






ORIGINAL ARTICLE OPEN ACCESS

Optimizing LID Practices in the Genoa Urban Drainage System Based on the Community's Call for Action Through Participatory Mapping

Enrico Creaco¹  | Ilaria Gnecco²  | Carlo Giudicianni¹  | Stefano Boilini³ | Shaahin Nazarpour Tameh²  | Anna Palla² 

¹Department of Civil Engineering and Architecture, University of Pavia, Pavia, Italy | ²Department of Civil, Chemical and Environmental Engineering, University of Genoa, Genoa, Italy | ³Municipality of Genoa, Genoa, Italy

Correspondence: Enrico Creaco (enrico.creaco@unipv.it)

Received: 5 August 2025 | **Revised:** 15 November 2025 | **Accepted:** 14 December 2025

Keywords: community's engagement | LID | optimization | participatory mapping | pluvial flooding | sustainability | urban drainage

ABSTRACT

This paper presents a novel methodology for optimizing installation of low impact development practices (LIDs) in an urban hydrological catchment. This methodology helps stakeholders in deciding on what kind and area of LID must be installed in each sub-catchment to attenuate pluvial flooding as a result of intense rain events. The main novelty consists of the community's engagement in the optimization process, by means of an additional objective function to consider the community's appreciation for the choice of LIDs. The methodology is applied to a real case study, i.e., a part of the urban drainage system (UDS) of Genoa, which is frequently plagued by pluvial flooding events that annoy the community. Following a survey of community preferences, the results of which were collected by means of participatory mapping, the methodology yields a Pareto front of trade-off solutions between installation costs, pluvial flooding volumes, and community satisfaction. From the front, stakeholders can select the ultimate solution based on budget constraints and/or on expected joint performance in terms of flood attenuation and community satisfaction.

1 | Introduction

In urban areas, urbanization processes take place through replacement of natural/rural/pervious areas with impervious areas for residential, commercial, and transportation purposes, causing significant variations in hydrological cycles, i.e., increased runoff water volumes and discharges, as well as reduced concentration times, evapotranspiration, and groundwater recharge. Due to the currently strong urbanization patterns, urban drainage systems (UDSs) are often unable to convey increased runoff volumes and discharges (e.g., see Galuppini et al. 2020; Boyu et al. 2021). This situation is aggravated by climate change, which is alleged to be concentrating yearly rainwater volumes

into increasingly few and intense rain events (e.g., see Mailhot and Duchesne 2010; Ma et al. 2018).

The mismatch between runoff inputs to UDSs and UDS capacities results in the increased frequency/intensity of pluvial flooding. The first remedy for this consists of the increase in UDS capacities, by means of interventions such as upgrade and rehabilitation (e.g., see Diogo et al. 2018; Diogo and do Carmo 2019; Reyna et al. 1994; Ugarelli and Di Federico 2010) or implementation of real time control (e.g., see Campisano et al. 2016; Li and Burian 2023), for the improvement of conveyance capacity or for the activation of inline/outline storages, respectively. A virtuous alternative is represented by

This is an open access article under the terms of the [Creative Commons Attribution-NonCommercial-NoDerivs](https://creativecommons.org/licenses/by-nc-nd/4.0/) License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.

© 2026 The Author(s). *Journal of Flood Risk Management* published by Chartered Institution of Water and Environmental Management and John Wiley & Sons Ltd.

installations of interventions on sub-catchments (e.g., see Zahmatkesh et al. 2015; Duan et al. 2016) to attenuate runoff input to underground channels. These interventions include sustainable/nature-based solutions, such as retention ponds, green roofs, infiltration trenches/basins and vegetated depressions, to preventively reduce runoff discharges and volumes entering the network of underground channels. These solutions are also called low impact development practices (LIDs).

Besides technical aspects and considerations, the broad implementation of LIDs and nature-based solutions is currently slowed down by governance and social challenges (Langemeyer and Connolly 2020; Stork et al. 2023; Remme et al. 2024; Marchioni et al. 2025). In fact, the design, implementation, and long-term management and maintenance of nature-based solutions require appropriate governance arrangements in various phases of the process, ranging from identification of urban challenges to assessing and selecting potential nature-based solutions, managing urban ecosystems and their processes, distributing and managing in an equitable way flows of ecosystem services and related benefits. The whole process involves and affects different stakeholder groups, which ought to be involved at the decision level of the flood risk governance (Watkins and Collins 2025).

Leaving aside the governance and social challenges associated with the uptake of LIDs, the scientific literature is rich in works analyzing the benefits of LID systems for the attenuation of pluvial flooding. These benefits were analyzed by Zahmatkesh et al. (2015) and Mora-Melià et al. (2018) on real case studies. Other relevant topics are the optimal selection and placement of LIDs, in which various kinds of algorithms were used, including linear programming (Sebti et al. 2015), simulated annealing (Cunha et al. 2016), Harmony-Search (De Paola et al. 2018), pseudo-genetic heuristic algorithm (Ngamalieu-Nengoue, Iglesias-Rey, et al. 2019), multi-criteria decision-making analysis (Tameh et al. 2024), and genetic algorithm (Ghodsi et al. 2020) from the single-objective perspective. Recent endeavors have also concerned the extension of the optimal location problem to the multi-objective perspective, considering a single phase (Duan et al. 2016; Ngamalieu-Nengoue, Martínez-Solano, et al. 2019) or multiple phases (Creaco et al. 2025) of construction.

Though being indisputably important contributions to the research field, the works mentioned above, aimed at analyzing the performance of LIDs and/or optimizing their installation, fail to consider social and governance aspects. Based on the recent review of Bista et al. (2025), most research works, i.e., around 90% of the work in the scientific literature, consider objective functions related to water quantity and costs, with only 11% considering socio-environmental objectives, such as the green score, landscape quality/aesthetic beauty, environmental return on investment, and socioecological index. As social objectives are of paramount importance to ensure the long-time acceptance of designed solutions, more research efforts are advocated in this direction for the future. Nowadays, the growing awareness of environmental issues entails the population's increasing interest in LIDs, as these practices can play a key role in making our cities more sustainable. The design and implementation of LIDs are recently

considered a collaborative effort in which scientists, experts, policy makers, practitioners, citizens, and other stakeholders work together on the planning and implementation of these systems/practices (Kabisch et al. 2022). Indeed, co-creation and co-governance are recognized as crucial elements for the effective deployment of LIDs in different contexts in Europe (EC 2023). Different approaches have recently been developed by the social science applied to urban planning: starting with the community's understanding and mapping, moving to systematic strategies to involve stakeholders, and ending with the monitoring of actions. For instance, participatory mapping includes all approaches and techniques that combine the tools of modern cartography with participatory methods to record and represent the spatial knowledge and desires of local communities (Rall et al. 2019; Brown et al. 2018). Since the community's appreciation and call for LIDs represent an indispensable factor inside the decision-making process, the question arises whether or how numerical optimization can be enhanced to incorporate them. The integration of the standard optimization approach based only on cost and water quantity-related aspects with community's appreciation is expected to provide a wider range solution than those yielded by the standard approach, as the community can express viewpoints transcending the merely hydraulic aspects, including the harmonic integration of solutions with territory and individuals' preferences.

The present paper aims to give an answer to the question reported above by providing a multi-objective optimization framework including cost, total pluvial flooding volume, and the community's satisfaction/role. The structure of the paper is as follows: the next section describes the methodology, followed by the application to a real world case study and the conclusions.

2 | Methodology

2.1 | Overview

The methodology encompasses four elements, described in the following subsections. The first element concerns the use of participatory mapping inside a municipality for revealing the community's knowledge, understanding, and preferences about LID installation. The second and third elements are about the hydrological/hydraulic modeling of an urban catchment and the hydrologic modeling of LID interventions, respectively. Finally, the fourth element concerns the multi-objective optimization of LIDs in a hydrological catchment while considering an innovative objective function to express the community's level of preference/appreciation for various kinds of LIDs.

2.2 | Participatory Mapping

The proposed participatory approach pursues the objective of increasing awareness of stormwater management and climate change by encouraging interactions between different actors to support water-sensitive urban and regional planning, including the community's appreciation and call for LIDs. The participatory process aims to integrate, in an environment of

co-responsibility, the technical know-how of experts and local authorities with the pool of local community knowledge encouraging intergenerationality, to co-build a strategic vision of the case study, including possible areas of LIDs intervention and ways to exploit available resources (Palla et al. 2024). A dedicated consent form, comprising the information sheet and privacy notice, is implemented to assure the informed consent of all the stakeholders involved in research. Ad hoc working groups are established, consistent with the methodology of community-based participatory research, and specific activities programs are set up based on the targeted groups:

- regular meetings and in-depth interviews with individual representatives (high-profile working group—both institutional and technical);
- thematic focus groups and customized activities according to school grade (6–19-year-old students);
- co-creation workshops on paper and digital map (all stakeholders over 11-year-old);
- online survey (all stakeholders over 11-year-old).

2.3 | Urban Drainage Modeling

The event modeling of the UDS serving an urban catchment is carried out by means of the United States Environmental Protection Agency Storm Water Management Model EPASWMM (Rossman 2015) software. In this work, sub-catchments are subdivided into pervious and impervious areas drained in parallel and are modeled hydrologically as nonlinear reservoirs. The water input to these elements is specified in terms of rainfall intensity pattern, e.g., a Chicago hyetograph associated with a preset return period, at a rain gauge station. The water output takes place in two ways, namely infiltration and runoff, modeled by means of the Curve Number approach (Soil Conservation Service 1972) and the Manning uniform flow equation (Chow et al. 1988), respectively. The presence of depression storage is considered in pervious areas to subtract part of the rainfall from runoff. In the absence of LIDs, runoff from each sub-catchment reaches an outlet in correspondence to a junction of an underground channel. The Saint-Venant equations (Chow et al. 1988) are used to model each underground channel of the UDS, considering the fully dynamic wave model.

2.4 | LID Modeling

When a LID is installed in a sub-catchment, it intercepts its runoff before it reaches the sub-catchment outlet. As Oberascher et al. (2024) showed, many kinds of LIDs can be modeled inside EPASWMM, including soakaways, bio-retention systems, dry swales, extensive green roofs, intensive green roofs, cisterns and permeable pavements. The generic LID is made up of a single layer or of multiple layers, each of which is modeled by means of a continuity equation. Only vertical flow exchanges between surface and upper layer, between the various layers and between the lower layer and the surrounding soil are modeled in the generic LID, as sub-horizontal flow propagation inside each layer is neglected. The EPASWMM modeling of LIDs enables estimation of the effects in terms of runoff volume reduction and

runoff hydrograph attenuation upstream from the network of underground channels. No drain is assumed to be present at the bottom of LIDs.

2.5 | Multi-Objective Optimization

The multi-objective genetic algorithm of Matlab 2025a is used to optimize the installation of LIDs in a hydrological catchment served by a UDS. The genetic algorithm is a metaheuristic technique inspired by the processes ruling the evolution of natural species to find the solution of optimization problems (Goldberg 1989). Inside the genetic algorithm, a population of individuals, each of which is made up of a number of genes equal to the number of decision variables inside the optimization problem being considered, is initially generated. Specifically, an individual is a combination of values assigned to genes, which are representative of decision variables. Then, the population evolves by means of crossover and mutation processes till it reaches convergence after a certain number of generations. In the multi-objective context, the convergence is at a set of optimal trade-off solutions between objective functions. This set of ultimate solutions is called “Pareto front.”

In the specific case of LID optimization, the multi-objective genetic algorithm decides on what kind and what area of LID, inside a list of potential devices, is installed. The simplification that only one kind of LID can be installed in the generic sub-catchment is assumed.

Three objective functions are considered. The first objective function is the total cost of the LIDs in €, including a base term and another term growing as a function of the installed area. The total cost to be minimized takes on the following form:

$$f_1 = \sum_{i=1}^{N_c} \sum_{j=1}^{N_{LID}} (c_{b,j} \delta_{i,j} + c_{u,j} A_i) \quad (1)$$

in which $c_{b,j}$ (€) and $c_{u,j}$ (€/m²) are the base and unit cost of the generic j -th kind of LID, respectively; $\delta_{i,j}$ (–) is a variable which is equal to 1 or 0, if the j -th kind of LID is present or absent in the i -th sub-catchment, respectively; finally, A_i (m²) is the area of the i -th sub-catchment converted into LID. Finally, N_c and N_{LID} are the number of sub-catchments that can be fitted with a LID and the number of LID options considered in the analysis, respectively.

The second objective function f_2 is the total pluvial flooding volume in m³ to be minimized, as is obtained from the EPASWMM software. It is equal to the sum of the pluvial flooding volume calculated by the software at all junctions.

Following the assignment of a weight w_j to express the community's appreciation for the generic j -th LID practice, which can be obtained by means of a survey, the third objective function expresses the level of community's satisfaction for a certain distribution of LIDs in the catchment, to be maximized.

$$f_3 = \frac{\sum_{i=1}^{N_c} \sum_{j=1}^{N_{LID}} (w_{i,j}^* \delta_{i,j})}{\sum_{i=1}^{N_c} \sum_{j=1}^{N_{LID}} (\delta_{i,j})} \quad (2)$$

in which w_j^* is a weight rescaled between 0 and 1, obtained through the following Equation (3):

$$w_{i,j}^* = \frac{w_j}{\max(w_j)} k_{i,j} \quad (3)$$

in which $k_{i,j}$ is a coefficient ranging from [0,1], to potentially tune preference weights expressed on the single sub-catchment based on heterogeneity, spatial equity, and sample representativeness (age, geography, socioeconomics) of community members expressing their preferences.

At this stage, some comments must be made about the structure and meaning of Equation (2) for the assessment of f_3 . Considering the generic solution proposed by the optimizer for the optimal placement of LIDs, the expression in the numerator is useful for summing the weights associated with all LIDs present in the generic solution. However, as per se, it cannot be used as an objective function, since it favors the solutions featuring more numerous installed LIDs, and then higher cost. The presence of $\sum_{j=1}^{N_{LID}} \delta_{i,j}$ and in the denominator cancels the dependence of f_3 on the number of LIDs installed and, indirectly, on cost. Being poorly connected to cost and hydraulic performance, which does not appear in the equation, f_3 expressed like in Equation (2) lends itself to being used as an objective function in the multi-objective framework in the trade-off with cost and flooding volumes. As the numerator in Equation (2) differs from the denominator due to the presence of a multiplying coefficient ranging from 0 to 1 in the term to be summed, f_3 ranges from 0 to 1. Namely, it will be equal to 0 or 1 in the hypothetical cases in which a totally unappreciated LID option ($w_j^* = 0$) or a fully appreciated LID option ($w_j^* = 1$) is installed, respectively, in all sub-catchments. Otherwise, it will take on values in between the bounds.

The number of decision variables considered is equal to $2 N_c$. The first N_c decision variables concern the kind of LID installed in the N_c sub-catchments whereas the N_c following decision variables concern the sub-catchment area A_i converted to LID. The generic individual of the population inside the genetic algorithm is then made up of $2 N_c$ genes. Each of the first N_c genes takes on integer values between 0 and N_{LID} . When it is equal to 0, no LID is installed. When it is larger than 0, it suggests installation of the corresponding LID practice. This results in the possibility of considering only one LID practice installable in each sub-catchment in each solution proposed by the optimizer. $A_{maxi,j}$ being the maximum area of the i -th sub-catchment that can be converted into the j -th kind of LID, each of the N_c following genes ranges in a continuous way between a minimum value (e.g., 0.05) and 1, to be multiplied by $A_{maxi,j}$ for encoding the fraction of $A_{maxi,j}$ that must be actually converted in each sub-catchment. The constraint that only one LID practice can be installed in each sub-catchment in the generic solution proposed by the optimizer is justified as follows: typically, in case studies, $A_{maxi,j}$ and the impervious area connectable to the generic LID practice are defined based on this constraint. The adoption of multiple LID practices in each sub-catchment would require the parceling out of the latter to obtain an accurate definition of LID geometry, $A_{maxi,j}$ and connectable impervious areas in each parcel of the sub-catchment, entailing that each parcel should be re-configured as a new sub-catchment.

When the genetic algorithm is run, the EPASWMM model is updated with the spatial disposition of LIDs proposed by each individual of the genetic algorithm, to which a certain value of the installation cost (first objective function, see Equation 1) and a certain value of community's satisfaction (third objective function, see Equation 2) correspond. Then, EPASWMM is run to evaluate the total pluvial flooding in the urban catchment (second objective function). This value is automatically extracted from the flooding loss information in the flow routing continuity section of the EPASWMM report. The execution of the genetic algorithm results in a Pareto front of optimal solutions in the trade-off between the various objective functions.

3 | Applications

3.1 | Case Study

The case study in this paper was selected in the framework of the URCA! project in agreement with the Municipality of Genoa, focusing on urban areas prone to frequent pluvial flood events and characterized by strategic activities and services (Gnecco et al. 2024). The URCA! project (Urban Resilience to Climate change: Activation of participatory mapping and decision support tool for enhancing the sustainable urban drainage), founded within the PRIN 2020 program by the Italian Ministry for Universities and Research, aimed to strengthen the resilience of urban areas by promoting the implementation of sustainable water management strategies in territorial planning at both a catchment and a local scale. The selected case study has an extension of about 1.4 km², corresponding to the Sampierdarena district. As illustrated in Figure 1a, the Sampierdarena district is an urban cluster located in the western part of Genoa between the commercial port and the left bank of the Polcevera river. It includes minor streams that are partially culverted. As far as stormwater management is concerned, the Sampierdarena district is mainly served by a combined sewer system and no sustainable/nature-based solutions are installed in the area. The degree of imperviousness in the area is high. Specifically, impervious surfaces account for over 65% of the catchment area on average. Green spaces are not widespread and are mainly concentrated in the northern part of the catchment. The morphological configuration of the basin reflects typical Ligurian watershed characteristics, with steep upstream gradients resulting from orographic elevations, and a downstream alluvial plain aligning with the coastal boundary.

The EPASWMM model (Figure 1b) of the UDS is made up of 142 nodes, namely 137 junction nodes, 3 outfall nodes, and 2 storage nodes, 137 conduit links, and 90 sub-catchments. The sub-catchments are defined according to the spatial resolution of the drainage network and are characterized by nonhomogeneous land use characteristics. No observed data are available concerning stormwater discharges. Therefore, the hydrological model was validated through qualitative methods for the rainfall event that occurred on 24 September 2022 (characterized by a return period of 5-year for the 1-h duration). The validation was performed by comparing the predicted flooding area with different documentary photographs used as ground truth (Figure S1). Prediction performance was assessed through extension and average depth indexes.

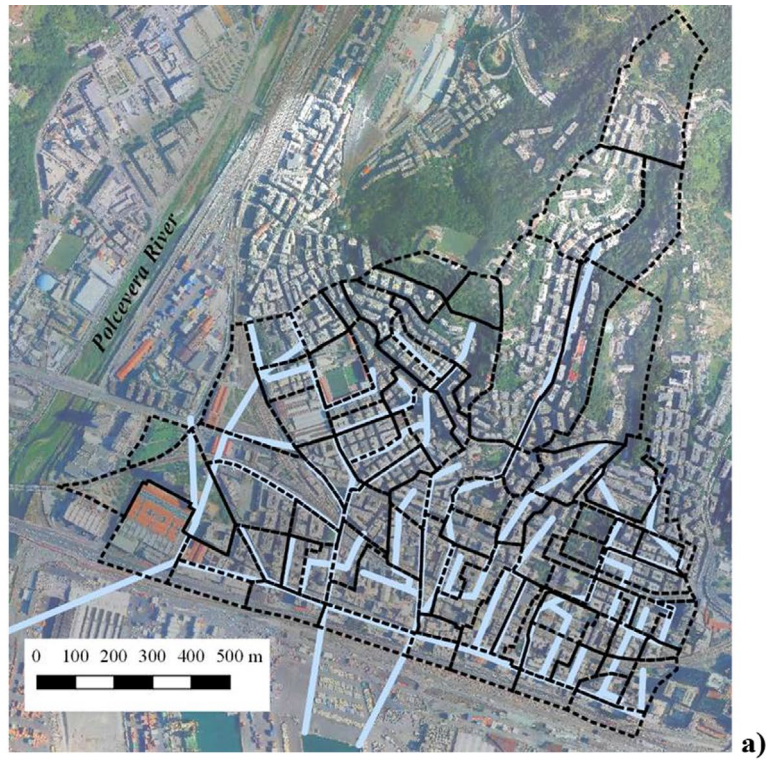


FIGURE 1 | (a) Overview of the case study area in the Sampierdarena district (Genoa, IT), drainage network (blue solid lines) and subcatchments' perimeters (black dotted lines); (b) EPASWMM model of the case study network.

Based on the intensity-duration-frequency curves derived by means of the approach of Gnecco et al. (2023), the Chicago hyetographs for return periods of 5 and 10 years (Figure 2) were constructed as an input to put the UDS to the test. As Figure 3 shows, pluvial flooding takes place with both hyetographs at some network

junctions with an overall volume of 3.2×10^3 and $6.3 \times 10^3 \text{ m}^3$, respectively for the 5 and 10-year return period events, calling for urgent remedies. The flooded junctions are located in specific areas where section contractions and slope reductions occur limiting the flow capacity of the conduit, as expected.

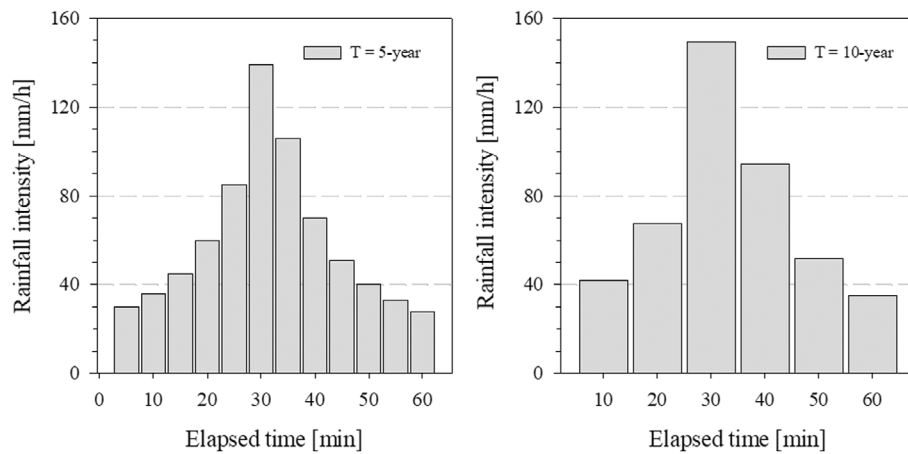


FIGURE 2 | The Chicago hyetographs for the Sampierdarena district (Genoa, IT) case study for 5-year (left graph) and 10-year (right graph) return periods.

$N_{LID} = 7$ kinds of LID practices are considered in the analysis, namely soakaways, bio-retention systems, dry swales, extensive green roofs, intensive green roofs, cisterns, and permeable pavements.

Soakaways, bio-retention systems and permeable pavements are modeled with the bio-retention cell LID type of EPASWMM. Dry swales are modeled with the Rain garden LID type. Extensive and intensive green roofs are modeled with the Green roof LID type. Finally, cisterns are modeled with the Rain barrel LID type. The technical characteristics, base and unit costs of these practices are adapted from Oberascher et al. (2024) along with the parameters concerning their implementation in the EPASWMM environment (see Tables S1–S3). It must be noted that for soakaways, bio-retention systems and dry swales, ponding before overflow as well as exfiltration in surrounding soil can occur; for permeable pavement solely the exfiltration process is allowed. Due to specific constraints of the case study (highly urbanized area), the maximum ponding depth of soakaway is limited to 300 mm and the related unit cost is updated accordingly. Table 1 reports base and unit costs for each kind of LID practice.

After the area A_i of LID conversion has been proposed by the optimizer in the i -th subcatchment, a square shape of the LID is considered with side equal to the square root of A_i . The maximum area of LID conversion is evaluated for each sub-catchment based on the specific LID practice according to technical criteria defined during meetings with the high-profile working group based on the co-created knowledge of the study area. To this end, the available ground area for LID conversion was evaluated as the difference between the sub-catchment area and the sum of building areas, green areas and railway infrastructure areas. Subsequently the maximum converted area is determined for each LID, as follows:

- For Soakaway, Bioretention Cell, Dry swale, Permeable pavement, and Cistern: the minimum between the 10% of the catchment area and the 20% of the available ground area (if the available ground area is larger than 1.5 times the street areas) or the 15% of the street areas;

- For Extensive Green Roof: the area of public buildings or the minimum between 10% of the catchment area and 70% of the building areas;
- For Intensive Green Roof: the area of public buildings

The maximum possible impervious area is connected to the LID, based on the kind of practice; in particular for the cistern, the connected area is limited to the rooftop areas. No change in sub-catchment characteristics is assumed following LID installation for the sake of simplification.

Finally, to define the community's appreciation and call for LIDs, findings obtained during the overall participation process (including thematic focus groups; co-creation workshops on paper and digital map; online survey opened to all community members over 11-year-old) were deeply analyzed. In Table 2 a summary of the participant characteristics is reported for all the involved community members (total study participants) and for those who provided LID suggestions (LID suggestion participants) for the case study area. The 76 participants that provided LID suggestions were a representative sample of all the stakeholder involved in the participatory process in terms of gender, age and education as supported by the similar observed values: 41% of male (with respect to 45%); 62% of 15–26 years-old (with respect to 50%) and 36% of graduate and postgraduate education (with respect to 35%). The spatial coverage of the suggested LID locations and of the most-frequented areas by all the involved community members was good all over the case study area and no favorite or (most mentioned) locations were identified. Further details on the spatial coverage are reported in Gnecco et al. (2024). Based on the assumption that the community's appreciation for LID practices did not change across sub-catchments, the total number of suggestions by the 76 participants resulted in 544 quotes for the cases study area, which were aggregated and categorized for the 7 selected LID practices as shown in Table 3. Weight w for each LID practice was set equal to the number of preferences received by that practice. Note that soakaways were not appreciated by the community reflecting the limited preference for engineering solutions that promote high exfiltration rates into the surrounding soil. For each kind of LID,



FIGURE 3 | Node flooding volumes in the Sampierdarena district (Genoa, IT) case study simulated for the current urban drainage system during the (a) 5-year and (b) 10-year return period rainfall events.

the rescaled weight w^* was then calculated by dividing the weight w of that LID by the weight received by the most appreciated LID practice (see Equation 3) and assuming a uniform appreciation for LID practices across sub-catchments ($k_{i,j} = 1$), as is shown in Table 4.

3.2 | Results

Two runs of optimization were carried out, considering the more severe stressing conditions from the hydrological viewpoint, i.e., the Chicago hyetograph with return period of 10 years. The first

TABLE 1 | Base c_b and unit c_u costs for each kind of LID.

Costs	Soakaway	Bioretention cell	Swale	Extensive green roof	Intensive green roof	Cistern	Pervious pavement
c_b (€)	608	608	103	486	486	161	344
c_u (€/m ²)	300	200	177	25	46	100	70

TABLE 2 | Participant characteristics including gender, age, education and LID knowledge for all the involved community (total study participants) and for those who provided LID suggestions (LID suggestion participants).

Participant characteristics	Category	LID suggestion participants (N=76)	Total study participants (N=161)
Gender	Male	41%	45%
	Female	55%	52%
	Not to say	4%	3%
Age	11–14	0%	1%
	15–26	62%	50%
	27–45	20%	22%
	46–75	17%	25%
	> 75	1%	2%
Education	<12 years	41%	32%
	12 years	16%	24%
	15 years	8%	9%
	>15 years	36%	35%

TABLE 3 | Community's preference for each kind of LID (weight w).

Soakaway	Bioretention cell	Swale	Extensive green roof	Intensive green roof	Cistern	Pervious pavement
0	105	105	102	102	24	106

TABLE 4 | Rescaled weight w^* for each kind of LID.

Soakaway	Bioretention cell	Swale	Extensive green roof	Intensive green roof	Cistern	Pervious pavement
0.000	0.991	0.991	0.962	0.962	0.226	1.000

was carried out considering only the first two objective functions, i.e., cost f_1 and pluvial flooding volume f_2 , adopting a population of 500 individuals. The second was carried out with the whole set of objective functions, namely cost f_1 , pluvial flooding volume f_2 and community's satisfaction f_3 , and adopting a larger population of 1000 individuals. The population was increased in this second run, as the addition of one objective function increases the computational complexity of the problem. The reason for performing these two optimization runs, instead of a single run with the three objective functions, is that, due to numerical difficulties, the run with three objective functions struggled to find solutions in the f_1 - f_2 restriction, which belongs to the boundary of the solution space f_1 - f_2 - f_3 (Creaco et al. 2016). Therefore, the two-runs strategy

enabled obtaining a more accurate picture of the optimal trade-off solutions between the three objectives.

In the bi-objective framework, the selection of a LID practice obtained by the optimizer for a sub-catchment was motivated by cost and hydraulic performance, as well as by the suitability of the sub-catchment to host that LID practice in terms of maximum convertible area and connectable impervious area. In the tri-objective framework, the selection was also affected by the community's appreciation for LID practices.

The first optimization run converged in 120 generations, i.e., 60,000 objective function evaluations. The second optimization

run converged in 105 generations, i.e., 105,000 objective function evaluations.

The results of the optimization run with two objective functions are shown in Figure 4. The two dimensional Pareto front in Figure 4 shows, expectedly, the decrease in pluvial flooding volumes as the installation cost increases, due to more numerous and extended LIDs being installed in the catchment area. The results of the optimization run with three objective functions are shown in Figure 5a. The three dimensional Pareto front in Figure 5a includes, for increasing values of the cost, various solutions corresponding to different combinations of pluvial flooding volumes and community's satisfaction. After being evaluated in terms of the nondominance criterion, the results of the two optimization runs were then put together on the two dimensional graph in Figure 5b, which then reports the improved version of the three dimensional Pareto front. In this graph the value of the third objective function is indicated with the dot darkness: the darker the dots, the lower the community's satisfaction. The analysis of the graph in Figure 5b shows that, expectedly, the three dimensional Pareto front is delimited below by solutions obtained from the first run of optimization, which only considered the first two objective functions (compare Figure 5b with Figure 4). The exclusive carrying-out of the tri-objective optimization would not have yielded an accurate representation of the research space in proximity to the f_1-f_2 restriction of the three dimensional Pareto front, which includes very important solutions from the engineering viewpoint. In fact, these solutions yield the best pluvial flooding attenuation results for different values of the cost. Furthermore, the graph in Figure 5b shows that, the cost being the same, solutions with different performance in terms of pluvial flooding attenuation and community's satisfaction can be found. Overall, the results show that, compared to the current scenario in which the pluvial flooding volume adds up to $6.3 \times 10^3 \text{ m}^3$, the optimal installation of LIDs with investment between about $15 \times 10^6 \text{ €}$ and about $23 \times 10^6 \text{ €}$ is capable of nearly eliminating the pluvial flooding problem in the urban area being analyzed.

To provide insight into solution coverage, the graph in Figure 6a shows the number of solutions yielded by the two optimization runs for eight groups of cost with equal amplitude, in the range 0M€–24M€. Based on the analysis of this graph, the large majority (around 250) of the solutions belong to the first group with costs ranging from 0 to about 3M€. The other cost groups include a number of solutions ranging from 17 (eighth group, with costs ranging from about 21 M€ to about 24 M€) to 48 (second group, with costs ranging from about 3 M€ to about 6 M€). Overall, the number of group solutions tends to decrease as the group cost increases. The graph in Figure 6b shows the box plot statistics of flooding volumes, by visualizing for each cost group the five-number summary: lower adjacent value, lower quartile (25th percentile), median (50th percentile), upper quartile (75th percentile), upper adjacent value, plus outliers. Looking at the maxima in the boxplots, there is a clear decreasing flooding volume pattern as the group cost increases, because the installation of increasingly numerous LID practices tends to result in reduced flooding volumes, independently of the community's satisfaction. The whisker range of each box, which generally corresponds to the distance between maximum and minimum

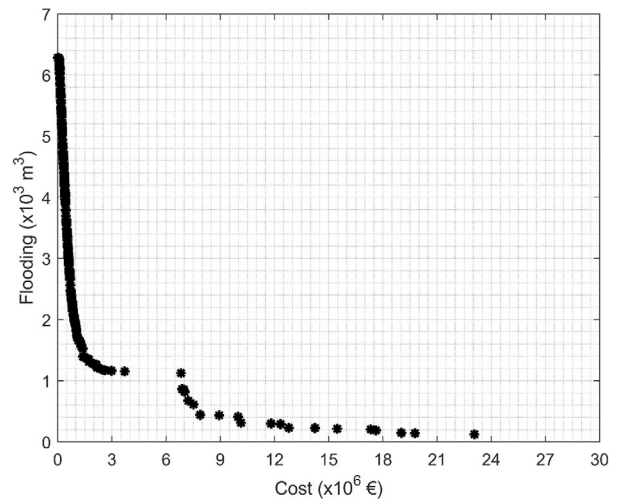


FIGURE 4 | Bi-objective optimization. Pareto front of optimal solutions in the trade-off between cost and flooding volumes. Optimization results refer to the 10-year return period rainfall event.

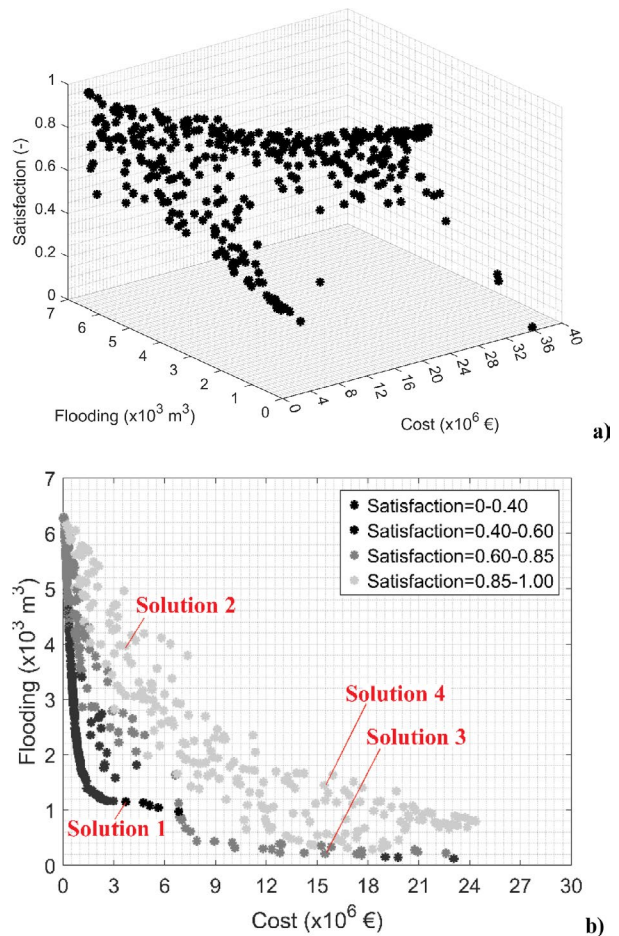


FIGURE 5 | (a) Pareto front of optimal solutions in the trade-off between cost, flooding volumes, and community's satisfaction, obtained from the tri-objective optimization; (b) results of bi and tri-objective optimizations. Cost and flooding volumes are on the x and y axes, respectively. Community's satisfaction is shown with dot darkness. The lighter the dot, the higher the community's satisfaction. Optimization results refer to the 10-year return period rainfall event. 4 Optimal solutions are targeted by a red line under budget constraints of about 4 M€ and 15 M€.

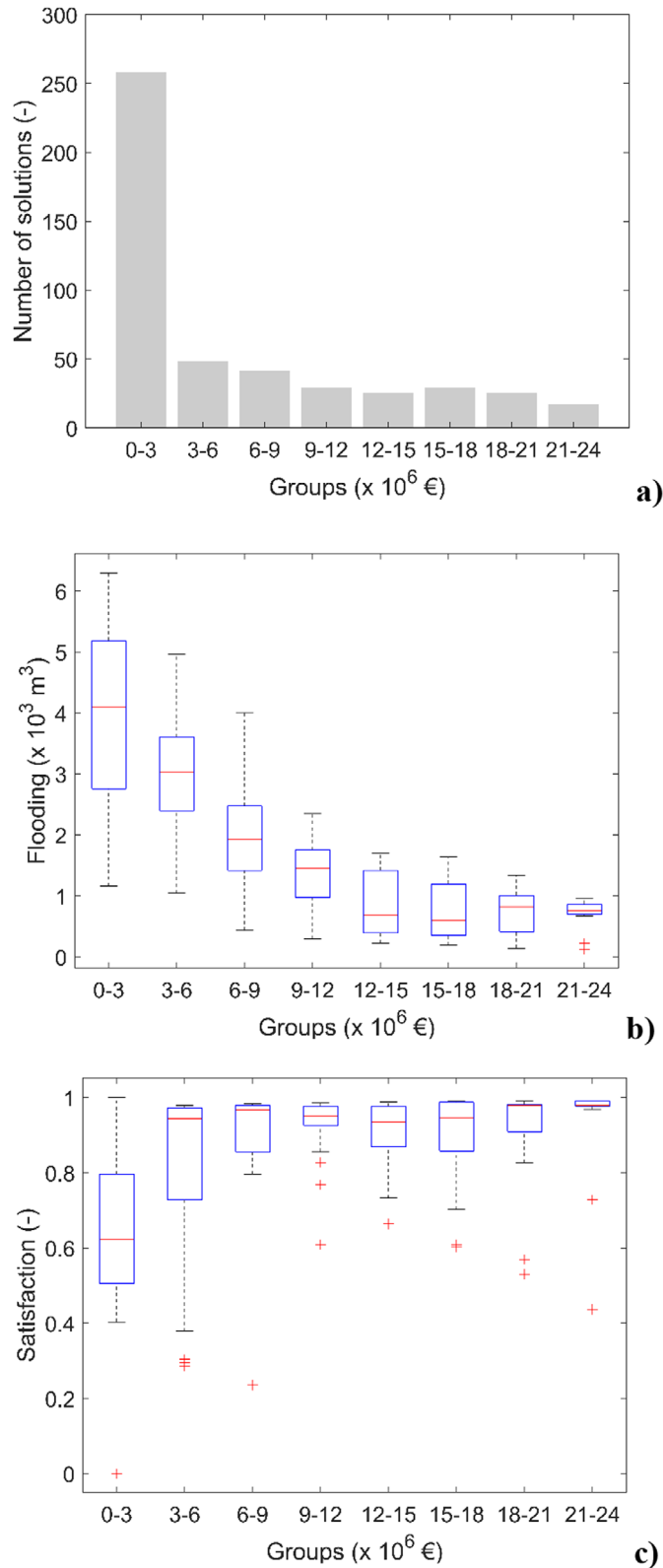


FIGURE 6 | Postprocessing of bi and tri-objective optimizations results in terms of (a) coverage of solutions and boxplots of (b) flooding and (c) satisfaction for groups of solutions differentiated based on cost, which is rounded in the x axis.

flooding volumes in each cost group, also tends to decrease as the cost grows. The minimum flooding volume from the first to the seventh cost group and the low outliers in the eighth cost group represent the bi-objective optimization solutions, corresponding to the lower envelope of the Pareto front in

Figure 5b. The graph in Figure 6c shows the box plot statistics of satisfaction. Whereas the maximum value of satisfaction is close to 1 in all cost groups, the minimum value of satisfaction and the box plot height fluctuate as the cost grows across cost groups. While the first and second cost groups include

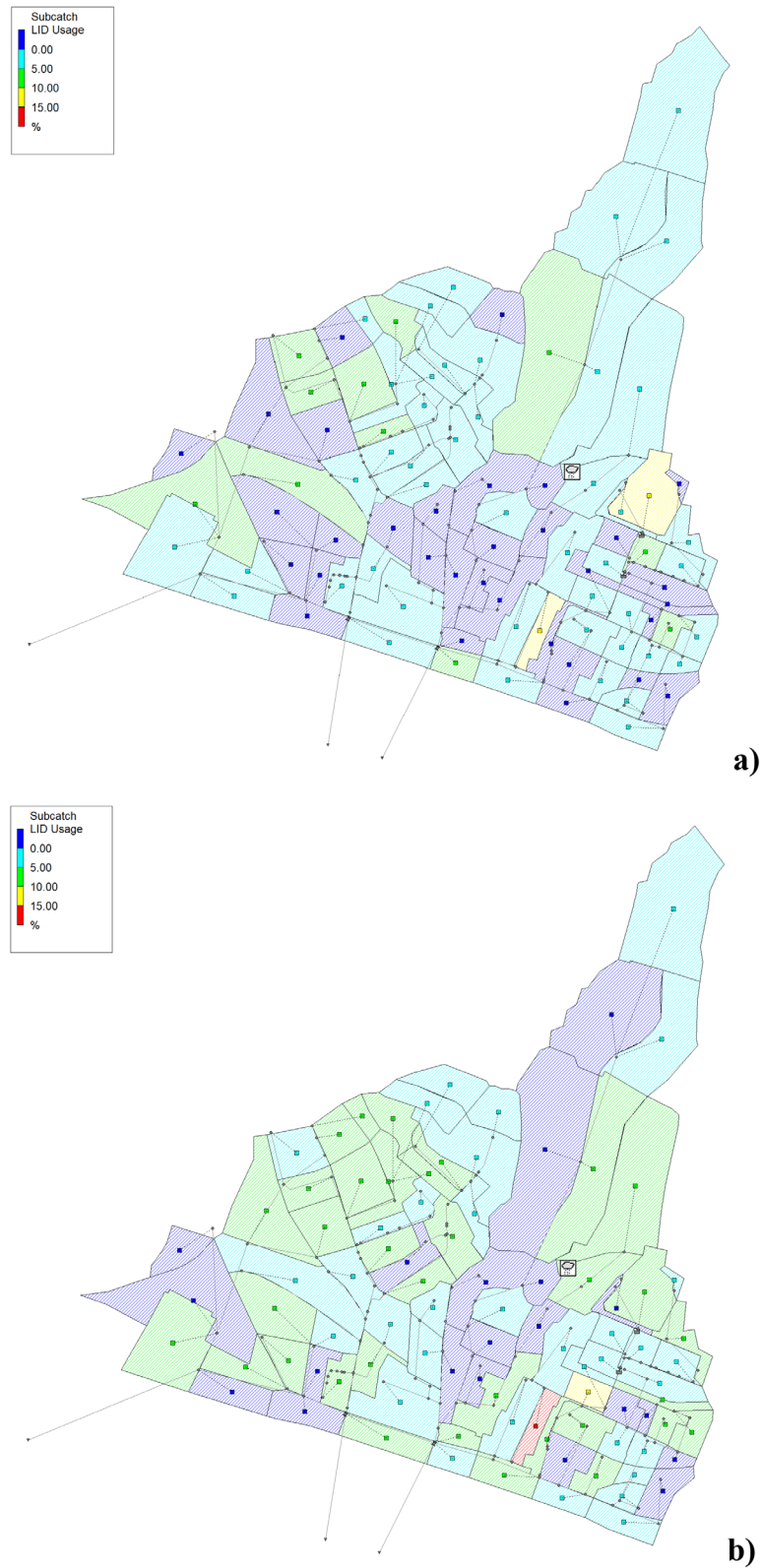


FIGURE 7 | (a) Optimal solution 1 with cost, flooding volume and community's satisfaction equal to 3.70 M€, $1.15 \times 10^3 \text{ m}^3$ and 0.38, respectively; (b) optimal solution 2 with cost, flooding volume and community's satisfaction equal to 3.68 M€, $3.96 \times 10^3 \text{ m}^3$ and 0.96, respectively. Optimal solutions refer to the 10-year return period rainfall event.

solutions featuring satisfaction values from about 0.4 to about 1, the other cost groups mainly include solutions with higher satisfaction values, ranging from about 0.65 to about 1. This is because the higher the number of LID practices installed, the

higher the chance of having LID practices complying with the community's preferences. In all cost groups, the lowest outliers represent the bi-objective optimization solutions, corresponding to the darker dots in Figure 5b.

TABLE 5 | Number of installations for each kind of LID for solutions 1 and 2 shown in Figure 7.

Solution	Soakaway	Bioretention cell	Swale	Extensive green roof	Intensive green roof	Cistern	Pervious pavement
1	0	0	0	0	12	46	0
2	0	7	21	37	4	1	0

The decision maker may choose the ultimate solution from the three dimensional Pareto front by using some additional criteria, such as those related to available budget and/or to required performance in terms of pluvial flooding attenuation and community's satisfaction. As an example, under constraints of a maximum budget of about 4M€, Solutions 1 and 2 in Figure 5b can be selected. While featuring a very similar value of the cost (3.70M€ vs. 3.68M€), the first is better in terms of pluvial flooding volume ($1.15 \times 10^3 \text{ m}^3$) and worse in terms of the community's satisfaction (0.38). The second is instead worse in terms of pluvial flooding volume ($3.96 \times 10^3 \text{ m}^3$) and better in terms of the community's satisfaction (0.96). Whereas the two solutions have a similar LID usage (see Figure 7) with most sub-catchments featuring a LID conversion rate between 0% and 10%, the kinds of LIDs installed is quite different (see Table 5). Solution 1 (higher performance in pluvial flooding mitigation) is primarily characterized by the implementation of cisterns and intensive green roofs. Cisterns, in particular, constitute a cost-effective engineering measure that enables the hydraulic disconnection of impervious surfaces—although limited to rooftops—from the conventional drainage system, due to their storage capacity. To pursue a better satisfaction rate in compliance with the community's preferences (Table 3) and with the preference weights (Table 4), Solution 2 features a much lower adoption of cisterns and the adoption of extensive green roofs, bioretention cells and swales. Solution 2 (lower performance in pluvial flooding mitigation) includes mainly swales, which are the most cost-effective engineering solution among the LIDs that promote exfiltration processes (such as soakaways, bioretention cells, swales, and pervious pavements).

An additional evaluation criterion may be the pluvial flooding estimation in the 5-year return period scenario. This variable is equal to $0.40 \times 10^3 \text{ m}^3$ and $1.42 \times 10^3 \text{ m}^3$ for Solutions 1 and 2, respectively, both attesting to significant improvements compared to the no LID scenario ($3.2 \times 10^3 \text{ m}^3$).

As an additional example, under constraints of a maximum budget of about 15M€, Solutions 3 and 4 in Figure 5b can be selected. While featuring a very similar value of the cost (15.47M€ vs. 15.42M€), the first is better in terms of pluvial flooding volume ($0.21 \times 10^3 \text{ m}^3$) and worse in terms of the community's satisfaction (0.70). The second is instead worse in terms of pluvial flooding volume ($1.45 \times 10^3 \text{ m}^3$) and better in terms of the community's satisfaction (0.99). Whereas the two solutions have a similar LID usage (see Figure 8) with most sub-catchments featuring a LID conversion rate between 5% and 10%, the kinds of LIDs installed are quite different (see Table 6). In fact, the comparison of the composition of the two solutions reveals that Solution 3 features installation of almost all kinds of LIDs, including soakaways (25 installations) and cisterns (1 installation). Solution 3 represents almost the best performance in pluvial

flooding mitigation (revealing flooding volume of $0.21 \times 10^3 \text{ m}^3$) achievable with LID installations (without interventions on the network of underground channels). The flooding mitigation is mainly obtained through the installation of LIDs that promote exfiltration processes. In Solution 4, the number of installations for soakaways and cisterns goes down to 0, to better match the community's preferences (Table 3) and the preference weights (Table 4). Indeed, solution 4 features an exclusive presence of LIDs appreciated by the community, namely bioretention cells, swales, and green roofs. Solutions 3 and 4 are both capable of almost eliminating the flooding, leading the pluvial flooding volume in the 5-year return period scenario to $0.04 \times 10^3 \text{ m}^3$ and $0.28 \times 10^3 \text{ m}^3$, respectively.

Interestingly, pervious pavements are absent in all four solutions described above in detail, though they are the most appreciated kind of LIDs by the community (see Tables 2 and 3). This is because the methodology developed in this work considers both the community's preferences and the flood attenuation performance, which proved to be low for this kind of LIDs due to the limited stratigraphy depth.

Table S4 confirms the flooding attenuation performance of solutions 1–4, taking as benchmark the current urban drainage system with no LIDs for the event on 24 September 2022. The ranking of the four solutions in terms of flooding is the same as that observed for the Chicago hyetograph with 5 and 10 year return periods. As was expected based on the estimated return period of the event on 24 September 2022, the flooding volumes for this event are slightly smaller than those obtained with the Chicago hyetograph of 5 year return period. This is consistent with the tendency of the Chicago hyetograph to overestimate rainfall volumes while properly describing peak rainfall intensities.

4 | Conclusions

In this paper, a novel methodology was proposed to design LID practices for flood mitigation in urban areas. This methodology encompasses various elements, including participatory mapping to detect the community's preferences for kinds of LIDs, physically-based modeling of UDS and LIDs and multi-objective optimization with three objective functions, namely cost, pluvial flooding volume and the community's satisfaction about the kinds of LIDs installed in the catchment.

The main outcomes of this work are:

- The methodology proved successful at considering the community's appreciation inside the optimization framework.

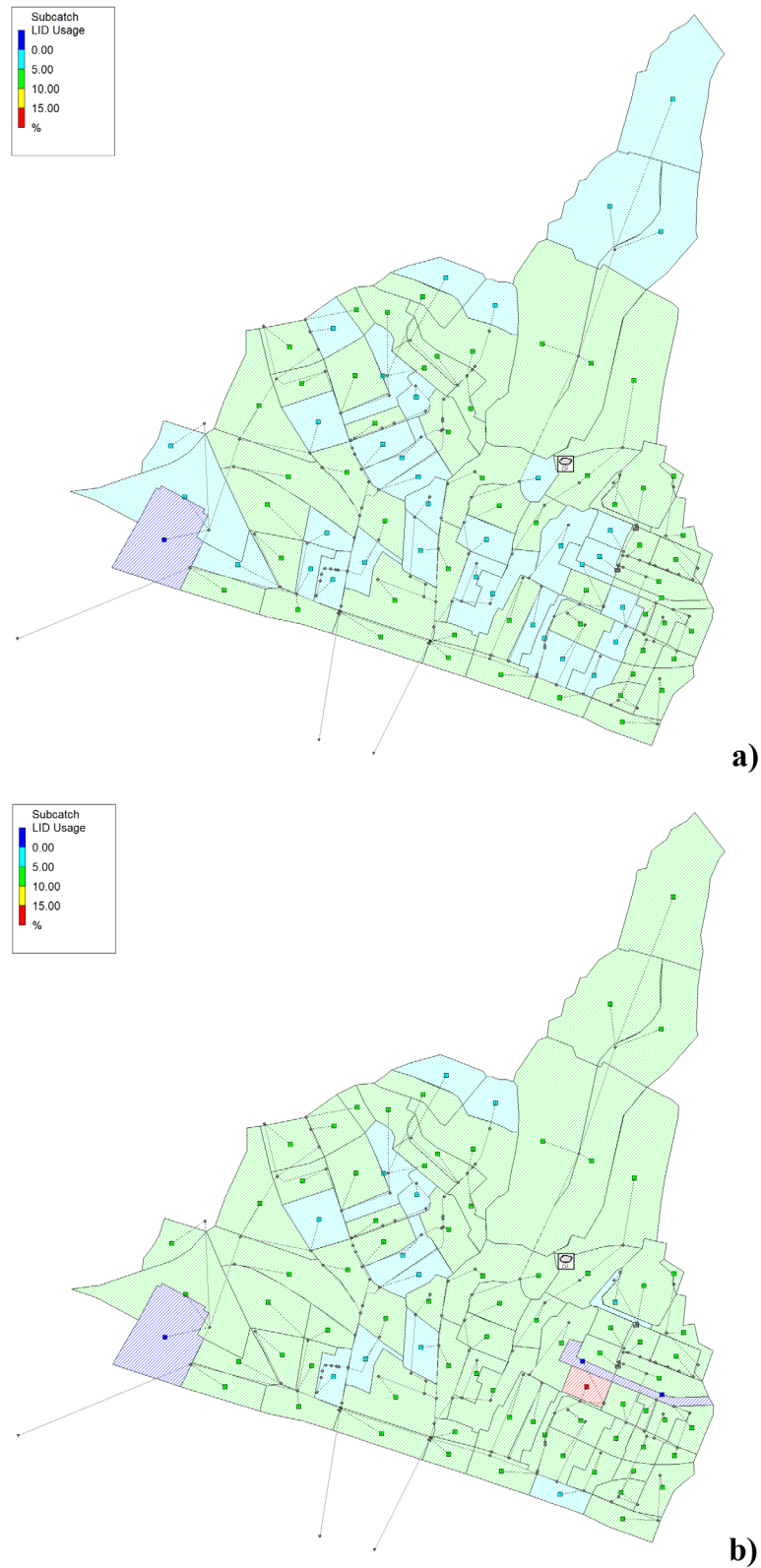


FIGURE 8 | (a) Optimal solution 3 with cost, flooding volume and community’s satisfaction equal to 15.47 M€, $0.21 \times 10^3 \text{ m}^3$ and 0.70, respectively; (b) optimal solution 4 with cost, flooding volume and community’s satisfaction equal to 15.42 M€, $1.45 \times 10^3 \text{ m}^3$ and 0.99, respectively. Optimal solutions refer to the 10-year return period rainfall event.

– At increasing costs, the methodology provided solutions with increasing levels of joint performance in the trade-off between flood attenuation and the community’s satisfaction.

– The solutions yielded by the methodology can be evaluated considering budget constraints and performance targets, or post-processed in other scenarios than that considered

TABLE 6 | Number of installations for each kind of LID for solutions 3 and 4 shown in Figure 8.

Solution	Soakaway	Bioretention cell	Swale	Extensive green roof	Intensive green roof	Cistern	Pervious pavement
3	25	42	17	4	0	1	0
4	0	26	48	12	1	0	0

in the design, to help stakeholders in selecting the ultimate solution to implement in the field.

Overall, the paper showed the importance of elevating the community's role from a passive stakeholder to an active driver of design decisions. By quantifying the community's preferences through participatory mapping and integrating them directly into the mathematical optimization of LID practices, a balance was achieved in infrastructure planning between engineering performance, financial feasibility, and social legitimacy. The adoption of community's appreciation as an optimization dimension is both innovative and impactful and provides a replicable model for cities worldwide seeking to design water-sensitive infrastructures that not only function effectively but also earn public trust and long-term acceptance.

Whereas the methodology developed in this paper considers only installation of LIDs, future research endeavours will be dedicated to the simultaneous optimization of LIDs on sub-catchments and interventions on the network of underground channels, as well as the application of real time control to increase the operational effectiveness of LIDs. Other developments will concern:

- Expansion of objective functions to include other sources of cost, such as the maintenance cost.
- Upgrade of the methodology to include other kinds of constraints, such as the siting constraints
- Integration of the optimization methodology accounting for the community's satisfaction for LIDs with the phasing-of-construction approach presented by Creaco et al. (2025) in climate change scenarios.

Acknowledgments

This work was funded by the Italian Ministry for Research within the national project "PRIN 2020 – URCA!". Support from Italian MIUR and University of Pavia is acknowledged within the program Dipartimenti di Eccellenza 2023–2027.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Bista, A., K. A. H. Paus, and I. Seifert-Dahnn. 2025. "Multi-Objective Optimization of Nature-Based Solutions in Urban Stormwater

Management: A Scoping Review." *Environmental Modelling and Software* 194: 106659. <https://doi.org/10.1016/j.envsoft.2025.106659>.

Boyu, F., Y. Zhang, and R. Bourke. 2021. "Urbanization Impacts on Flood Risks Based on Urban Growth Data and Coupled Flood Models." *Natural Hazards* 106: 613–627. <https://doi.org/10.1007/s11069-020-04480-0>.

Brown, G., S. Sanders, and P. Reed. 2018. "Using Public Participatory Mapping to Inform General Land Use Planning and Zoning." *Landscape and Urban Planning* 177: 64–74. <https://doi.org/10.1016/j.landurbplan.2018.04.011>.

Campisano, A., E. Creaco, and C. Modica. 2016. "Application of Real-Time Control Techniques to Reduce Water Volume Discharges From Quality-Oriented CSO Devices." *Journal of Environmental Engineering* 142, no. 1: 04015049. [https://doi.org/10.1061/\(ASCE\)EE.1943-7870.000101](https://doi.org/10.1061/(ASCE)EE.1943-7870.000101).

Chow, V. T., D. R. Maidment, and L. W. Mays. 1988. *Applied Hydrology*. McGraw Hill.

Creaco, E., A. Dada, G. Grossi, and S. Todeschini. 2025. "Phasing LID Implementation for Flood Mitigation in Urban Drainage Systems Considering Climate Change Scenarios and Using Genetic Algorithms." *Journal of Water Resources Planning and Management* 151, no. 8: 04025026-1–04025026-10. <https://doi.org/10.1061/JWRMD5.WRENG-6741>.

Creaco, E., M. Franchini, and E. Todini. 2016. "The Combined Use of Resilience and Loop Diameter Uniformity as a Good Indirect Measure of Network Reliability." *Urban Water Journal* 13, no. 2: 167–181. <https://doi.org/10.1080/1573062X.2014.949799>.

Cunha, M. C., J. A. Zeferino, N. E. Simões, and J. G. Saldarriaga. 2016. "Optimal Location and Sizing of Storage Units in a Drainage System." *Environmental Modelling & Software* 83: 155–166. <https://doi.org/10.1016/j.envsoft.2016.05.015>.

De Paola, F., M. Giugni, F. Pugliese, and P. Romano. 2018. "Optimal Design of LIDs in Urban Stormwater Systems Using a Harmony-Search Decision Support System." *Water Resources Management* 32: 4933–4951. <https://doi.org/10.1007/s11269-018-2064-8>.

Diogo, A. F., L. T. Barros, J. Santos, and J. S. Temido. 2018. "An Effective and Comprehensive Model for Optimal Rehabilitation of Separate Sanitary Sewer Systems." *Science of the Total Environment* 612: 1042–1057. <https://doi.org/10.1016/j.scitotenv.2017.08.315>.

Diogo, A. F., and J. A. do Carmo. 2019. "Peak Flows and Stormwater Networks Design—Current and Future Management of Urban Surface Watersheds." *Water* 11, no. 4: 759. <https://doi.org/10.3390/w11040759>.

Duan, H.-F., F. Li, and H. Yan. 2016. "Multi-Objective Optimal Design of Detention Tanks in the Urban Stormwater Drainage System: LID Implementation and Analysis." *Water Resources Management* 30: 4635–4648. <https://doi.org/10.1007/s11269-016-1444-1>.

E.C., European Commission, Directorate-General for Research and Innovation. 2023. *Guidelines for Co-Creation and Co-Governance of Nature-Based Solutions: Insights From EU-Funded Projects*, edited by I. Ferreira, G. Lupp, and I. Mahmoud, 1–98. Publications Office of the European Union. <https://data.europa.eu/doi/10.2777/157060>.

Galuppini, G., C. Quintilliani, M. Arosio, et al. 2020. "A Unified Framework for the Assessment of Multiple Source Urban Flash Flood

- Hazard: The Case Study of Monza, Italy.” *Urban Water Journal* 17, no. 1: 65–77. <https://doi.org/10.1080/1573062X.2020.1734950>.
- Ghods, S. H., Z. Zahmatkesh, E. Goharian, R. Kerachian, and Z. Zhu. 2020. “Optimal Design of Low Impact Development Practices in Response to Climate Change.” *Journal of Hydrology* 580: 124266. <https://doi.org/10.1016/j.jhydrol.2019.124266>.
- Gnecco, I., A. Palla, P. La Barbera, G. Roth, and F. Giannoni. 2023. “Defining Intensity–Duration–Frequency Curves at Short Durations: A Methodological Framework.” *Hydrological Sciences Journal* 68, no. 11: 1499–1512. <https://doi.org/10.1080/02626667.2023.2224002>.
- Gnecco, I., F. Pirlone, I. Spadaro, et al. 2024. “Participatory Mapping for Enhancing Flood Risk Resilient and Sustainable Urban Drainage: A Collaborative Approach for the Genoa Case Study.” *Sustainability* 16, no. 5: 1936. <https://doi.org/10.3390/su16051936>.
- Goldberg, D. E. 1989. *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley Publishing Company, Inc.
- Kabisch, N., N. Frantzeskaki, and R. Hansen. 2022. “Principles for Urban Nature-Based Solutions.” *Ambio* 51: 1388–1401. <https://doi.org/10.1007/s13280-021-01685-w>.
- Langemeyer, J., and J. J. T. Connolly. 2020. “Weaving Notions of Justice Into Urban Ecosystem Services Research and Practice.” *Environmental Science & Policy* 109: 1–14. <https://doi.org/10.1016/j.envsci.2020.03.021>.
- Li, J., and S. J. Burian. 2023. “Evaluating Real-Time Control of Stormwater Drainage Network and Green Stormwater Infrastructure for Enhancing Flooding Resilience Under Future Rainfall Projections.” *Resources, Conservation and Recycling* 198: 107123. <https://doi.org/10.1016/j.resconrec.2023.107123>.
- Ma, M., B. He, J. Wan, et al. 2018. “Characterizing the Flash Flooding Risks From 2011 to 2016 Over China.” *Water* 10: 704. <https://doi.org/10.3390/w10060704>.
- Mailhot, A., and S. Duchesne. 2010. “Design Criteria of Urban Drainage Infrastructures Under Climate Change.” *Journal of Water Resources Planning and Management* 136: 201–208. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000023](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000023).
- Marchioni, M., F. Raimondi, G. Becciu, and C. Dresti. 2025. “Nature-Based Solutions for Watershed Management: An Investigation on Water-Related Ecosystem Services Delivery at Multiple Spatial Scales.” *Ecosystem Services* 73: 101718. <https://doi.org/10.1016/j.ecoser.2025.101718>.
- Mora-Melià, D., C. López-Aburto, P. Ballesteros-Pérez, and P. Muñoz-Velasco. 2018. “Viability of Green Roofs as a Flood Mitigation Element in the Central Region of Chile.” *Sustainability* 10: 1130. <https://doi.org/10.3390/su10041130>.
- Ngamaliu-Nengoue, U., P. Iglesias-Rey, F. Martínez-Solano, D. Mora-Melià, and J. Saldarriaga Valderrama. 2019. “Urban Drainage Network Rehabilitation Considering Storm Tank Installation and Pipe Substitution.” *Water* 11: 515. <https://doi.org/10.3390/w11030515>.
- Ngamaliu-Nengoue, U., F. Martínez-Solano, P. Iglesias-Rey, and D. Mora-Melià. 2019. “Multi-Objective Optimization for Urban Drainage or Sewer Networks Rehabilitation Through Pipes Substitution and Storage Tanks Installation.” *Water* 11: 935. <https://doi.org/10.3390/w11050935>.
- Oberascher, M., F. Funke, R. Satish, et al. 2024. “Combat of Retrofitting Urban Drainage Networks With Nature-Based Solutions.” In *Proc., 13th Urban Drainage Modelling Conference (UDM)*. <https://www.uibk.ac.at/en/congress/udm2025/program/udm-nbs-combat/>.
- Palla, A., M. Pezzagno, I. Spadaro, and R. Ermini. 2024. “Participatory Approach to Planning Urban Resilience to Climate Change: Brescia, Genoa, and Matera—Three Case Studies From Italy Compared.” *Sustainability* 16, no. 5: 2170. <https://doi.org/10.3390/su16052170>.
- Rall, E., R. Hansen, and S. Pauleit. 2019. “The Added Value of Public Participation GIS (PPGIS) for Urban Green Infrastructure Planning.” *Urban Forestry & Urban Greening* 40: 264–274. <https://doi.org/10.1016/j.ufug.2018.06.016>.
- Remme, R. P., M. Meacham, K. E. Pellowe, et al. 2024. “Aligning Nature-Based Solutions With Ecosystem Services in the Urban Century.” *Ecosystem Services* 66: 101610. <https://doi.org/10.1016/j.ecoser.2024.101610>.
- Reyna, S. M., J. A. Vanegas, and A. H. Khan. 1994. “Construction Technologies for Sewer Rehabilitation.” *Journal of Construction Engineering and Management* 120: 467–487. [https://doi.org/10.1061/\(ASCE\)0733-9364\(1994\)120:3\(467\)](https://doi.org/10.1061/(ASCE)0733-9364(1994)120:3(467)).
- Rossman, L. A. 2015. *Storm Water Management Model User's Manual Version 5.1*. EPA/600/R-14/413b Revised September 2015. EPA. https://www.epa.gov/sites/default/files/2019-02/documents/epaswmm5_1_manual_master_8-2-15.pdf.
- Sebti, A., M. Fuamba, and S. Bennis. 2015. “Optimization Model for BMP Selection and Placement in a Combined Sewer.” *Journal of Water Resources Planning and Management* 142: 04015068. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000620](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000620).
- Soil Conservation Service. 1972. *National Engineering Handbook, Section 4, Hydrology*. U. S. Dept. of Agriculture, U. S. Government Printing Office.
- Stork, S., B. Pölling, W. Lorleberg, R. Morgenstern, and J. H. Feil. 2023. “Clustering Business Models of Heterogeneous Nature-Based Solutions Implementing Innovative Governance and Financing Concepts.” *Land* 12: 2116. <https://doi.org/10.3390/land12122116>.
- Tameh, S. N., I. Gnecco, and A. Palla. 2024. “Analytic Hierarchy Process in Selecting Bioretention Cells in Urban Residential Settlement: Analysing Hydrologic and Hydraulic Metrics for Sustainable Stormwater Management.” *Journal of Environmental Management* 371: 123142. <https://doi.org/10.1016/j.jenvman.2024.123142>.
- Ugarelli, R., and V. Di Federico. 2010. “Optimal Scheduling of Replacement and Rehabilitation in Wastewater Pipeline Networks.” *Journal of Water Resources Planning and Management* 136: 348–356. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000038](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000038).
- Watkins, S., and A. Collins. 2025. “From Community Engagement to Community Inclusion for Socially and Procedurally Just Flood Risk Governance.” *Journal of Flood Risk Management* 18, no. 1: e13042. <https://doi.org/10.1111/jfr3.13042>.
- Zahmatkesh, Z., S. J. Burian, M. Karamouz, H. Tavakol-Davani, and E. Goharian. 2015. “Low-Impact Development Practices to Mitigate Climate Change Effects on Urban Stormwater Runoff: Case Study of New York City.” *Journal of Irrigation and Drainage Engineering* 141: 04014043. [https://doi.org/10.1061/\(ASCE\)IR.1943-4774.0000770](https://doi.org/10.1061/(ASCE)IR.1943-4774.0000770).

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Data S1:** Supporting Information.