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A decision support system for urban stormwater drainage management

F. De Paola*, M. Giugni, F. Pugliese and P. Romano
Department of Civil, Architectural and Environmental Engineering. University of Naples Federico II, Naples, Italy
* *e-mail: depaola@unina.it*

Abstract: In the last decades, urban pluvial floods are occurring with increasing frequency all over the world, including developed countries (e.g. Italy) due to factors mainly referable to Climate and Land Use Changes (coupled with urbanization and increasing population). Urbanization is typically accompanied by increases in impervious surfaces, compaction of soils, and modifications to vegetation. This results in increased surface runoff, increased runoff velocity and stream erosion, decreased time of concentration of watersheds, and decreased water quality, due to water contamination from suspended sediments, heavy metals, hydrocarbons, nutrients, and pathogens. In the context of Urban Water Management, a useful role can be represented by innovative approaches, implementing optimization techniques and new technologies for Low Impact Development (LID) type of stormwater Best Management Practices (BMPs) for urban runoff control. The main goal of these strategies should be the improvement of the resilience of the cities against the increase of the storm water flows and the risk of flooding (urban flash floods). In this paper a Decision Support System for the identification of the best strategy for adapting to climate and land use changes is presented. This System allows to identify the most useful BMPs, among the usual ones in the technical literature (i.e. detention ponds, infiltration trenches, pervious pavement, green roofs, etc.). In particular the System interfaces a simulation model (SWMM5.1) with an optimization module (Harmony Search) able to identify the best combination of BMPs to adequately reduce flood peak discharges and volumes.

Key words: Best Management Practices, Low Impact Development, SWMM 5.1, Harmony Search, Urban Drainage Systems, Optimization Algorithms

1. INTRODUCTION

During the last decades, urban floods events have increased in frequency and intensity, as a consequence of the ongoing Climate and Land Use changes. Mitigation and adaptation to the in-development forcing are intended as one of the most pressing and, at the same, difficult challenges to deal into the field of the urban drainage system management, especially for developing countries, where the uncontrolled and indiscriminate expansion of both the urban centres and the related socio-economical activities is evolving.

Recent studies pointed out how the excessive runoff, caused by the significant increments of impervious surfaces (such as building roofs, parking area, roads), is causing uncontrolled flooding in urban areas, increasing the deterioration of water quality in receiving water bodies (Khan et al., 2006; Dietz, 2007). However, the urbanization represents an in-progress phenomenon with global interest in many countries, predicting to reach in 2050 percentages of 80% and 75% of areas having levels of urbanization greater than 50% and 75%, respectively (DESA, 2015). Among these countries, China represents one of the most pregnant examples, with an urbanization rate, intended as the ratio between the population living in urban areas and the overall population, increasing from 12.5% in 1952 up to 60%, predicted in 2020 (Wei, 2012). This trend is strongly impacting on the natural ecosystems, predicting more severe future configurations (Du et al., 2012; Hager et al., 2013). Stormwater drainage management is undergoing significant changes, moving from operative approaches mainly based upon flood mitigation and health protection to others strongly addressed to environmental, social and economical considerations (Fletcher et al., 2015). Specifically, one of the most interesting challenge for engineering research regards the definition of innovative environmental criteria to limit and face the detrimental impacts of urbanization. Among them, the application of LID-BMPs (Low Impact Development-Best Management Practices) technologies to control and manage the stormwater runoff quality and quantity (Davis, 2005; Field et al., 2006) represents a recognized environmental technique for measurement, control and management of quali-quantitative stormwater runoff in a cost-effective manner (US EPA, 2004). To this category, bioretention cells, porous pavements, green roofs, vegetative swales, rooftop gardens and infiltration trenches are included, having different removal efficiencies, costs, environmental impacts and disposal capacities.

Due to the recent application, and still yet not complete knowledge about the performances of various technologies in urban areas, with unavoidable uncertainties in their uses (Li et al., 2013), the definition of LID-BMPs effectiveness and suitability results a complex but unavoidable step in the field of the urban runoff control planning. Furthermore, the planning process related to the application of LID-BMPs techniques is strictly correlated to urban master planning, land use, landscape, drainage system and water pollution planning, for the selection of the most appropriate practices, able to accomplish the required development goals and objectives, in compliance with the socio-economical constraints, guaranteeing, at the same time, the effectiveness of costs, sizing and placement selection (Cheng et al., 2009; Jia et al., 2012; Barbosa et al., 2012). In this field, several urban runoff simulation and optimization tools (Elliot and Trowsdale, 2007), such as SUSTAIN (System Urban Stormwater Treatment and INtegration), were implemented to perform analyses on LID-BMPs applications (US EPA, 2009; Lee et al., 2012; Fletcher et al., 2013; Mao et al. 2016), aiming to identify a suitable combination of LID-BMPs techniques in urban areas, as a function of the available cost resources.

To this aim, in the present paper the implementation of a Decision Support System (DSS) to LID design for urban stormwater drainage development was analyzed and discussed. An interface between the Harmony Search meta-heuristic algorithm (Geem et al., 2001) and the EPA SWMM 5.1 solver was implemented for optimal design of LID-BMPs practices.

The Harmony Search was widely applied in the field of hydraulic engineering both for optimization of water supply systems (Geem et al., 2002; Geem, 2006; De Paola et al., 2016a) and urban drainage systems (De Paola et al., 2015, 2016b), resulting strongly competitive for searching for optimal solutions in short computational times (De Paola et al., 2016c).

2. A DECISION SUPPORT SYSTEM MODEL TO DESIGN LID-BMPS IN STORMWATER DRAINAGE SYSTEMS: THE CASE-STUDY OF FUORIGROTTA (NA)

This work was devoted to the definition of benefits connected to the application of LID-BMPs practices in stormwater drainage systems to manage and control the urban flow, aiming at both decreasing the total volume of rainfall water drained into urban stormwater systems and reducing the urban flooding risk.

Case-study in question regarded a sub-area located in the Fuorigrotta district in Naples (IT), bounded by exploiting the natural limits, set by both buildings and natural orographic configuration. The boundary limit is constituted by Via Terracina in the northern side, by Posillipo Hill in the est and south sides and by the Mostra d'Oltremare building in the west side. The investigated study area was equal to 1.89 km^2 with perimeter of 6975 m.

2.1 Urban-operational analysis by using a GIS software

Territorial analyses were performed by using the UTM WGS84 33N multi-precision topographic geo-database, available from the Campania Region Authority, in reference to year 2004. To update the actual urban territorial configuration, specific analyses were performed, in reference to the considered area, analysing the land use, its intended use, the pervious and impervious surface partition, the urban traffic density and the location of urban areas, potentially reliable to be converted into LID-BMP practices. A GIS model was applied to define the properties of each point of interest, combined with a Digital Terrain Model (DTM), made available from the Campania Region Authority.

2.2 The urban stormwater system of Fuorigrotta (NA) basin. Modelling in SWMM 5.1

The urban stormwater system of the Fuorigrotta (NA) basin was built in 1950, undergoing to multiple integrations during the following years. The main sewer was composed of the Arena Sant'Antonio sewer to convey the rainwater, whereas the Cuma outflowing stream collects the wastewaters.

As a result of the study about the operation of the sewer system, two hydrographic basins were defined, named *North Basin* and *South Basin*, respectively (Fig. 1). The sewers, which compose the *North Basin*, totally flow into the Arena Sant'Antonio main sewer, whereas the main sewer in Via Diocleziano conveys all the water volumes coming from the *South Basin*. This configuration is exclusively referred to the rainfall volumes, because the wastewaters are conveyed into the Cuma main sewer. The model in SWMM 5.1 consisted of a significant simplification, which brought to model the solely main sewers, located downstream the two abovementioned basins and connected through a final node.

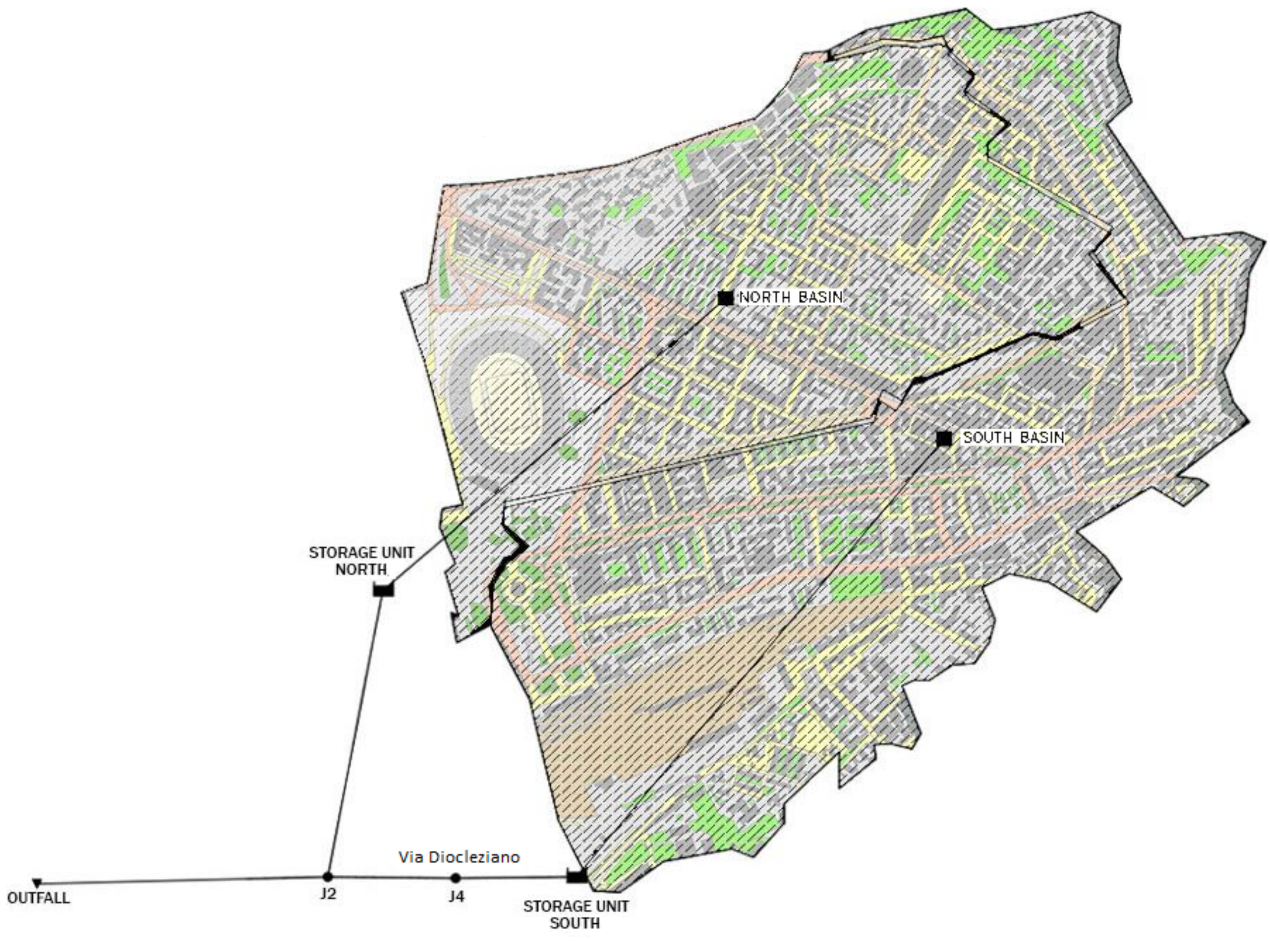

Figure 1. SWMM model of Fuorigrotta (NA) basin.

The above described configuration defined the so-called "Baseline Scenario" which represented the rainwater configuration before the introduction of LID-BMP practices.

An interface between the hydraulic solver SWMM 5.1 and the Harmony Search meta-heuristic code was implemented, according to the operative procedure summarized in the flow-chart in Fig. 2.

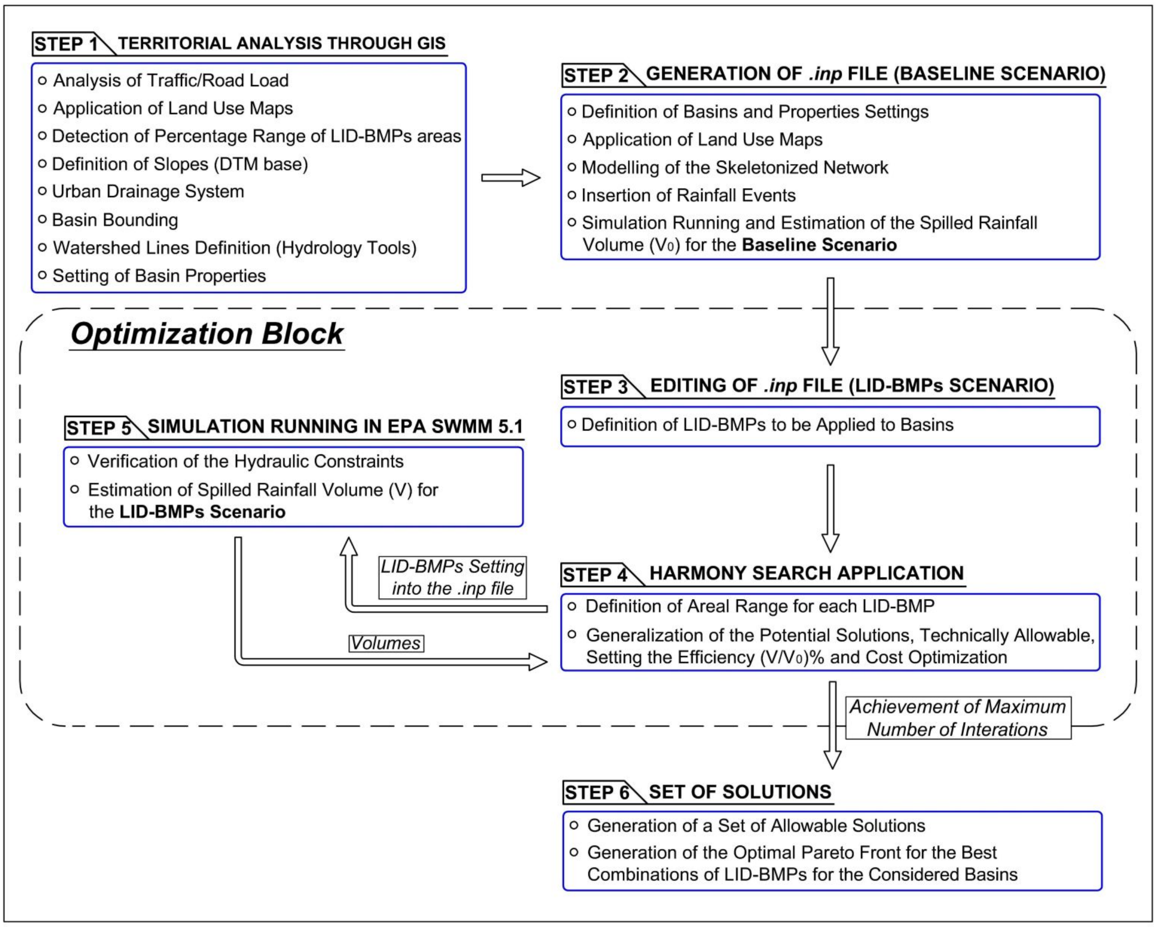

Figure 2. Flow-chart of the applied procedure to design the LID-BMPs applications.

2.3 Design of LID-BMPs by using the Harmony Search algorithm

Simulations were performed as a function of 18 rainfall events, whose historical rainfall data were provided by the Basin Authority of Campania Centrale, in reference to 6 durations. Three return periods were accounted for, equal to 5, 10 and 20 years, and spilled volume V_0, referred to the Baseline Scenario, was calculated in order to estimate the improvements obtainable by applying LID-BMPs in terms of spilled volume reduction with respect to the Baseline Scenario V/V_0. A critical duration d = 1 h was considered for simulations.

Considered LID-BMP practices, among those available in SWMM 5.1, were porous pavements, bioretention and roof garden. The choice was done as a consequence of the analysis of the land use map about the availability of the potentially convertible areas in the studied zone. A storage unit was also set for each final node of the basins, fixing a maximum potential capacity of 1'000 m^2 (Fig. 2). In the following Table 1, set input properties are summarized to calculate the LID-BMPs extension.

Table 1. Setting parameters of LID-BMPs.

	North Basin	South Basin
Area (m^2)	821'400	1'072'700
Width (m)	4'086.6	6'476.4
Impervious Surface (%)	92.90	81.40
Bioretention Max Area (m^2)	66'184.25	199'955
Green Roof Max Area (m^2)	11'505.05	141'851.5
Porous Pavement Max Area (m^2)	383'629.05	419'552.9

For both each LID-BMP type and final storage units, the maximum potential areas were set (Table 1) and simulations were run, by considering 10'000 iterations. A maximum allowable total cost was fixed. Unitary cost for each LID-BMP practice was evaluated according to Zheng (2013). Three levels of simulations were performed, by varying the volume ratio V/V_0 with respect to the Baseline Scenario in the ranges: (a) 100-77%; (b) 77-47% and (c) 47-34%. A total of 30'000 solutions, in terms of costs and volume V/V_0 rate, was found, defining the Pareto Front, on which the dominant solutions were included. Thus, they represented the solutions, referring to which, for a fixed cost, the volume reduction was maximized; conversely, for a fixed volume rate V/V_0, they defined the relative minimum costs (Fig. 3).

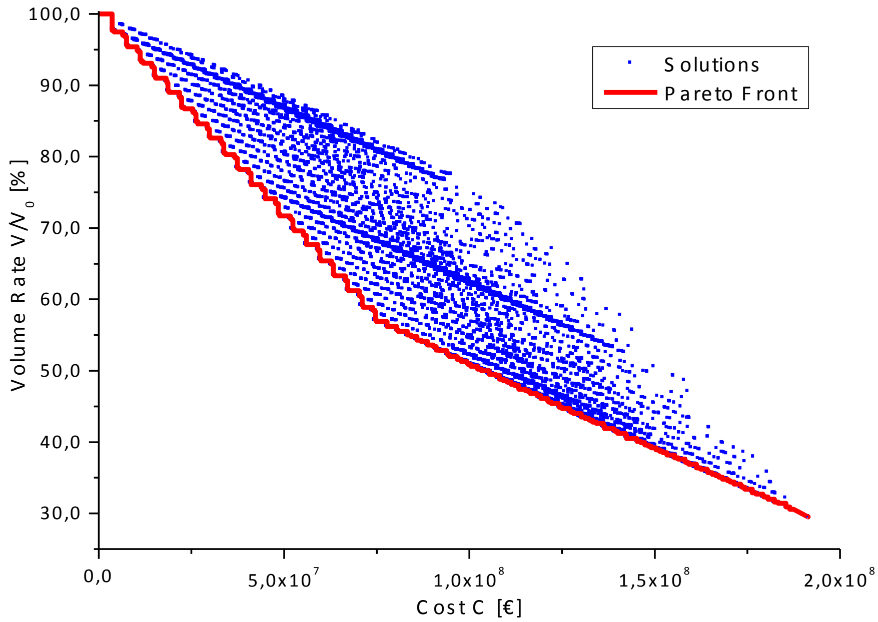

Figure 3. Cost-volume solutions and Pareto Front.

2.4 Solution selection and data validation

The developed model can be intended as a DSS (Decision Support System) because it allows to define the optimal design of LID-BMP practices, as a function of the available economic budget.

In reference to the considered case-study, a maximum budget in the range 50-55 millions € was set and a maximum volume rate V/V_0 equal to 70% to choose the optimal solution. With reference to the *North Basin*, areas converted into porous pavements were equal to 269'155.5 m^2, whereas bioretention areas had extension of 65.21 m^2. Green roofs were not considered for the selected solution. Concerning the *South Basin*, porous pavements were designed for an area of 294'291.2 m^2, whereas neither bioretention nor green roof practices were included into the solution. Conversely, a storage unit of 113.26 m^2 was considered for the *South Basin*.

It is interesting to point out that the evaluation of the required volume rate V/V_0 has to be accomplished by taking into account also the geological composition of the considered site. In the studied case-study, the soil was mainly constituted by loose pyroclasts, which could determine significant compaction if strongly imbibed.

The repetition of the 18 simulations was performed in order to compare results of the Baseline Scenario and of the LID-BMPs ones. Moreover, a further simulation comparison between pre/post LID-BMP scenarios was performed by considering the historical rainfall event which involved the Fuorigrotta (NA) district on 15/09/2011, clustered into two intense showers with a mean intensity larger than 50 mm/h. It corresponded to a return period of 500 years, causing damages estimated in about actualized 240 millions €. This last comparison was useful to quantify the environmental and economic improvements, obtainable by applying LID-BMPs practices, when catastrophic events occur. Specifically, a volume rate V/V_0 equal to 68.3% was estimated.

3. CONCLUSIONS

In this work the implementation of a Decision Support System to manage urban stormwater systems was presented and discussed. The model was implemented by combining the Harmony Search meta-heuristic code with the SWMM 5.1 hydraulic solver, aiming at defining the optimal design of LID-BMP practices in urban stormwater systems. The case-study of Fuorigrotta (NA) urban basin was analyzed, with reference to the installation of porous pavements, bioretention and roof gardens, with the aim of reducing the flooded urban areas when high rainfall events occur. Analysis of both the orographic configuration and the land use and definition of areas potentially convertible in LID-BMPs was developed by using a GIS software. The model was able to define the solution which, for a fixed available budget, maximizes the reduction of flooded volume. Conversely, having chosen a technical threshold of flooded volume, it allows to quantify the required budget. Comparison between pre and post intervention scenarios pointed out the reliability of the developed model to estimate the reachable environmental and economic benefits of LID-BMPs, in case of extreme rainfall events.

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