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Hydrologic modeling of Low Impact Development systems at the urban catchment scale

Anna Palla *, Ilaria Gnecco

Department of Civil, Chemical and Environmental Engineering, University of Genova, Via Montallegro 1, 16145 Genoa, Italy

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SUMMARY

In this paper, the implementation of Low Impact Development systems (LIDs) as source control solutions that contribute to restore the critical components of natural flow regimes, is analyzed at the urban catchment scale. The hydrologic response of a small urban catchment is investigated under different land use conversion scenarios including the installation of green roofs and permeable pavements. The modeling is undertaken using the EPA SWMM; the "do nothing" scenario is calibrated and validated based on field measurements while the LID control modules are calibrated and validated based on laboratory test measurements. The simulations are carried out by using as input the synthetic hyetographs derived for three different return periods (T = 2, 5 and 10 years). Modeling results confirm the effectiveness of LID solutions even for the design storm event (T = 10 years): in particular a minimum land use conversion area, corresponding to the Effective Impervious Area reduction of 5%, is required to obtain noticeable hydrologic benefits. The conversion scenario response is analyzed by using the peak flow reduction, the volume reduction and the hydrograph delay as hydrologic performance indexes. Findings of the present research show that the hydrologic performance linearly increases with increasing the EIA reduction percentages: at 36% EIA reduction (corresponding to the whole conversion of rooftops and parking lot areas), the peak and volume reductions rise till 0.45 and 0.23 respectively while the hydrograph delay increases till 0.19.

1. Introduction

The increasing imperviousness in urban areas brings significant changes in the properties of land. In particular native vegetation is reduced, the shallow depression of the natural soil and the native drainage patterns that intercept, store and infiltrate storm water are limited. The loss of the natural soil and vegetation within the urban catchment significantly affects the hydrologic cycle by increasing runoff rates and volumes and limiting evapotranspiration and interception (Jacobson, 2011). The Effective Impervious Area (EIA) in a watershed is the impervious area directly connected to the storm drainage system that contributes to increase storm water volumes and runoff rates (Shuster et al., 2005). It is shown in the literature that a reduction of EIA could compensate the adverse impact of possible global warming scenarios on urban hydrology and on the efficiency of a urban drainage system (e.g. Damodaram et al., 2010; Liu et al., 2014; Lucas and Sample, 2015).

Low Impact Development (LID) principles and applications have been developed to mitigate the impact of imperviousness in urban areas on storm water runoff for both quantity and quality aspects. In particular LIDs are designed to mimic the pre-development hydrologic conditions thus promoting storage, infiltration and evapotranspiration processes (Ahiablame et al., 2012). Similarly, Sustainable Urban Drainage Systems (SUDS) or Water Sensitive Urban Design (WSUD) principles and applications are source reduction approaches (Palla et al., 2010).

In the present study, among LID solutions, green roofs and permeable pavements are selected as source control systems to be applied to rooftops and parking lot areas respectively in order to reduce the impact of imperviousness at the catchment scale. Green roofs and permeable pavements beneficially contribute to manage storm water quantity and quality issues, thus promoting the outflow volume reduction, the hydrologic response delay and the control of pollutant loads washed-off from urban surfaces. Results of experimental studies performed in the laboratory at the pilot scale and in-situ at the full scale demonstrate the positive impact of green roofs (e.g. Czemiel Berndtsson, 2010; Palla et al., 2012; Stovin et al., 2012) and permeable pavements (e.g. Dreelin et al., 2006; Fassman and Blackbourn, 2010) in reducing storm water volume and outflow peaks as well as limiting total pollutant mass delivery (e.g. Sansalone et al., 2012; Gnecco et al., 2013).

* Corresponding author. Tel.: +39 010 353 2485; fax: +39 010 353 2481.
E-mail addresses: anna.palla@dicat.unige.it (A. Palla), ilaria.gnecco@unige.it (I. Gnecco).

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In spite of the fact that LID hydrologic performance is widely recognized, the effectiveness of LID implementation at the urban catchment scale is still debated.

Since Elliott and Trowsdale (2007) published a comprehensive review of hydrologic models to simulate the LID impact on urban drainage, the gaps in model capabilities are continuously narrowed. Recently, modeling results demonstrate the beneficial uses of LID source control solutions at the catchment scale (Lee et al., 2013; Burszta-Adamiak and Mrowiec, 2013; Trinh and Chui, 2013). Ahiablame et al. (2013) confirm that the application of rain barrels and porous pavements contribute to a runoff volume reduction ranging between 2% and 12% on a yearly basis. Further Qin et al. (2013) show that the performance of LIDs is mainly affected by the percentage of both the LID installation area and the related drainage areas. On the other hand, the installation of LIDs at the catchment scale is still scarce (Loperfido et al., 2014; Zhang et al., 2012) thus resulting in limited availability of field measurements for model calibration/validation. In addition, in order to properly assess the LID performance at the catchment scale, a high spatial resolution of hydrological models is required. With high spatial resolution models, homogenous subcatchments can be defined and this results in a simplified parametrization (i.e. narrow parameter ranges) and in a consequently optimization of the calibration process (Krebs et al., 2014).

In this framework, the main objective of the present study is to investigate the effect of LIDs as source control solutions at the catchment scale by implementing a high spatial resolution model for a small urban catchment. The first specific objective is to assess the impact of green roofs and permeable pavements on the hydrologic response of the urban catchment; for this purpose, different land use conversion scenarios (i.e. EIA reductions) are considered. The second specific objective is to evaluate the impact of the rainfall intensity on the hydrologic response; for this purpose the selected conversion scenarios are simulated under three synthetic hyetographs characterized by different return periods, *T*, namely 2, 5 and 10 years. Finally the third objective aims at examining the influence of the green roof conditions on the hydrologic response. To support this investigation a sensitivity analysis on the Initial Saturation (IS) conditions of the green roof is carried out for a selected conversion scenario simulated under the 2-year rainfall event.

2. Methodology

2.1. Site description

The urban catchment of Colle Ometti, in the town of Genoa (Italy) is selected as a test site for the hydrologic modeling of land use conversion scenarios. Storm water runoff was monitored for both quantity and quality aspects in 2005 when the site was equipped with a technological station to measure on-site rainfall and flow rate data and to collect discrete runoff samples (Palla, 2009). This 5.5 ha catchment was urbanized in the eighties with 500 houses built on a previously undeveloped hill slope. The management of storm water is addressed according to the traditional approach; in particular the separate sewer system consists of a main collector and eight lateral sewers and no LID source control solutions (green roofs and permeable pavements) are installed in the catchment.

As illustrated in Table 1, land uses are classified as rooftop, road and parking lot, green area and farmland, and total impervious/pervious areas are calculated based on the regional cartography and aerial photographs. The analysis of land use data reveals that 60% of the Colle Ometti catchment is covered with impervious surfaces and that rooftops account for 31% of the total areas.

Table 1
Land use characteristics of the urban catchment.

Land use	Area	
	(ha)	(%)
Rooftop	1.41	31
Road and parking lot	1.28	28
Other impervious	0.06	1
Total impervious	2.75	60
Green area	1.28	28
Farmland	0.53	12
Total pervious	1.81	40
Total areas	4.56	100

2.2. Simulation scenarios

In the present study green roofs and permeable pavements are the LID source control solutions selected for the implementation within the urban catchment. The current configuration which corresponds to the "do nothing" scenario, is assumed as the reference scenario in order to measure the impact of the LID application.

Table 2 illustrates the land use conversion scenario and the corresponding EIA reduction percentage. In particular, the proposed scenarios are designed combining the following criteria: four percentages of rooftops conversion (namely 0%, 20%, 50% and 100%) and a single ratio of road and parking lot (namely 16%) corresponding to the whole public parking area.

Concerning rainfall conditions, the analysis is carried out by using as input the synthetic hyetographs derived from the analysis of the rain data collected at the rain gauge station of Genoa Villa Cambiaso (1990–2013). The synthetic hyetographs are computed using the Chicago method based on the parameters of the Intensity–Duration-Frequency relationship for three return periods (namely 2, 5 and 10 years). The rainfall duration is assumed 30 min and the time-to-peak ratio is 0.5. The selected return periods refer to high-intensity rainfall events characterized by a frequency greater than the one of the design event for urban drainage system. Fig. 1 shows the Chicago hyetographs evaluated for the three selected return periods ($T = 2$, 5 and 10 years).

Since the simulations are performed at the rainfall event scale, the initial saturation of LIDs is required and it is assumed 0.38 for the green roof module.

The conversion scenarios response is analyzed by using the following hydrologic performance indexes: the peak flow reduction, the volume reduction and the hydrograph delay. The peak flow reduction is calculated as the relative percentage difference between the outflow peaks of the reference and the conversion scenarios; the volume reduction and the hydrograph delay are similarly calculated. In particular, the hydrograph delay is evaluated based on the hydrograph centroids of the reference and the conversion scenarios.

2.3. The EPA SWMM model

The EPA Storm Water Management Model (SWMM) (Rossman, 2010) is selected to simulate the hydrologic response of the urban catchment. SWMM is a dynamic hydrology-hydraulic and water

Table 2
Land use conversion scenarios and EIA reductions.

LID source control solution	Conversion scenario			
	I	II	III	IV
Green roof (% of rooftops)	0	20	50	100
Permeable pavement (% of road and parking lot)	16	16	16	16
EIA reduction (% of catchment area)	5	11	21	36