On the LID systems effectiveness for urban stormwater management: case study in Southern Italy

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Abstract. Here we present the hydrological effectiveness of Low Impact development (LID) solutions at urban catchment scale, by modelling a highly urbanised area located in South Italy. For the model creation and simulation, PCSWMM based on the Storm Water Management Model (SWMM) was used. The analysis was carried out by considering different land use conversion scenarios including the implementation of LID practices. Therefore, a specific permeable pavement and green roof developed and implemented at full scale at University of Calabria were chosen as source-control measures. The simulations were run by using as input a synthetic hyetograph of 30 min with return period of 10 years. Three hydrological performance indexes, Runoff Coefficient (RC), Runoff Reduction (RR) and Peak Flow Reduction (PFR) were evaluated at subcatchment scale and, a mean value was estimated for an overall evaluation. Main findings show that RR and PFR linearly increase with the reduction of imperviousness due to the modelling of a major percentage of LID solutions, while the RC decreases. In addition, first detailed results reveal the suitability of LID solutions to reduce surface runoff also for the scenario 1 which considers the conversion of only 30% of specific impervious surface in green roofs and permeable pavements.

Keywords: Rainfall-Runoff, Green Roof, Permeable Pavement, PCSWMM, Hydrodynamic Modelling

1. Introduction

Climate change and on-going urbanization can be considered the main factors which lead several environmental impacts from the watershed scale to urban catchment scale, as increase of flooding risk, water pollution, urban heat island, air pollution, biodiversity, problems related to water bodies alteration, and so on [1-3].

In this context, to enhance the environmental quality and restore the exosystemic balance affected by urbanization and climate change, sustainable solutions and assessment methodologies at different spatial scale (urban, peri-urban, watershed, and so on) are become a priority, and in this direction several studies have been carried out [4-6].

Focusing on urban environment, the highly imperviousness led a drastic change in the natural hydrological cycle components with consequences in terms of reduction of infiltration and evapotranspiration and increase of runoff volumes. Therefore, during extreme stormwater events such volumes can overload the sewer systems causing local floods [7].
In this scenario, it is relevant to find solutions to reduce the impacts [8]. A promising strategy is the implementation of decentralized stormwater controls, also known as LID (Low Impact Development) systems which provide several benefits at multiple scales [9-11]. These techniques allow a management of stormwater directly at the source by a nature-based approach.

Green roofs and permeable pavements, largely investigated, have been considered among the most efficient strategies in terms of urban flooding risk mitigation, water quality enhancement, and urban heat islands reduction [12-18].

Based on this framework, main objective of this study is to analyse how the implementation of Low Impact Development systems (LIDs) can contribute to mitigate the effect of climate change and urbanization in terms of surface runoff reduction and, consequently urban flooding risk mitigation.

To achieve this, the hydrological response of a small selected urban area - located in Southern Italy - was investigated under different land use conversion scenarios, by considering the modelling implementation of Green Roofs and Permeable Pavements integrated in the existing drainage network, by using PCSWMM [19].

2. Materials and Methods

2.1. Study Area

A highly urbanized area of an urban catchment (catchment of San Domenico Creek) located in the municipality of Paola in Calabria Region (Italy) in Mediterranean Climate Region, was selected as test site for modelling the land use conversion scenarios.

In this area the stormwater management is achieved by a combined sewer network consisting of different conduits in terms of section and materials. More specifically, based on the detailed information of a previous study [20], the concrete conduits present sections of 350x450mm, 400x400mm and 450x450mm, while the circular ones in stoneware material have diameters of 200 mm and 300 mm.

The residential area, here considered, with a total surface of around 7.6 ha, presents a grade of imperviousness of 96.0%. The analysis of land use data, carried out on the base of regional cartography and aerial photographs, illustrated in Table 1, shows that the study area consists of 28.9% of rooftops and 67.1% of roads, parking lots and others impervious surfaces; only a small portion of around 4.0% of the total surface is covered by green spaces.

This landscape analysis reveals as the area, almost totally covered by impervious surfaces, can be a suitable site for LID systems implementation for urban stormwater management.

| Table 1. Land use of the selected area. |
|---------------------------------------|
| **Land use**                          | **Area** |
|                                       | ha | % |
| Rooftop                               | 2.2 | 28.9 |
| Parking lot, roads and other impervious | 5.1 | 67.1 |
| **Total Impervious**                  | **7.3** | **96.0** |
| Green Area                            | 0.3 | 4.0 |
| **Total Pervious**                    | **0.3** | **4.0** |
| **Total Areas**                       | **7.6** | **100.00** |

2.2. LID Simulation Scenarios

To assess the hydrological effectiveness of LID systems for urban stormwater management, Green Roofs (GRs) and Permeable Pavements (PPs) are the LID systems selected to model the response of the urban area under different conversions scenarios:
(i) **Scenario 0** is the reference scenario, implemented based on the current land use data, in order to investigate the impact of the LID implementation;

(ii) **Scenario 1** consists in the replacement of 30% of conventional rooftop area with Green Roofs and in the installation of Pemeable Pavements on the 30% of impervious surfaces (excluding roads opened to traffic);

(iii) **Scenario 2**, where 60% of conventional roofs are substituted with Green Roofs and 60% of impervious areas (excluding roads opened to traffic) with Pemeable Pavements;

(iv) **Scenario 3** considers the implementation of Green Roofs on all rooftops, and the replacement of 100% of impervious surfaces (excluding roads opened to traffic) with Pemeable Pavements.

### 2.3. Model development

To simulate the hydrological response of urban catchment a dynamic rainfall-runoff simulation model PCSWMM (CHI-PCSWMM), based on the EPA-SWMM version 5.1.012 [21], was used. This choice was carried out based on the results of other studies, which confirm the suitability of SWMM to assess the LID performances and to support their implementation at catchment scale [22,23].

The model was built considering topographical data, land use classification and data on the existing stormwater system, already investigated in a previous study [20].

To obtain a detailed model, and improve the previous one, the study area of around 7.6 ha was divided into 26 subcatchments, defined in function of land use and homogeneous properties (the surface slope, area, etc.). More in detail, based on the land use analysis, for each subcatchment, before the modelling implementation, the land use features in terms of pervious and impervious area were defined. In function of this analysis for each subcatchment the Curve Number parameter (\(C\)), the Depression Depth value (\(mm\)), n Manning coefficient (\(s/m^{1/3}\)) were defined, and then considered with the others geometrical data (area, width, slope, etc.) as input subcatchment parameters to implement the model.

The Soil Conservation Service (SCS) Curve Number (CN) method was considered for the infiltration method and the flow routing computations were based on the Dynamic Wave Equations.

The drainage network was defined in agreement with the data retrieved from the design plans in terms of conduit length, section and material.

Based on this, the implemented model consists of 26 subcatchments, 28 Conduits, 28 Junctions Nodes, and 1 Outfall node. This model is representative of the existing system configuration, i.e. the reference scenario (Scenario 0) of this study.

To simulate the hydrological response of this urban area with the implementation of LID solutions (Scenario 1,2,3), the model, previous defined, was integrated with the use of the LID Control Editor; this is an additional SWMM module developed to simulate the hydrological behaviour of source control solutions as bio-retention cell, rain gardens, green roof, infiltration trench, permeable pavement, rain barrel, rooftop disconnection, vegetative swale [21].

In this study green roof and permeable pavement modules were selected. To assign the properties for each layer, required by the LID Control section, the stratigraphy features and the physical parameters (based on previous laboratory test measurements) of the green roof and the permeable pavement located at University of Calabria were considered. More detail, the features of these two LID solutions can be found in [7,24,25].

For the hydrodynamic simulation, synthetic Chicago hyetograph was used. The rainfall duration was assumed 30 min and the time-to-peak-ratio 0.4. The hyetograph was defined based on the parameters of the Intensity–Duration–Frequency relationship computed by the analysis of historical records (1945–2005) obtained from the Regional Agency for Prevention, Environmental in Calabria Region [26] by considering the rain gauge station of Paola.

The hydrodynamic model here presented, as stated above, was used to simulate the response of an urban catchments under different conversion scenarios with the aims to evaluate the hydrological effectiveness of LID systems for stormwater management.
2.4. Hydrological Performance Indexes

The response of each scenario was evaluated in terms of runoff coefficient (RC), runoff reduction (RR), and peak flow reduction (PFR). These values were estimated for each subcatchment and the mean values for each index were calculated in order to analyse the overall result.

More in detail:

The Runoff Coefficient for each scenario \((RC_0, RC_1, RC_2, RC_3)\) was expressed as percentage ratio between the total Runoff Depth in mm \((RD_0, RD_1, RD_2, RD_3)\) and the total Precipitation Depth in mm \((PD)\).

| SCENARIO 0 | SCENARIO 1 | SCENARIO 2 | SCENARIO 3 |
|------------|------------|------------|------------|
| \(RC_0 = \frac{RD_0}{PD} \cdot 100\) | \(RC_1 = \frac{RD_1}{PD} \cdot 100\) | \(RC_2 = \frac{RD_2}{PD} \cdot 100\) | \(RC_3 = \frac{RD_3}{PD} \cdot 100\) |

While, the Runoff Reduction \((RR_{0,1}, RR_{0,2}, RR_{0,3})\) was estimated as the percentage difference between the total Runoff Depth of Scenario 0 \((RD_0)\) and the corresponding total Runoff Depth of the other conversion scenarios \((RD_1, RD_2, RD_3)\).

Similarly, the Peak Flow Reduction \((PFR_{0,1}, PFR_{0,2}, PFR_{0,3})\) was evaluated as the percentage difference between the hydrograph peak of Scenario 0 \((PF_0)\) and the corresponding hydrograph peak for each LID conversion scenarios \((PF_1, PF_2, PF_3)\).

| SCENARIO 0 vs SCENARIO 1 | SCENARIO 0 vs SCENARIO 2 | SCENARIO 0 vs SCENARIO 3 |
|--------------------------|--------------------------|--------------------------|
| \(RR_{0-1} = \frac{RD_0 - RD_1}{RD_0} \cdot 100\) | \(RR_{0-2} = \frac{RD_0 - RD_2}{RD_0} \cdot 100\) | \(RR_{0-3} = \frac{RD_0 - RD_3}{RD_0} \cdot 100\) |
| \(PFR_{0-1} = \frac{PF_0 - PF_1}{PF_0} \cdot 100\) | \(PFR_{0-2} = \frac{PF_0 - PF_2}{PF_0} \cdot 100\) | \(PFR_{0-3} = \frac{PF_0 - PF_3}{PF_0} \cdot 100\) |

3. Results and Discussion

The introduction of different percentage of LID units aims at improving the infiltration capability of the selected area reducing the surface runoff. By analysing the Scenario 0 model configuration, it was possible to observe the high imperviousness percentage of this urbanised area: 22 subcatchments present an imperviousness more than 90%. While, by implementing the different LID scenarios, it was detected a great reduction of imperviousness until to reach the optimal and final condition related to scenario 3, where most of the subcatchments have an imperviousness less than 40%.

To assess the LID hydrological effectiveness, the results were evaluated in terms of outflow for the reference condition (Scenario 0) and those one obtained for the conversions scenarios (Scenarios 1,2,3).

More in detail, first the total Runoff Depth (RD) and the Peak Flow (PF) were estimated at subcatchment scale for each conversion scenario (Figure 1). For both cases, the bargraphs confirm the good performance of the LID systems, by showing how the RD and PF values reduced to the increase of LID percentages in the urban area.

Therefore, based on the data of all subcatchments, the three Hydrological Performance Indexes (RC, RR, PFR) were evaluated at subcatchment scale (Figure 2), and then average values calculated in order to analyse the overall result (Table 4).

Specifically, by observing Figure 2, it is possible to detect the range of variation of the three Hydrological Performance Indexes.
Figure 1. Total Runoff Depth [mm] and Peak Flow [l/s] for each subcatchment by comparing all scenarios.

Table 4. Rainfall Depth and Average Values of Performance indexes

| Scenario          | Rainfall depth [mm] | Average RC [%] | Average RR [%] | Average PFR [%] |
|-------------------|---------------------|----------------|----------------|-----------------|
| Scenario 0        | 33.5                | 98.1           | 25.9           | 31.4            |
| Scenario 1        | 33.5                | 72.6           | 45.8           | 59.3            |
| Scenario 2        | 33.5                | 53.0           | 45.8           | 83.8            |
| Scenario 3        | 33.5                | 36.4           | 62.8           |                 |

The values reported in Table 4 reveal the suitability of the LIDs to improve retention capacity of a highly urbanised basin.

The RC average value decreases from 98.1% in the condition of almost total imperviousness to 36.4% in Scenario 3, obtaining also good results for the inter-medium scenarios. RC values of 25.5% and 45.1% less than the Scenario 0 were observed for the Scenario 1 and 2 respectively.

While the Runoff Reduction (RR) [%] and Peak Flow Reduction (PFR) [%] present a linear increase of their values with the reduction of the impervious surfaces, simulated from scenario 1 to scenario 3.

More in detail, the implementation of GR and PP on the 30% of the corresponding impervious surface (as specified above) allow a runoff reduction of 25.9 % and a peak reduction of 31.4%. Although the imperviousness change is limited to only this percentage (30%), a good result was the same achieved by the implementation of the specific GR and PP in Mediterranean climate condition.

As expected, more high performances have been reached in the second and third scenarios, where the percentage of LID reached 60% and 100%, respectively, and the RR and PFR reached values of 45.8% and 54.3% for scenario 2 and 62.8% and 83.8% for the last one.
All findings, here presented, confirm the suitability of LID solutions for the surface runoff mitigation in terms of volume and hydrographs peak for all three LID conversion scenarios.

By analysing the modelling results emerges the role of LID practices to restore the component of natural hydrological cycle at the urban scale. And, even if, practical and economic considerations are needed to select the optimal LIDs distribution, this study demonstrates that also a small change of imperviousness, considered for example for the Scenario 1, can enhance the hydrological response of an urban catchment.

4. Conclusions

To evaluate the hydrological performances of LID systems, in this study the hydrological response of a highly urbanised area locate din Southern Italy has been simulated under different conversions scenarios. The selected area was modelled by using PCSWMM. A specific permeable pavement and green roof, developed at University of Calabria, have been considered for the modelling implementation by the LID modules in PCSWMM. Modelling results confirm the suitability of these LID solutions to reduce surface runoff and, therefore, urban flooding risk. The findings reveal that this beneficial effect can be reached by converting also only a small percentage of the impervious surfaces. Considering that practical and economic conditions could limit the implementation of these sustainable practices in urban area, this can be considered a relevant finding.

In conclusion, the LID strategy achieves a sustainable management of urban drainage network, limiting the environmental impact due to urbanization and climate change.
Future investigation will take into account the response of the same area under different rainfall event and by considering others combination of LID systems not only in terms of percentage distribution, but also in terms of different design systems.

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