19th century, resulting in a complex sewer network with a total length of around 800 km. The sewage is almost completely connected to wastewater treatment plants, however there are some collectors that discharge the excess water in the Arno River and its tributaries.

In addition to the flood risk associated to the presence of the Arno River (Caporali, 2016), the whole city area is exposed to flash and pluvial flood events that involve the minor hydrographic network and the sewer system. In the last decades, due to the high level of urbanization, the inadequacy of the sewer network to population growth and the increasing frequency and intensity of rainfall events, numerous pluvial floods in various parts of the city have been observed.

3. Materials and methods

The proposed methodology is based on two phases, starting with the definition and mapping of the Pluvial Flood Index (PFI) to identify the areas most affected by pluvial flood risk in the entire municipality. In the second phase, the areas suitable for the installation of NBS are located, according to planning and technical constraints, with reference to a single district among those having on average, the higher PFI values. Finally, priority areas for NBS installation to mitigate the pluvial flood problems are identified (Fig. 2).

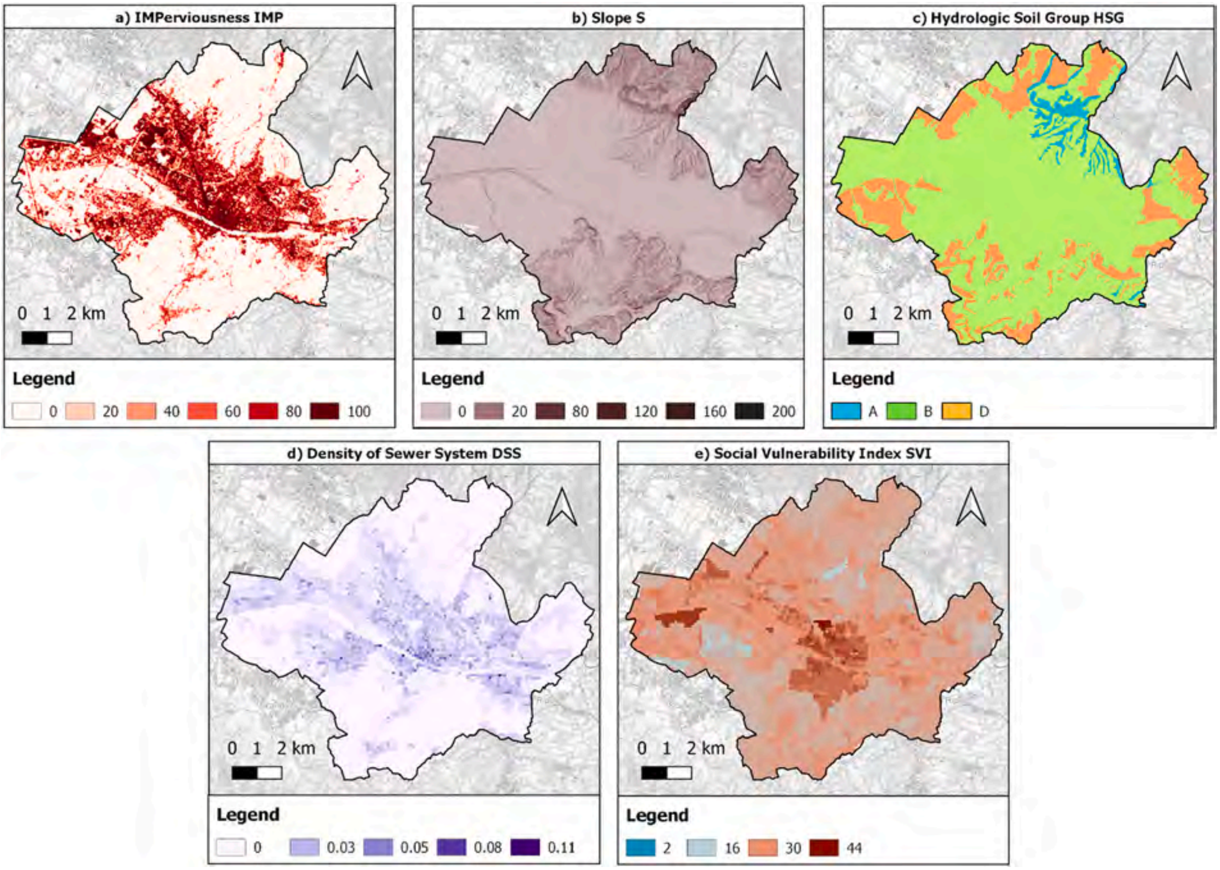

Fig. 3. Map of criteria used in the analysis: a) IMPerviousness (IMP%), b) Slope (S%), c) Hydrologic Soil Groups (HSG), d) Density of Sewer System (DSS 1/m), e) Social Vulnerability Index (SVI %).

3.1. Pluvial Flood Index (PFI)

The construction of PFI is based on the use of five criteria (Table 1): i) Imperviousness (IMP); ii) Slope (S); iii) Hydrologic Soil Group (HSG); iv) Density of Sewer System (DSS); v) Social Vulnerability Index (SVI). The combination of environmental and socio-economic criteria is crucial to determine the risk and to identify the most critical areas (Crichton, 1999) as shown by various recent studies (Li et al., 2020; Kaykhosravi et al., 2019; Meerow and Newell, 2017). All data used in the analysis are summarized in Table 1.

3.1.1. Description of criteria for the construction of PFI

3.1.1.1. IMPerviousness (IMP). The impervious areas inhibit the infiltration of rainwater in the soil, thus determining a greater volume of runoff. Therefore, the evaluation of imperviousness allows to identify the areas prone to flood, due to their inability to effectively drain the rainwater. The Imperviousness Density dataset of 2015 provided by Copernicus Land Monitoring Service (Table 1) is used to map the percentage of IMP [%] with 20 m spatial resolution.

3.1.1.2. Slope (S). Slope is a measure of the inclination of a surface relative to the horizontal plane and it has an important role in the rainfall-runoff transformation. Steeper slopes contribute to generating major floods, while areas with a lower slope have higher probability to be inundated (Kandilioti et al., 2012). The slope S [%] is obtained by the Digital Terrain Model (DTM) of Tuscany Region, with 10-m spatial resolution, integrated and corrected, if necessary, with reference to the DTM Lidar (Table 1), and it is expressed as a percentage.

3.1.1.3. Hydrologic Soil Group (HSG). Soil characteristics have an important role in the runoff formation: based on the percentage of sand, gravel, silt and clay, a soil can have a high or low infiltration capacity. Indeed, all the rainfall not infiltrating in the soil contributes to generate runoff. HSG information has been derived by the pedology dataset of Tuscany Region (Table 1) where soils are classified in four hydrological groups (Gardin, 2015) based on their runoff potential, according to the classification introduced by the U.S. Department of Agriculture (USDA, 2009). The first group A includes soils with low runoff potential, with typically less than 10% of clay and more than 90% of sand and gravel; the second group B includes soils with medium-low runoff potential, characterized by an amount of clay between 10% and 20% and sand between 50% and 90%; the third group C includes soils with medium-high runoff potential, characterized by an amount of clay between 20% and less than 50% of sand; the fourth group D includes soils with high runoff potential, with typically greater than 40% of clay and less than 50% of sand. Only the A, B and D classes are present in the municipality of Florence.

3.1.1.4. Density of Sewer System (DSS). A widespread distribution of the sewer system is fundamental to reduce the impact of stormwater. In this study, the DSS [m/m^2] is evaluated as the total length of the pipes (provided by the local water management company) per unit drainage basin area (corresponding to the census area defined by ISTAT, Table 1). Despite the complex dynamics that water can have in areas with high DSS (Kandilioti et al., 2012), it is assumed that high density values correspond to high levels of the sewer system functionality (Palla et al., 2018).

3.1.1.5. Social Vulnerability Index (SVI). The effects of a flood event depend also on the vulnerability of the affected socio-economic and ecological systems (Messner and Meyer, 2006). In general, the term social vulnerability refers to the combinations of social, cultural, economic, political, and institutional processes that influence population sensitivity to hazard events and its ability to prepare, respond, cope, and recover from it (Zhou et al., 2014; Spielman et al., 2020). In this case, the main interest is on the analysis of the social vulnerability related to flood hazard, i.e. how the population may react in different ways to it, depending on its economic, social and physical status (Oulahen et al., 2015). Therefore, we adopted the (SVI) map obtained by Pileggi et al. (2018) analyzing the social vulnerability to flood hazard in the municipality of Florence. In particular, the index is composed by a set of sixteen variables grouped into six clusters according to literature (Morrow, 1999 and Cutter et al., 2003): ability to react, presence of foreigners, access to resources, family composition, population and housing, and education. The selected variables are then combined with a Spatial Multi-Criteria Evaluation (SMCE). After their standardization the weight assigned to each variable is determined by expert judgment

Table 1
Name, format and data source of the utilized layers.

GIS layer	Format/Resolution	Data source
Census areas	Vector / nominal scale 1:10000	National Statistical Institute (2019)
DTM Lidar	Raster / 1 m	Tuscany Region (2020a)
DTM10	Raster / 10 m	Tuscany Region (2020a)
Imperviousness	Raster / 20 m	Copernicus Land Monitoring Service (2016)
Land Cover - Land Use (LCLU)	Vector / Minimum Mapping Unit (MMU): Class 1: 0.25 ha	Copernicus Land Monitoring Service (2018)
Hydrologic Soil Group	Vector / nominal scale 1:10000	Tuscany Region (2020b)
Sewer system	Vector / nominal scale 1:10000	Florence water management company[a]
Streets network	Vector/ nominal scale 1:10000	Florence Municipality (2020)
Social Vulnerability Index (SVI)	Raster / 100 m	Pileggi et al. (2018)

[a] Data not published.

(Table 2).

3.1.2. Spatial Multi-Criteria Evaluation (SMCE)

SMCE was implemented to map PFI using the Integrated Land and Water Information System (ILWIS; ITC, 2001). Within a SMCE approach the following steps must be followed to transform a set of criteria into a decision:

- define a structure of the decision problem,
- standardize the criteria so that they can be compared,
- determine the importance of one criterion over another,
- and combine the information.

The structuring of the decision-making process involves the construction of a "criteria tree" to break up the problem into simpler and more easily manageable parts. In ILWIS, criteria can be divided into “factors” and “constraints”.

Factors can have a positive or a negative correlation to the analysis output (ITC, 2001) in accordance with the problem definition and the analysis goals (i.e. evaluate the areas most affected by pluvial flood risk). In this study the criteria IMP, HSG and SVI, identifying respectively areas with high percentage of impervious areas, soils with high runoff potential and areas with high social vulnerability index, have a positive correlation with PFI. The criteria S and DSS, describing respectively areas with low slope, more prone to be inundated and areas with low density drainage of the sewer system, less able to drain rainwater, have a negative correlation with PFI.

Constraints, instead, are criteria that identify areas that must be considered as not suitable for NBS installation. In this case, areas with slope major of 10% and the riparian areas of Arno rivers and its tributaries are defined as constraints, since it is assumed that the implementation of NBS in such areas could be difficult or even impossible.

Each criterion is then standardized, transforming the original scale of measurement into a dimensionless scale between 0 and 1. The standardization of factors is carried out using Maximum and Interval standardization functions described in ITC (2001) (Table 3). With *Maximum* function, the input values are linearly standardized dividing them by the maximum value of the selected map, maintaining their relative differences. The *Interval* function standardizes the input with a linear function that uses the minimum value and the maximum value of the input map, emphasizing the differences among alternatives (Bagli et al., 2011).

Unlike factors standardization, standardized constraints will either obtain value 0 (areas excluded from the analysis) or value 1 (area included in the analysis). After standardization, the next step is determining the weight of each factor criterion. A pairwise comparison method is used to calculate factor criteria weights, allowing the comparison of their relative importance. Pairwise comparison is the basic step of Analytic Hierarchy Process (AHP), a technique for relating different criteria, characterized by qualitative and quantitative evaluations and, therefore, not directly comparable. The criteria are ranked according to their importance and a weight is assigned to each of them (Saaty, 1987).

To compute the weights, a comparison matrix A is created: it is a n x n real matrix, where n is the number of used criteria. Each matrix component a_{ij} represents the importance of the i-th criterion relative to the j-th criterion. To compare the criteria, a scale of evaluation ranging from 1 to 9 is considered, according to the Saaty’s scale: score 1 indicates that i and j are equally important, 3 that i is slightly important than j, 5 that i is more important than j, 7 is strongly more important than j and 9 is absolutely more important than j. On the other hand, their reciprocal ones indicate the minor importance of criterion i compared to j. In this work, the relative importance of each criterion is assigned based on literature review (Kandilioti et al., 2012; Lawal et al., 2012; Gigović et al., 2017;

Table 2
Variables and weights used to map the Social Vulnerability Index – SVI (Pileggi et al., 2018).

Clusters	Variables[a]	Weights
Ability to react	% population of age 14 and under	0.110
	% population of age 74 and over	0.103
	% women population	0.026
Presence of foreigners	% foreigners	0.066
Access to resources	average value of dwellings	-0.051
	% family with potential economic hardship	0.088
	% households in rented housing	0.015
	% unemployed	0.059
	% public transport use	0.037
Education	% population with elementary and illiterate education	0.096
	% population with university education	- 0.026
Family composition	incidence of alone elderly	0.118
	% single person family	0.007
Population and housing	population density	0.074
	% dwellings built before 1970	0.044
	% dwellings with poor state of conservation	0.081

All criteria explained above can be seen in Fig. 3.

[a] All the data are derived from ISTAT’s 2011 Census of Population (Istat, 2011) and from the City of Florence’s Statistical Yearbook (Florence municipality, 2018).

Table 3
List of factors criteria, their correlation with the main goal, input value and type of standardization.

Criterion	Correlation	Range input value	Standardization
Imperviousness (IMP)	Positive correlation	0–100.0	Maximum
Slope (S)	Negative correlation	0–199.4	Maximum
Hydrologic Soil Group (HSG)	Positive correlation	0–1.0	Maximum
Density of Sewer System (DSS)	Negative correlation	0–0.1	Maximum
Social Vulnerability Index (SVI)	Positive correlation	8–44	Interval

Kazakis et al., 2015; Caprario et al., 2019; Rimba et al., 2017) as shown in Table 4.

After obtaining the matrix A, to calculate the vector of percentage weights to be assigned to each criterion, it is necessary to calculate the normalized principal eigenvector of the matrix. To do this, the eigenvectors of the matrix A and their respective eigenvalues are calculated. The largest eigenvalue is called the principal eigenvalue and the principal eigenvector corresponds to it. Normalizing the principal eigenvector, we obtain the vector of weights corresponding to each criterion.

After that, it is necessary to check the consistency of the matrix A through the following index:

$$\mathrm{CR} = \mathrm{CI} / \mathrm{RI} \tag{2}$$

where CR is the Consistency Ratio, CI is the Consistency Index and RI is the Random Index. RI value is dependent on the number n of criteria, while CI value is calculated by Eq. (3):

$$\mathrm{CI} = (\lambda_{\max} - \mathrm{n}) / (\mathrm{n} - 1) \tag{3}$$

where $\lambda_{\max}$ is the maximum eigenvalue of the matrix and n the number of criteria. In this case, $n = 5$, so RI = 1.12 and CR = 0.069. A matrix is consistent if CR < 0.1, so the condition is respected, and the matrix is well constructed.

The final PFI map is constructed according to Eq. (4):

$$\mathrm{PFI} = 0.267\bullet\mathrm{IMP} - 0.460\bullet\mathrm{S} + 0.112\bullet\mathrm{HSG} - 0.090\bullet\mathrm{DSS} + 0.071\bullet\mathrm{SVI} \tag{4}$$

The PFI mapping results are then analyzed to validate the map (i.e. verify correct identification of areas previously affected by pluvial flooding) and to set up a PFI threshold value useful to identify potential hotspots (i.e. identification of the areas where pluvial flood can represent a high risk). Due to the unavailability of a pluvial flood event database for the city of Florence, an investigation on media libraries (Tuscany Region, 2020c) has been carried out to gather information on the areas most frequently hit by pluvial flooding in the 2012–2019 period. Flooded areas are identified based on the pluvial flood events description and photographic information available and mapped using the streets map provided by the municipality of Florence (Florence Municipality, 2020).

This allows defining multiple control points to validate the PFI results, checking the correspondence between the location of floods occurring in the reference period and the areas associated with higher PFI values. In particular, the mean value (μ) and the standard deviation (σ) *of PFI* are calculated for the identified flooded areas, checking the index consistency. Then, the minimum value of PFI in the flooded areas is selected as a threshold to identify the main hotspots in the entire city territory.

3.2. Spatial planning of NBS for flood mitigation

After the identification of the most critical areas during pluvial flood events, the most suitable locations for NBS are investigated, taking into account two categories of constraints: those related to urban planning and determined by the city characteristics (e.g. presence of heritage sites to be protected) and those related to technical feasibility, thus connected to the NBS design limitations (e.g. spatial requirements for their installation). Since the extent of the areas with high criticality is wide, the analysis focused on one district among those having the higher PFI. The selected district is the district D5 Rifredi – Novoli (Fig. 4) which has many pluvial flood hotspots (32.5% of total area of district is considered as critical area according to FPI) and represents the district with the highest share of impermeable surfaces (i.e. roofs, roads, parking lots and other areas with different destinations) in the entire city territory.

The evaluation of urban planning constraints is fundamental in any territorial planning, but it is even more important in areas of considerable historical and cultural interest, such as the city of Florence, characterized by numerous areas that are restricted or protected both for cultural-landscape and security reasons. The two main urban planning normative tools on the municipal scale are

Table 4
Criteria pairwise comparison according to Saaty (1987). Criteria used are: IMPerviousness (IMP); Slope (S); Hydrologic Soil Groups (HSG); Density of Sewer System (DSS); Social Vulnerability Index (SVI).

	IMP	S	HSG	DSS	SVI	Weights
IMP	1	1/3	3	5	3	0.267
S	3	1	5	3	5	0.460
HSG	1/3	1/5	1	1	3	0.112
DSS	1/5	1/3	1	1	1	0.090
SVI	1/3	1/5	1/3	1	1	0.071

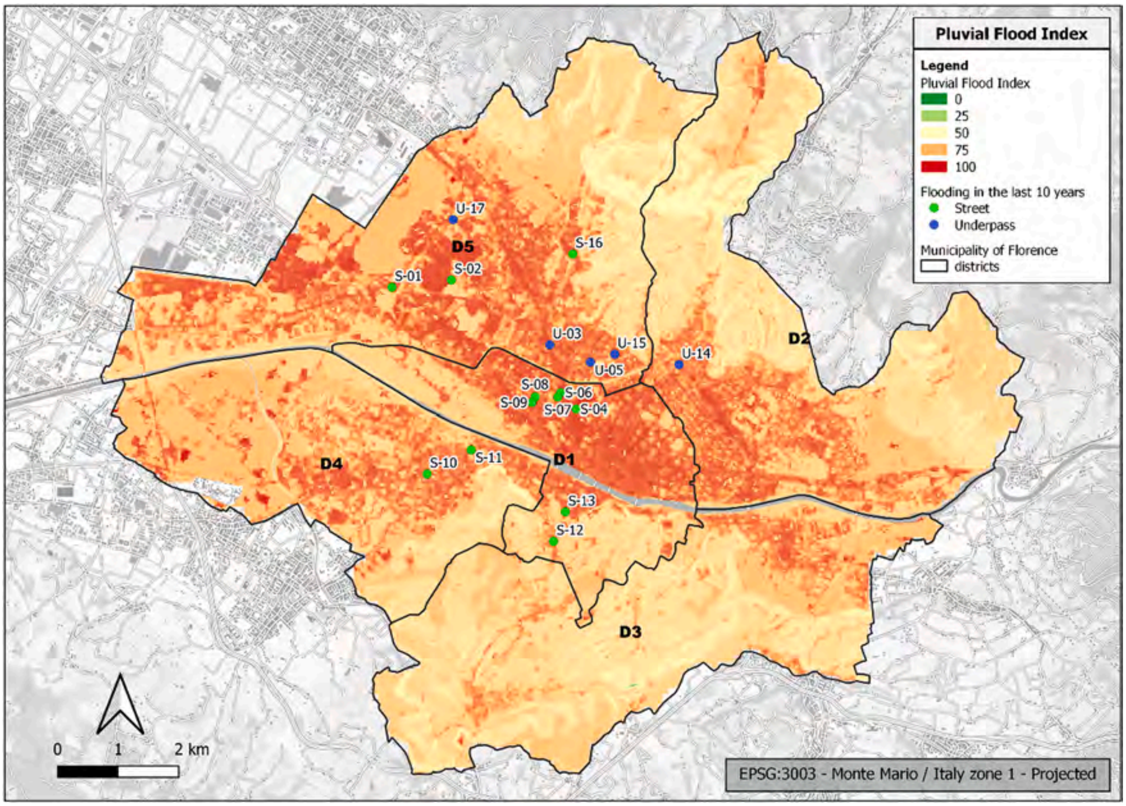

Fig. 4. Pluvial Flood Index (PFI) map with the locations of flooding in the last ten years, distinguishing between the events that have affected underpasses (U-#) and streets (S-#). In the map the subdivision in 5 districts is also reported: D1 Centro Storico; D2 Campo di Marte; D3 Gavinana – Galluzzo; D4 Isolotto – Legnaia; D5 Rifredi – Novoli.

analyzed, i.e. *Structural Plan* 2014 (Florence Municipality, 2014) and the *Urban Regulations* 2015 (Florence Municipality, 2015). The first is the general planning tool of the territory and is consistent with the overarching provincial and regional planning, while the second one downscales the Structural Plan guidelines into localized interventions.

As far as urban planning constraints are concerned, out of the eighteen rules defined by the city normative tools, five constraints are applicable in the area of study. These five constraints can be divided into two subgroups: total exclusion constraints (i.e. areas where NBS cannot be implemented) and conditional exclusion constraints (i.e. in which a specific authorization is needed). The total exclusion constraints include the archeological constraint and the presence of wells or springs. The archeological constraint does not allow territorial transformation interventions, including urban planning, within the subjected areas; springs and wells are characterized by an absolute protection zone with a radius of 10 m, within which only the works for water catchment can be located, and a

Table 5
Technical feasibility constraints for Nature Based Solutions (NBS) installation.

NBS type	Area (ha)	Slope (%)	Hydrologic Soil Groups	Distance from building foundations (m)	Types of public space suitable for the installation
Infiltration trench	< 2.0	< 15	A-B	6	Parks, traffic islands
Filter strip	–	< 5	–	–	Public open space, parking lots, paths, streets, pedestrian and cycling areas
Filter drain	–	< 2	–	–	Parking lots, streets, pedestrian and cycling areas
Vegetative swale	< 2.0	< 10	A-D	4	Parking lots, traffic islands
Bioretention area and rain garden	< 0.4	< 12	A-D	6	Parks, square, traffic islands, platforms, pedestrian and cycling areas
Tree box filter	> 0.0004	< 10	–	2	Existing planting site in parks, square, traffic islands, platforms
Permeable pavement	< 1.2	< 5	A-B	6	Square, platforms, parking lots, park, pedestrian and cycling areas
Detention basin	> 0.0045	< 15	–	6	Parks, traffic islands
Pond	> 0.015	< 15	–	6	Parks, traffic islands

buffer zone with a radius of 200 m for the qualitative and quantitative protection of the withdrawn water resource. Areas within these two zones can therefore be directly excluded from those where NBS can be installed. The group of conditional exclusion constraints includes landscape and hydrogeological constraints and archeological evidence: these are constraints whose main purpose is, respectively, to protect the areas and buildings with the greatest landscape value, to preserve the physical environment and regulate interventions related to the territory, and to protect the present archeological evidence. The areas subjected to conditional exclusion can be dedicated to NBS implementation only after a specific authorization process by a sectorial institution. The analysis focuses on public spaces only, therefore areas where neither total nor conditional constraints apply have been considered always suitable for NBS installation (i.e. no presence of urban planning constraints).

With regard to the technical feasibility of NBS, the most suitable locations and installation limits of each individual solution were analyzed on the basis of literature information (Jiménez Ariza et al., 2019; Jato-Espino et al., 2016; Ávila et al., 2016; Christman et al., 2018). According to the specific characteristics of the area of study, which would not allow large-scale NBS implementation, the types of NBS considered for pluvial flood risk mitigation were infiltration trenches, filter strips, filter drains, vegetative swales, bioretention systems, rain gardens, tree box filters, permeable pavements, detention basins and ponds (WWAP, 2018; European Commission et al., 2015; European Commission et al., 2020). The following parameters are considered, focusing only on public spaces intervention: maximum slope of the terrain, areal extension of the structure, typology of public space (e.g. parks, squares, traffic islands, pavements, cycle paths, parking areas), minimum distance from building foundations, Table 5).

All the urban planning and the technical feasibility constraints described have been mapped using a GIS. The overlapping of all the constraint maps allowed the definition of a suitability map for each type of NBS considered, showing their potential application in the selected district. Merging the NBS potential implementation map with the PFI map, the areas suitable for NBS implementation against urban pluvial flooding are identified. This allows us to have a useful overview of the priority for a NBS intervention strategy implementation.

4. Results

4.1. Pluvial Flood Index (PFI)

The PFI map realized according to the methodology presented in Section 3.1, allows the identification of the pluvial flood critical areas in the entire Florence territory (Fig. 4). The areas with higher values of PFI are mainly found in the historic city center (district D1 Centro Storico), in industrial areas and in expansion areas located in the south-eastern and north-eastern districts of the municipality (i.e. districts D3 Gavinana – Galluzzo and D2 Campo di Marte).

When analysing the physical urban setting, our results mainly reflect the slope and the level of imperviousness that strongly influence the capacity of the city to cope with pluvial flood events. Indeed, PFI hotspots are located in flat areas and mainly characterized by relevant share of impermeable surface. Indeed, the historical center of Florence, characterized by high values of PFI,is mostly paved with stone blocks that do not allow the infiltration of water into the soil and the green areas are limited to few gardens belonging to historical villas and religious buildings. Similar observations can also be made for the north-east area of the old town, on the right bank of Arno River (i.e. district D5 Rifredi – Novoli). These areas were built starting from the second half of the 19th century and today are dense with streets, residential and commercial blocks. The situation is different in the south-western part of the city (i.e. district D4 Isolotto – Legnaia) mainly characterized by residential areas with larger green spaces: in these areas the map shows lower PFI values than in other urbanized areas. However, in expansion areas, there are some sites that, despite the low value of imperviousness, have a medium PFI final value: this is caused by the hydrologic class characterized by high runoff potential and low slope values. In the

Table 6
Pluvial Flood Index maximum, minimum, mean (**μ**) and standard deviation (**σ**) values for the 17 flooded areas.

	Pluvial Flood Index (PFI)			
Place	**Min**	**Max**	**μ**	**σ**
S-01	81.0	91.0	84.9	3.3
S-02	88.0	90.0	89.3	0.8
U-03	84.0	90.0	87.5	2.2
S-04	80.0	89.0	84.6	2.5
U-05	83.0	89.0	86.0	2.0
S-06	85.0	87.0	86.4	0.7
S-07	84.0	88.0	85.8	1.6
S-08	81.0	87.0	82.6	2.2
S-09	88.0	90.0	88.8	0.9
S-10	87.0	89.0	88.0	0.8
S-11	82.0	88.0	86.7	2.2
S-12	84.0	86.0	85.7	0.6
S-13	82.0	87.0	85.5	1.8
U-14	85.0	87.0	85.8	0.8
U-15	82.0	83.0	82.5	0.5
S-16	86.0	91.0	87.0	2.0
U-17	84.0	87.0	85.6	1.0

historical center, there is also a high level of social vulnerability, mainly due to the high number of elderly people living alone, but also to a high population density, average percentage of immigrant population and the scattered presence of houses in a poor state of preservation. Most of the analyzed areas have low slope values that have a great influence on the result, also according to the weights in the multicriteria analysis, resulting in a small portion of the territory with PFI values below 50.

The media library investigation has identified 17 points where floods frequently occurred in the period 2012–2019. These events involved limited portion of the city, often being circumscribed at the level of single streets or underpasses that have been mapped (Fig. 4). Analyzing the PFI distribution in the 17 identified flooded areas, PFI values in the interval 80–91 are found, with low standard deviation in each area ranging between 0.6% and 3.8% of the mean PFI values (Table 6). This allows the definition of a threshold value for PFI that is equal to the minimum value of the index in the flooded areas (PFI=80) and that can be used to map the area with higher intervention priority (areas with PFI>80).

Applying the threshold to the selected pilot district (i.e. District 5), it is possible to obtain a map with the main PFI hotspots (Fig. 5) where the realization of NBS against pluvial flood would be highly beneficial.

4.2. Spatial planning of NBS for flood mitigation

The PFI hotspot map for the district (Fig. 5) is then combined with the analysis of NBS associated constraints for the selected area of analysis.

The results show that the areas where NBS are totally excluded are rare and mainly concentrated around the two main water abstraction points of the district. On the other hand, conditional constraints are widespread, restricting the suitable areas on the north-eastern border of the district where an overlapping of landscape, hydrogeological and archeological constraints is found and on other scattered areas, mainly characterized by potential archeological evidence (Fig. 6).

With regard to the technical feasibility constraints of the NBS, the most suitable areas to host each of the analyzed NBS are identified, based on the compatibility with their requirements (Table 4). Analyzing the results, it can be observed that bioretention systems, rain gardens and vegetated channels are among the most applicable solutions, as they can be installed even in areas with small extension. Filtering drains, infiltrating strips and infiltrating trenches also have a good distribution in the neighborhood for the same reason. Similarly, permeable pavements can be widely used to convert existing parking lots, footpaths and cycle paths that are widespread throughout the district. On the other hand, detention basins and ponds, requiring larger surface areas, can be installed only in more peripheral areas with less of a built environment. Intersecting technical feasibility constraints map with urban planning

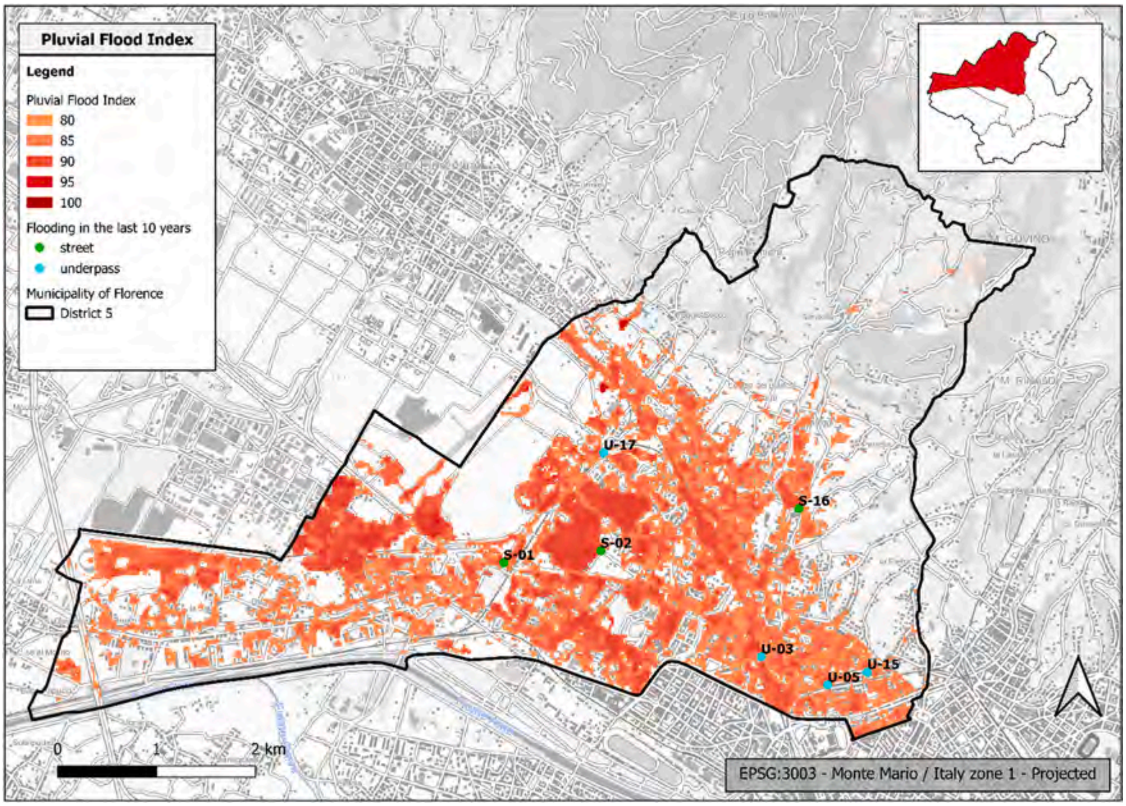

Fig. 5. Pluvial Flood Index (PFI) map of values greater than PFI= 81 with the locations of detected floods in the last ten years in District 5. The events that have affected underpasses (U-#) and streets (S-#) are also highlighted.

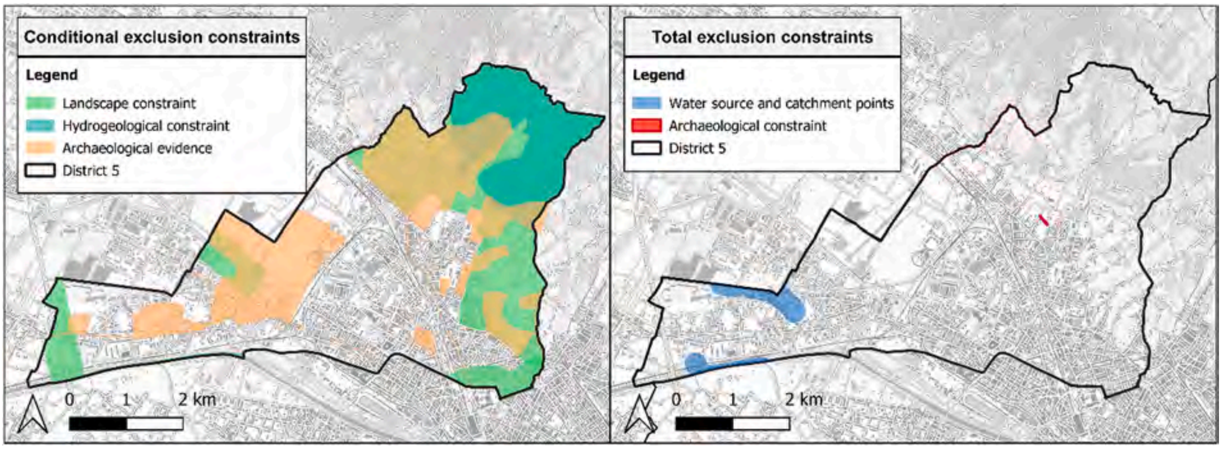

Fig. 6. Urban constraints within the district 5 of City of Florence for Nature Based Solutions (NBS) installation: conditional exclusion constraints and total exclusion constraints.

constraints, the final feasibility maps are obtained (Fig. 7).

As expected, the maps show a reduction in terms of areas where NBS can actually be implemented. In particular, conditional constraints exclude from NBS implementation the entire northern part of the district while the total exclusion constraints affect only a small portion of the area along the western borders of the district.

Comparing suitability areas with those hotspots associated with a PFI higher than 80, it is possible to determine a NBS

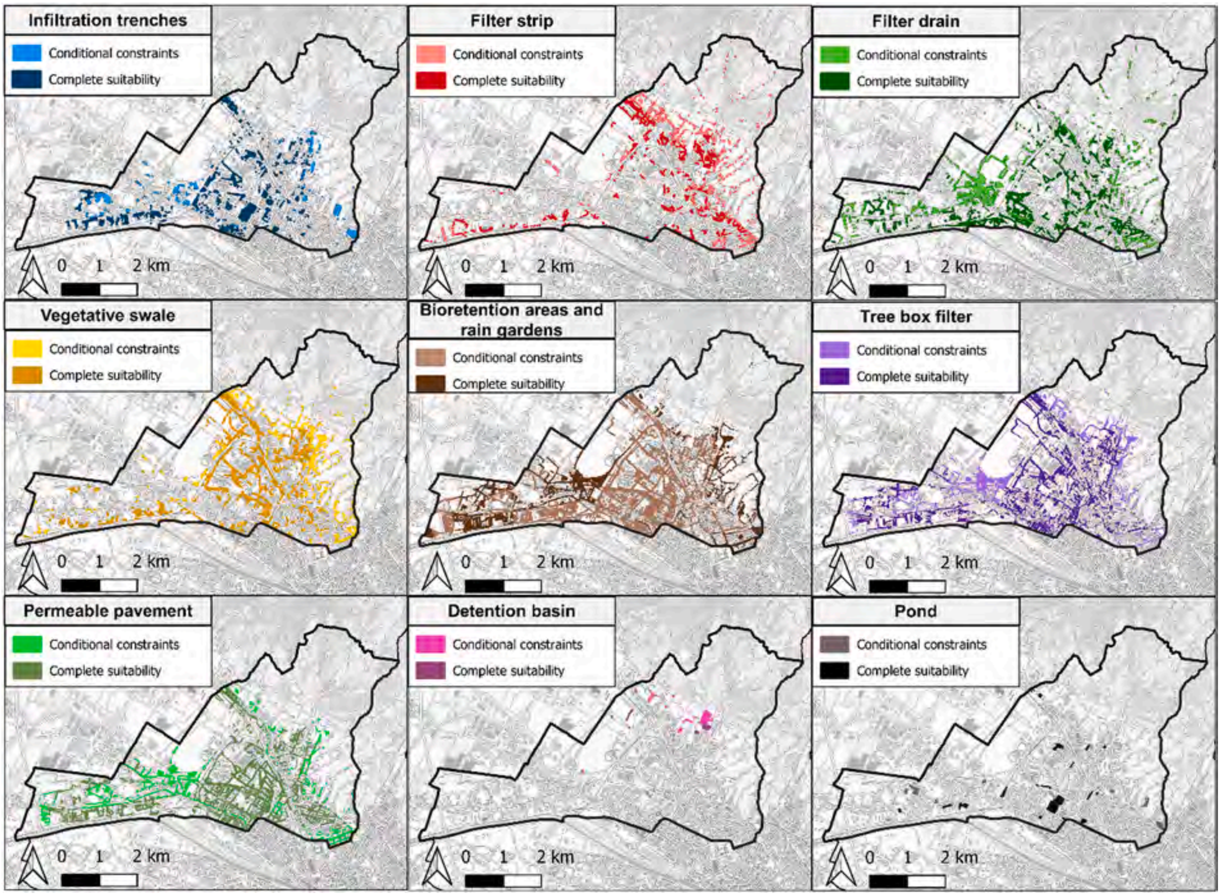

Fig. 7. Areas suitable for Nature Based Solutions (NBS) installation according to technical feasibility constraints and urban planning constraints (darker colors are associated to a complete suitability, while lighter color depend on conditional constraints verification).

implementation strategy against pluvial flooding, identifying for each pluvial flood hotspot, the set of measures that can be implemented to solve the problem (Fig. 8).

Results show that the possibility of implementing ponds and detention basins is limited by the availability of space while other NBS, such as permeable pavement or vegetated swale, can be spread around the main PFI hotspots, highlighting the multiple possibility of supporting existing drainage network with NBS interventions to reduce runoff volumes. This preliminary positioning of NBS in the district 5 allows the evaluation of alternative intervention scenarios, where NBS are implemented in synergy with existing gray infrastructures. The intervention maps obtained can provide a useful support to the design phase where, starting from the preliminary location of NBS, the efficiency in solving pluvial flood issues is analyzed through dedicated modeling (Huang et al., 2020; Pappalardo et al., 2017).

5. Discussion

The proposed analysis is oriented to the identification of NBS implementation areas to mitigate the risks associated with pluvial flood events. The wider perspective adopted, including socio economic factors in the definition of the PFI, is linked to the idea that management solutions should move beyond the single sector perspective, favoring the multifunctionality. The results reflect this approach, with the PFI being able to properly identify the areas where pluvial flood events occurred, but also including a larger part of the territory that should be considered as hotspots due to their negative combination of the other aspects, included in the SMCE (e.g. SVI). In this sense, solving a pluvial flood issue cannot be only limited to the correct management of water volumes, but should also consider the socio-economic context to define intervention priorities, favoring most vulnerable areas.

Our results are coherent with several studies, highlighting the higher risk of pluvial floods in industrial and expansion areas (Szewrański et al., 2018; Sperotto et al., 2016). Less evidence was found on higher pluvial floods risk in historical city centers, especially in Italy, but this could be linked to the limited availability of similar studies, most of which are limited to city center (Di Salvo et al., 2018), or are excluding them (Sperotto et al., 2016). However, like in other non-historical case studies (Quan, 2021), the higher risk of pluvial floods in Florence historical center is mainly linked to the high imperviousness of the paved surfaces of the area.

Similarly, the adoption of NBS should follow a similar approach, including the evaluation of the whole set of benefits they can provide, such as improving water quality, increasing the amenity of neighborhoods, reducing urban heat island and noise level. The obtained results represent a qualitative analysis, able to support the uptake of NBS for flood management through a preliminary selection of the potential solutions. As shown in Table 7, results show that the areas suitable for the realization of the different NBS types analyzed ranges between 0.1% and 7.1% of the districts analyzed. This suggests that in cities similar to Florence, where the urbanization is dense and there are many historical parts embedded, the NBS potential can be limited. Therefore, it is strategic to develop detailed mapping of NBS feasibility in order to quickly compare multiple intervention scenarios.

The final map obtained (Fig. 8) allows the identification of NBS potentially implementable to deal with PFI hotspots. After such a GIS-mapping approach, aiming at identifying all the areas where NBS can be implemented at the city scale, an additional in-depth analysis can be needed to quantify the capacity of the selected NBS to solve the pluvial flood issue. In this framework, hydrological and hydraulic modeling of NBS can help to identify their effects in terms of drainage network inflow reduction (Kumar et al., 2021; Quagliolo et al., 2021). Such modeling approaches could also allow the identification of the benefit provided by different levels of NBS implementation (Epelde et al., 2022; Castelli et al., 2017). In addition to this, integrated modeling approaches can allow the evaluation of other potential co-benefits, such as enhanced biodiversity, increased carbon storage, reduction of extreme temperatures (Epelde et al., 2022).

6. Conclusions

Rainwater management is one of the main challenges that characterizes urban areas in a global context of growing urbanization and climate change impacts. Flooding caused by heavy rainfall is increasingly frequent and new integrated solutions, such as NBS, are needed to improve existing grey infrastructures. The proposed methodology identifies the pluvial flooding hotspots in which the installation of NBS is recommended and can bring considerable benefits. The city of Florence is selected as an exemplar case study due to its complex historical structure and the ageing water infrastructures. PFI is defined to evaluate the areas most prone to flooding, using hydrological, environmental, technical and social criteria that were combined through a SMCE. The PFI map obtained, allows to analyze the distribution of the areas with high and low priority of intervention on the municipality territory, to mitigate the flooding impacts during pluvial flood events. The results obtained are validated by the comparison with the historically flooded areas during heavy rainy events: the comparison shows the results consistency, with high PFI map correctly identifying the main critical districts of the city. In particular, PFI hotspots are located in flat areas and mainly characterized by relevant share of impermeable surface as those located the historical center of Florence, mostly paved with stone blocks. High runoff potential and low slope values characterized also the other city districts, resulting in a small portion of the territory, with PFI values below 50. The SVI factor plays a relevant role in the area with high number of elderly people living alone, high population density, high presence of immigrant population and presence of houses in a poor state of preservation.

Among the critical districts, one was selected to explore a NBS implementation strategy for pluvial flood mitigation, considering urban planning constraints and technical feasibility parameters. A final map was then realized to determine which NBS types could fit in the areas with over threshold PFI values. The space available for the realization of the different NBS types analyzed ranges between 0.1% and 7.1% of the selected district area. This suggests that, in cities similar to Florence, the NBS potential can be limited due to dense urbanization and historical parts embedded. However, the introduction of NBS remains an option to be explored not only in

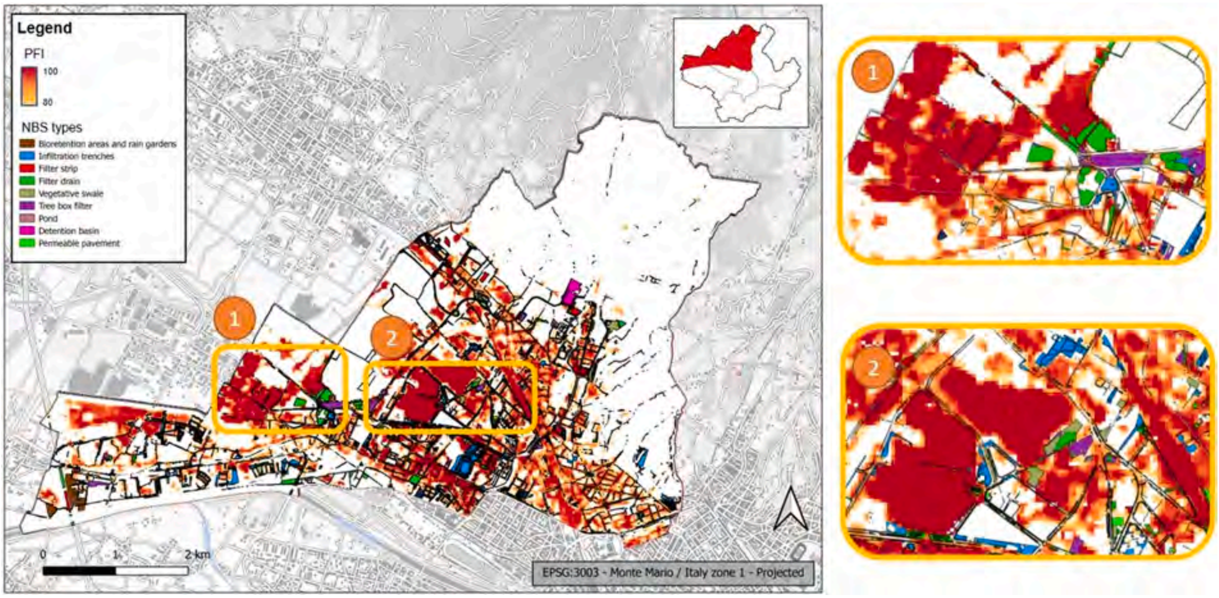

Fig. 8. NBS possible intervention strategies in PFI hotspots (only PFI higher than 80 is represented).

Table 7
Potential implementation areas for NBS in the selected district.

NBS type	Conditional constraints (% area of district)	Complete suitability (% area of district)
Infiltration trenches	0.4	1.8
Filter strip	0.3	0.7
Filter drain	0.6	1.2
Vegetative swale	0.5	1.7
Bioretention areas and rain garden	4.6	7.1
Tree box filter	1.2	2.4
Permeable pavement	1.7	2.5
Detention basin	0.1	0.3
Pond	0.7	0.9

terms of runoff flow management and reduction of impermeable areas but also evaluating the multiple ecosystem services associated. The results obtained can be a useful support for urban planning, providing a holistic approach to explore the potential of adopting NBS for urban pluvial flood management in heritage cities.

CRediT authorship contribution statement

Tommaso Pacetti: Conceptualization, Methodology, Data Curation, Formal analysis, Software, Writing – Original Draft, Writing - Review & Editing, Visualization, **Simona Cioli**: Data Curation, Formal Analysis, Software, Writing – Original Draft, Writing - Review & Editing, **Giulio Castelli**: Methodology, Data Curation, Writing – Original Draft, Writing - Review & Editing, **Elena Bresci**: Validation, Writing - Review & Editing, **Matteo Pampaloni**: Data Curation, Validation, **Tiziana Pileggi**: Data Curation, Writing - Review & Editing, **Enrica Caporali**: Supervision, Validation, Resources, Writing - Review & Editing.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101081.

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