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Optimal Location of Best Management Practices for Flood Mitigation in Urban Drainage Systems †

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Abstract: The present work presents a bi-objective optimization methodology, which is aimed at simultaneously minimizing the total installation costs of management systems as well as urban flooding, as a tool to be conveniently adopted as part of a decision support system to help identify the optimal location of best management practices (BMPs). For each sub-catchment present in an urban drainage system, the decision variables include the rate of impervious areas to be used for BMP installation. The performance of the urban drainage system following optimal BMP installation is tested against climate change scenarios obtained from a real case study conducted in the industrial area of Brescia; the numerical model of this study can be obtained via the EPASWMM software.

Keywords: urban drainage; flooding; overflows; resilience; BMPs; climate change

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1. Introduction

As described in the latest European Environment Agency (EEA) report on urban adaptation to climate change [1], the occurrence of extreme weather events (heatwaves, heavy precipitation, flooding, and droughts) is expected to increase in the future as a result of climate change, potentially having severe impacts in the urban context in terms of flooding and water body pollution due to overflows from combined sewer overflow devices. Nature-based solutions and best management practices (BMPs) are well known, effective, and inexpensive adaptation actions that can be implemented to mitigate these unpleasant effects and, therefore, to increase urban resilience [2]. Therefore, decision support systems are required to guide the installation of these solutions within specific territories, and specifically to identify their optimal locations that will maximize the flood mitigation effects with equal costs.

The present paper aims to analyze the extent to which the installation of BMPs can help to mitigate flooding in a real urban drainage system, while considering the effects of climate change. The following sections present the methodology adopted and the applications, namely a description of the case study and the results, followed by a discussion of the main outcomes and outlooks.

2. Methodology

The methodology proposed in this paper consists of three elements, i.e., hyetograph construction, urban drainage modeling, and optimization, which are described in the three following subsections.

2.1. Hyetograph Construction

Rainfall data recorded at fine temporal resolution over a long time horizon are used for hyetograph construction. These data are modified to account for climate change by using a novel approach based on a comparison of monthly rainfall depths at the beginning of the twenty-first century with those derived from regional climate models for 2050 to 2060, considering the three canonical growth factors for greenhouse gas emissions, i.e., Representative Concentration Pathway (RCP) 2.6, RCP 4.5, and RCP 8.5. The fine-resolution rainfall depth pattern at the beginning of our century can then be rescaled based on the ratio of the future to current monthly rainfall depth pattern.

Then, the future yearly maxima of rainfall depth at various durations can be obtained and processed by using the approach presented by Creaco [3] to derive the intensity–duration–frequency curve framework according to the adjusted scale invariance based on the following equations:

$$i_t(P) = a_1(1 + V\,K_P)(t + c)^n, \quad (1)$$

in which i_t is the average rainfall intensity as a function of event duration t and probability of non-exceedance P, which is related to the return period T according to relationship $P = 1 - 1/T$; a_1, V and n are the parameters to be estimated, as shown in [3]. Finally, K_P is the frequency factor that can be expressed with the GEV distribution [4]:

$$K_P = \mu + \sigma\{[-\ln(P)]^{-\xi} - 1\}/\xi \text{ for } \xi \neq 0 \quad (2)$$

$$K_P = \mu - \sigma \ln[-\ln(P)] \text{ for } \xi = 0$$

where μ, σ and ξ are the three parameters of the GEV distribution.

After obtaining the IDF curve associated with the desired return period T, the event duration t must be set. Then, the Chicago hyetograph [5] associated with return period T and event duration t is constructed.

2.2. Urban Drainage Modeling

The urban drainage modeling of EPASWMM [6] is considered. In this software, external sub-catchments receive water from the atmosphere according to the rainfall intensity pattern specified in a gauge element. Following gross/net rainfall transformation, each sub-catchment is modeled hydrologically like a nonlinear reservoir for rainfall/runoff transformation and discharges water into the underground network in correspondence to a junction. The underground network is made up of junctions and links and is modeled with the physically based De Saint Venant equations. BMPs can be installed on external sub-catchments to attenuate runoff upstream the underground network.

In order to dynamically manage the network features and inputs, the MAT-SWMM toolbox is used [7].

2.3. Optimization

A multi-objective optimization is set up to simultaneously minimize the total investment cost and flooding volume.

The ultimate Pareto front of optimal solutions in the trade-off between the two objective functions is obtained by applying a bi-objective genetic algorithm constructed using the Matlab® 2023b [8] optimization toolbox, which can be efficiently connected to MAT-SWMM.

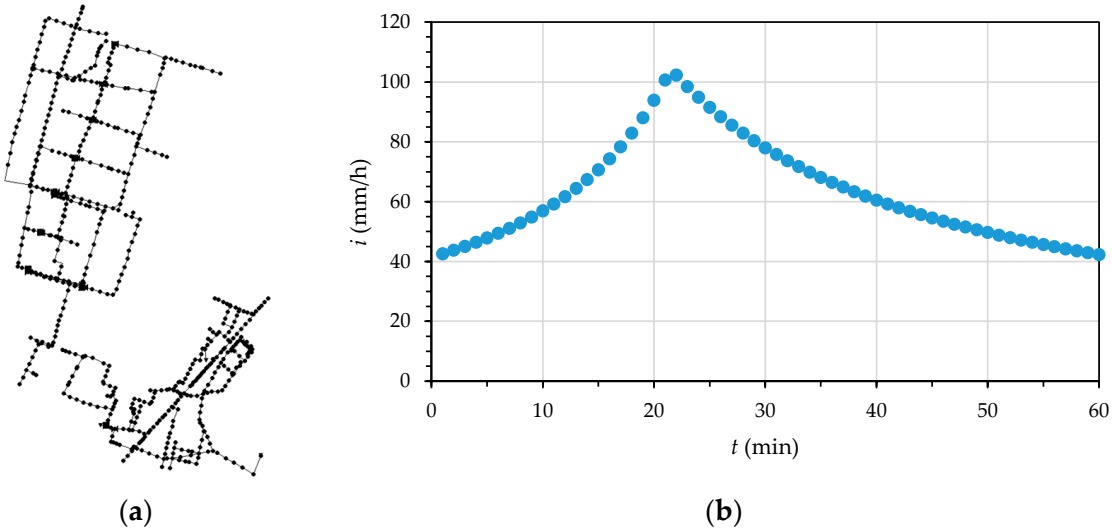
The decision variables are as numerous as the sub-catchments in the urban drainage system and concern the percentage rate of conversion of impervious areas into BMPs.

3. Applications

3.1. Case Study

The case study considered in this work is a part of the urban drainage system of the city of Brescia, shown in Figure 1a. This system serves a mainly industrial area of about 218 ha and includes 605 sub-catchments; 680 nodes, namely 659 junctions, 20 outfalls, and

1 storage areas; and 676 links, namely 641 conduits, 34 orifices, and 1 pump. This area is plagued by frequent and large-scale flooding.



(**a**) (**b**)

Figure 1. Case study network (**a**) and Chicago hyetograph (**b**) used in EPASWMM.

3.2. Results

The application of the methodology described in Section 2.1 to the city of Brescia results in the parameterization of the IDF framework of Equations (1) and (2), as shown in Table 1 for the three RCP scenarios. Then, the adoption of the intermediate RCP4.5 scenario, return period T = 10 years, and rainfall duration t = 1 h results in the Chicago hyetograph shown in Figure 1b.

Table 1. Parameters of the IDF framework described by means of Equations (1) and (2).

Climate Scenario	a_1	n	V	ξ	σ	μ	c
RCP 2.6	43.44	−0.90	0.48	0.006	0.773	−0.451	0.568
RCP 4.5	39.38	−0.90	0.46	0.023	0.755	−0.454	0.568
RCP 8.5	35.55	−0.90	0.49	0.000	0.780	−0.450	0.567

Finally, the optimization methodology described in Section 2.3 was applied to the hydrological modeling described in Section 2.2, considering a maximum conversion rate of pervious areas to BMPs of 10%. The infiltration trench was selected as the type of BMP to implement in the case study area. The results in terms of the Pareto front in the trade-off between cost and flooding volume are shown in Figure 2.

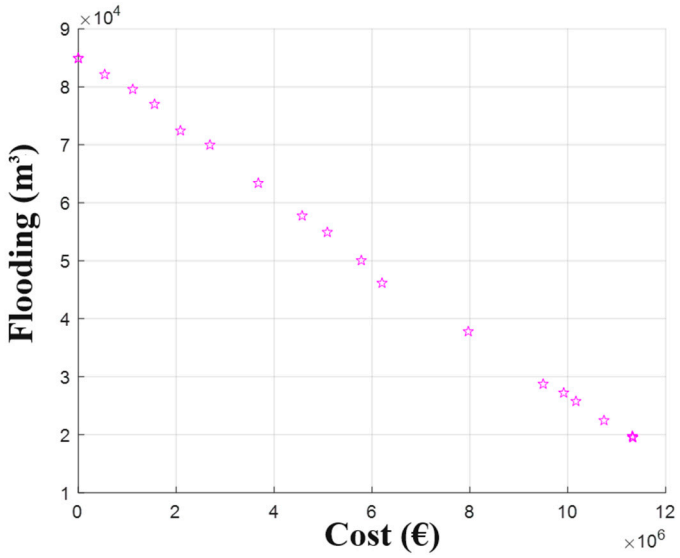


Figure 2. Pareto front of optimal solutions in the trade-off between costs and flooding volume.

4. Discussion

The methodology developed in this work can effectively and efficiently model the effects of climate change on real urban drainage systems, as well as the mitigation effects played by BMPs. The high potential of BMP interventions was highlighted, yielding flooding attenuation benefits up to 75%. Future work will focus on improving the calibration of the EPASWMM model based on measurements made available by the water utility and flooding observations by stakeholders according to the bottom–up approach, as well as the optimal sequencing of the interventions, as was tackled in [9] for distribution systems.

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Conflicts of Interest: The authors declare no conflicts of interest.

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