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

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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).

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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

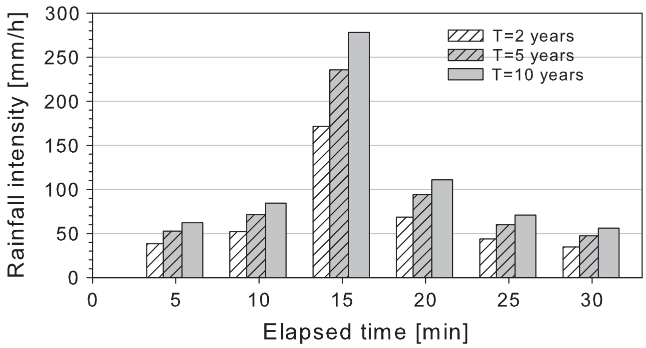

Fig. 1. Chicago hyetographs for three return periods namely 2, 5 and 10 years.

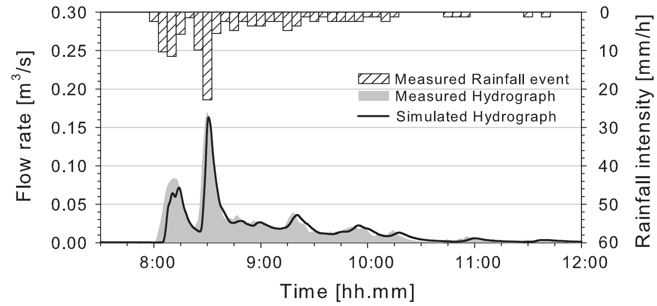

Fig. 2. The hyetographs, the corresponding measured hydrographs and the comparison of the simulated hydrographs for the 16 April 2005 rainfall-runoff event used for calibration.

quality simulation model. Focusing on the quantity aspect, the urban catchment consists of a collection of subcatchment areas that receive rainfall and generate different hydrologic components including surface runoff, infiltration and evaporation; the rainfall-runoff process is based on a nonlinear reservoir approach.

Recently LID control modules have been implemented in SWMM (v. 5.1.007) in order to simulate the hydrologic performance of source control solutions such as rain gardens, green roofs, infiltration trenches and permeable pavements. LID systems are represented by a combination of vertical layers whose properties (such as thickness, void volume, hydraulic conductivity, and underdrain characteristics) are defined on a per-unit-area basis; LIDs can be assigned within selected subcatchments by defining the corresponding areal coverage.

The study area is simplified in 286 subcatchments, 102 junctions and 101 conduits; this high-resolution discretization results in subcatchment areas characterized by single land use type and homogenous properties. Consequently, the LIDs are applied to selected subcatchments and occupy the full subcatchment area (i.e. roof surface is converted into green roof).

In the present study, the Soil Conservation Service Curve Number Method is used to estimate infiltration losses and runoff is calculated using the Manning's equation. As for flow routing computation, the dynamic wave theory is used.

2.4. Model calibration and validation

Model calibration and validation strategy is based on the comparison of the predicted and measured outflow hydrographs. In particular, two criteria are assessed on an event basis: the discharge volume and the peak outflow rate. In order to assess the model performance with respect to the above mentioned hydrograph variables, the Relative Percentage Difference (RPD) is calculated as the ratio of the difference between the simulated and the observed values to the observed one for each rainfall event/test. Furthermore the Nash–Sutcliffe Efficiency index (NSE) is evaluated to quantitatively assess the model accuracy in reproducing the outflow hydrographs (Nash and Sutcliffe, 1970).

2.4.1. The subcatchment model

The subcatchment model is calibrated and validated based on 7 events collected between February and May 2005; the 16 April 2005 event is selected for the calibration phase. The hyetograph, the corresponding measured and simulated hydrographs are illustrated in Fig. 2 for the selected calibration event.

The calibrated model parameters (CN values, depression depths and n-Manning values) are reported in Table 3. CN values are assumed 98 for rooftops, roads and parking lots and other impervious areas while CN values are assumed 70 and 76 for green areas and farmlands respectively.

Table 3
Parameters assigned in the SWMM model.

SWMM Parameters	CN (–)	Depression depth (mm)	n Manning ($s/m^{1/3}$)
Subcatchment land use			
Rooftop	98	0.5	0.012
Road and parking lot	98	1.5	0.015
Other impervious	98	0.5	0.012
Green area	70	5	0.41
Farmland	76	4	0.25
Conduit	–	–	0.015

The quantitative assessment of the model performance is summarized in Table 4, where the NSE index and the RPD values of the total effluent volume and peak flow rate are reported for the calibration and validation events. As for the calibration event, the simulated hydrograph reproduces with acceptable matching capabilities the complex-shape outflow regime; in particular the timing and magnitude of the peak flow rate are accurately predicted (see Fig. 2). Results of the validation procedure reveal the suitability of the model to describe the hydrologic response of the urban catchment as confirmed by the NSE values greater than 0.80. The mean values of the model performance indexes (RPDs) are lower than 5% and clearly reveal the model accuracy in predicting the effluent volume and the peak flow rate.

2.4.2. The LID control modules

The LID control modules are calibrated based on laboratory test measurements. The tests were performed in a small size laboratory test-bed realized at the University of Genoa to investigate the hydrologic response of an infiltration system per unit surface area under varying slope and rainfall conditions. The test-bed is composed of a plot (1×2.5 m), a rainfall simulator system, three cylindrical reservoirs and an automated monitoring system for

Table 4
Nash–Sutcliffe Efficiency (NSE) index and Relative Percentage Differences (RPDs) of the total effluent volume and peak flow rate for the observed rainfall events used for the calibration and validation. The superscript 'C' denotes the calibration event.

Events Date (dd/mm/yy)	NSE (–)	RPD Volume (%)	RPD Peak (%)
16/04/05^C	0.836	7	4
19/02/05	0.898	1	−4
03/03/05	0.805	12	28
23/04/05	0.918	3	−20
24/04/05	0.968	−8	−9
14/05/05	0.820	−4	17
17/05/05	0.931	6	20
Mean	0.840	−2	4
Standard deviation	0.115	14	16

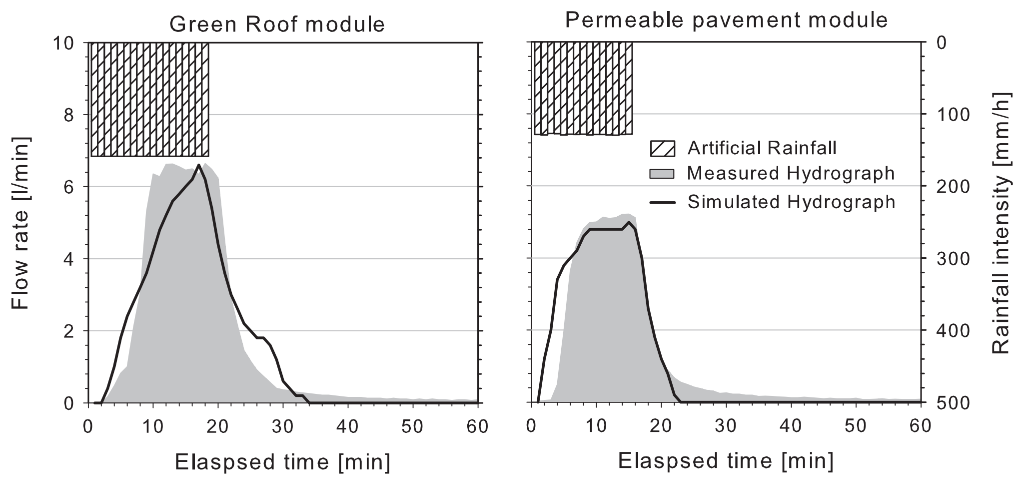

Fig. 3. The inflow, the corresponding measured sub-surface outflow and the comparison of the simulated outflow for the green roof (left side) and permeable pavement (right side) laboratory tests used for calibration.

Table 5
Green roof parameters assigned in the SWMM model – LID control section.

Layers	Field capacity (–)	Wilting point (–)	Hydraulic conductivity (mm/h)	Conductivity slope (–)	Porosity (–)	Manning coefficient ($s/m^{1/3}$)
Soil	0.43	0.07	1000	15	0.66	–
Drainage	–	–	–	–	0.4	0.02

Table 6
Permeable pavements parameters assigned in the SWMM model – LID control section.

Layers	Void ratio (–)	Permeability (mm/h)	Seepage rate (mm/h)	Flow coefficient ($mm^{1/3}/s$)	Flow exponent (–)	Offset (mm)
Pavement	0.18	9000	–	–	–	–
Storage	0.9	–	0	–	–	–
Underdrain	–	–	–	30	0.5	8

Table 7
Nash–Sutcliffe Efficiency (NSE) index and Relative Percentage Differences (RPDs) of the total effluent volume and peak flow rate for the tests used for the calibration and validation of the green roof module. The laboratory tests are identified based on the rainfall intensity. The superscript 'C' denotes the calibration tests.

Green roof test Rainfall intensity (mm/h)	NSE (–)	RPD volume (%)	RPD peak (%)
158^C	0.898	−7	−1
180	0.831	−3	−6
199	0.851	−3	−7
159	0.866	−1	−9
130	0.834	−2	−13
135	0.906	−1	−3
107	0.788	1	−21
Mean	0.853	−2	−9
Standard deviation	0.041	3	7

Table 8
Nash–Sutcliffe Efficiency (NSE) index and Relative Percentage Differences (RPDs) of the total effluent volume and peak flow rate for the tests used for the calibration and validation of the permeable pavement module. The laboratory tests are identified based on the rainfall intensity. The superscript 'C' denotes the calibration tests.

Permeable pavement test Rainfall intensity (mm/h)	NSE (–)	RPD volume (%)	RPD peak (%)
128 I^C	0.904	−2	−4
98 I	0.769	3	8
98 II	0.754	1	3
128 II	0.904	−3	−6
128 III	0.905	−3	−8
150 I	0.885	−1	−5
150 II	0.900	−1	−5
Mean	0.860	−1	−3
Standard deviation	0.068	2	6

measuring inflow and outflow; the detailed description of the laboratory device is provided elsewhere (Palla et al., 2015).

The tested green roof solutions can be classified as extensive green roofs (Berretta et al., 2014); in detail the stratigraphy is primarily comprised of a growing medium (total depth of 12 cm) and a loose-laid synthetic specialized layer (drainage and filter layers for a total depth of 2.5 cm). The materials used in the growing and drainage layers, named Substrato SEIC and MediDrain MD 25 are produced by Harpo Seic Verde Pensile (Trieste, Italy). A Specific investigation on the water retention characteristics of the Substrato SEIC is reported in Savi et al. (2013).

As for the permeable pavement, the tested typology is the most common for the realization of parking lots (Scholz and Grabowiecki, 2007); in particular the stratigraphy consists of a surface layer realized with pervious concrete bricks (total depth of 8 cm) and a storage layer made of a mix of gravel and coarse sand (total depth of 5 cm). A geotextile and a drainage layer made of plastic elements are posed under the storage layer. The materials used in the surface (Ecomattoncino) and drainage (Drainroof) layers are respectively produced by Senini S.p.a. (Brescia, Italy) and Geoplast (Padua, Italy). Regarding the storage layer, the particle size distribution reveals d_{60} and d_{10} values respectively of 6.5 and 3.5 mm, thus conforming to the ASTM No. 8 gradation.

For both the green roof and permeable pavement modules, the tests were performed at constant rainfall intensity for a 15-min duration and with rainfall rates varying between 100 and 200 mm/h. The system slope was set up at 2%. The laboratory test programme consists of 7 validated tests for both the green roof and permeable pavement modules; for each test, one-minute inflow and outflow measurements are available.

Fig. 3 illustrates the inflow, the corresponding measured sub-surface outflow and the comparison of the simulated outflow for the green roof (left side) and permeable pavement (right side) laboratory tests used for calibration.

The calibration parameters for the green roof and permeable pavement modules are reported in Tables 5 and 6 respectively.

The quantitative assessment of model performance is summarized in Tables 7 and 8 respectively for the green roof and permeable pavement modules, where the NSE index and the RPD values of the total effluent volume and peak flow rate are reported for the calibration and validation events. Results of the validation procedure demonstrate the suitability of the LID modules in reproducing the outflow as confirmed by the NSE values greater than 0.75 for the permeable pavement and 0.78 for the green roof. In both cases, the simulated peak flow rate and total effluent volume are

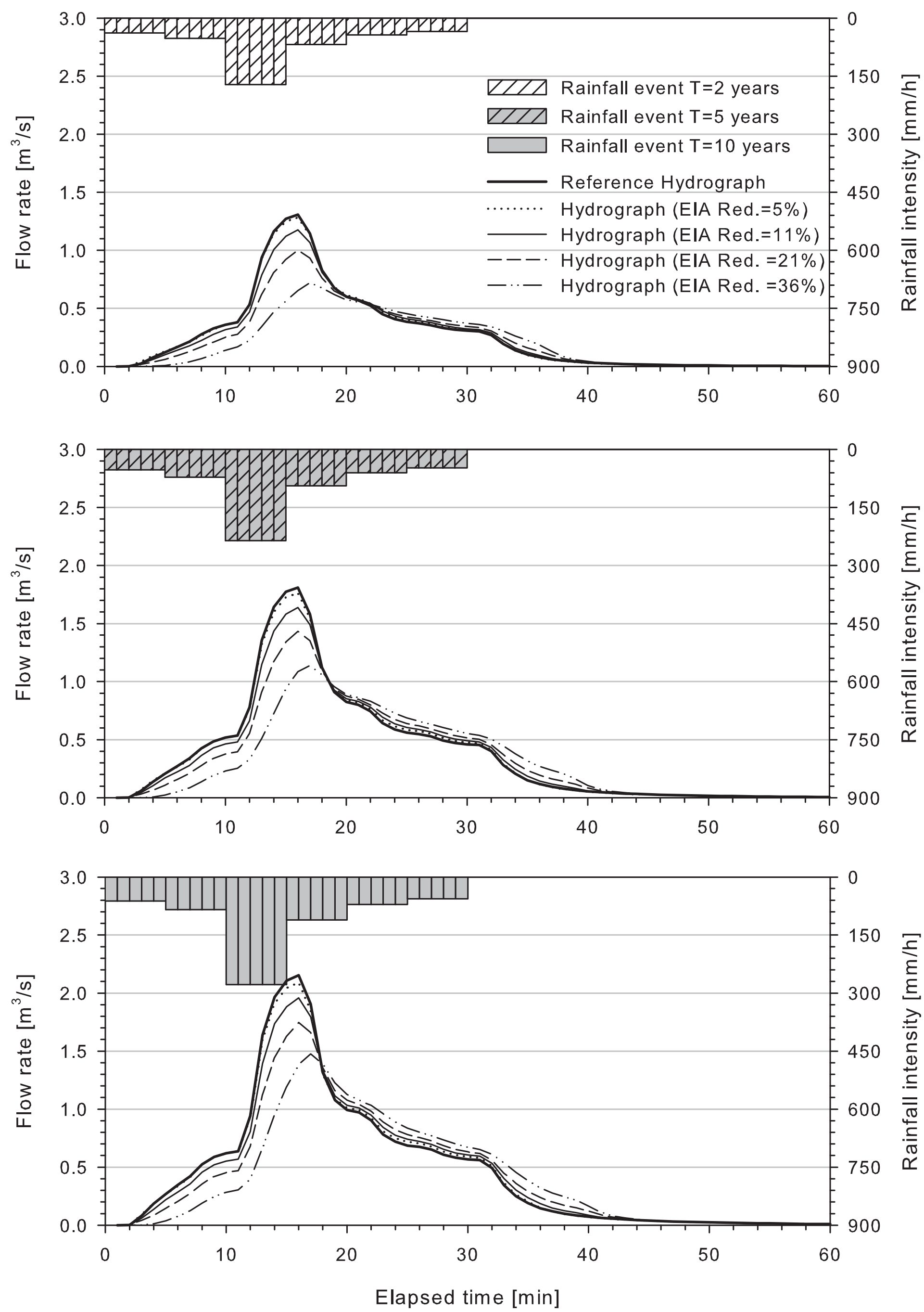

Fig. 4. The hyetographs, the corresponding hydrographs simulated for the different EIA reduction scenarios at assigned rainfall event return period ($T = 2$, 5 and 10 years). The reference scenario indicates the "do nothing" scenario.

Table 9
Hydrologic performance of the conversion scenarios at assigned rainfall event return period ($T = 2$, 5 and 10 years).

Hydrologic performance rate (–)	EIA reduction (%)			
	5	11	21	36
Rainfall event T = 2 years				
Peak reduction	0.03	0.10	0.23	0.45
Volume reduction	–	0.05	0.12	0.23
Hydrograph delay	–	0.03	0.08	0.19
Rainfall event T = 5 years				
Peak reduction	0.03	0.10	0.21	0.37
Volume reduction	–	0.03	0.08	0.17
Hydrograph delay	–	0.03	0.09	0.19
Rainfall event T = 10 years				
Peak reduction	0.03	0.09	0.19	0.31
Volume reduction	–	0.03	0.07	0.14
Hydrograph delay	–	0.03	0.08	0.18

generally underestimated with respect to the observed values. It has to be notice that, in spite of the complexity of the hydrologic process involved, the prediction of the total effluent volume is satisfactory as confirmed by RPD percentage values within a range of [−7,1] for the green roof and [−3, 3] for the permeable pavements (see Tables 7 and 8).

3. Results and discussion

Model simulation results consist of the outflow hydrographs for the reference and selected conversion scenarios. The reference scenario corresponds to the "do nothing" scenario while the four conversion scenarios differ in terms of EIA reduction percentages of the catchment area of 5%, 11%, 21% and 36% (see Table 2). In detail, each scenario is simulated under different rainfall conditions corresponding to return periods of 2, 5 and 10 years.

Fig. 4 shows the hyetographs and the corresponding simulated hydrographs for the three rainfall event return periods.

In Table 9 the hydrologic performance indexes referred to each conversion scenario are reported with respect to the three rainfall event return periods.

In the following section, the hydrologic performance is examined with respect to the EIA reduction percentages, the rainfall event return periods and the initial saturation conditions of the green roof.

3.1. Impact of the EIA reduction

In order to assess the effectiveness of LIDs as source control solutions at the urban catchment scale, the influence of the EIA reduction on the hydrologic performance is investigated.

From the results reported in Table 9 it emerges that an EIA reduction larger than 5% is required to obtain noticeable hydrologic benefits. In particular, for EIA reduction ranging between 11% and 36%, the hydrologic performance increases; as an example, for the 2-year return period event the peak reduction rises from 0.10 to 0.45, volume reduction from 0.05 to 0.23 and hydrograph delay from 0.03 to 0.19.

Looking at the hydrographs reported in Fig. 4, the larger is the EIA reduction the lower is the peak flow rate: by diminishing the urban catchment imperviousness the outflow hydrograph tends to come closer to the pre-development condition. The impact of EIA reduction significantly affects the initial portion of the hydrologic response: the rising limb is delayed; the peak flow decreases while the slow release is lightly detected in the decreasing hydrograph limb.

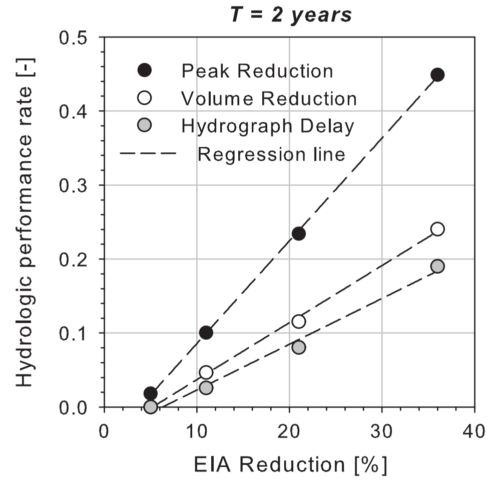

Fig. 5. Hydrologic performance vs. the EIA reduction at a rainfall event return period $T = 2$ years.

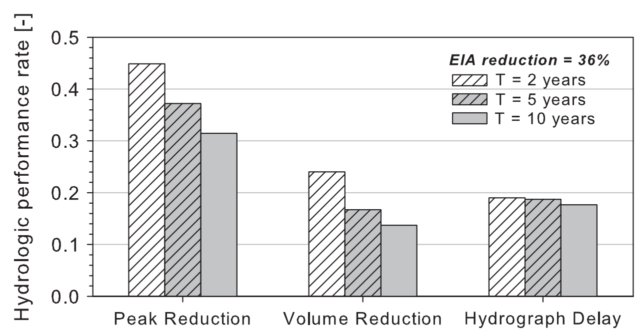

Fig. 6. Hydrologic performance vs. the rainfall event return period at the EIA reduction scenario of 36%.

Focusing on the 2-year return period event, Fig. 5 illustrates the hydrologic performance vs. the EIA reduction. Results point out that the hydrologic performance is linear dependent on the EIA reduction; furthermore the peak reduction reveals the best performance as confirmed by the steeper regression line. A linear relationship is similarly observed by Kleidorfer et al. (2014) who investigated the impact of land-use change expressed as either pavement of urban areas (increase of fraction imperviousness) or as unsealing and infiltration (decrease of fraction imperviousness) for an Alpine case study.

3.2. Impact of the rainfall event return period

The impact of the rainfall conditions is here examined by simulating the hydrologic response under three synthetic hydrographs corresponding to the 2, 5 and 10-year return period events. By comparing the hydrologic performance reported in Table 9, results demonstrate that the reduction in peak and volume are affected by the rainfall event return period contrary to what is observed for the hydrograph delay. Focusing on volume, the reduction is driven by the retention capability of the catchment that is strictly related to the physical characteristics of the LIDs (such as the void ratio and depth), therefore the performance is limited by the rainfall volume. Similarly Qin et al. (2013) observed that the performance of the LIDs is affected by their structure and properties; in particular by examining the flood volume that occurs for rainfall events with increasing volume, the system performance is enhanced by increasing the effective storage capacity of the systems.

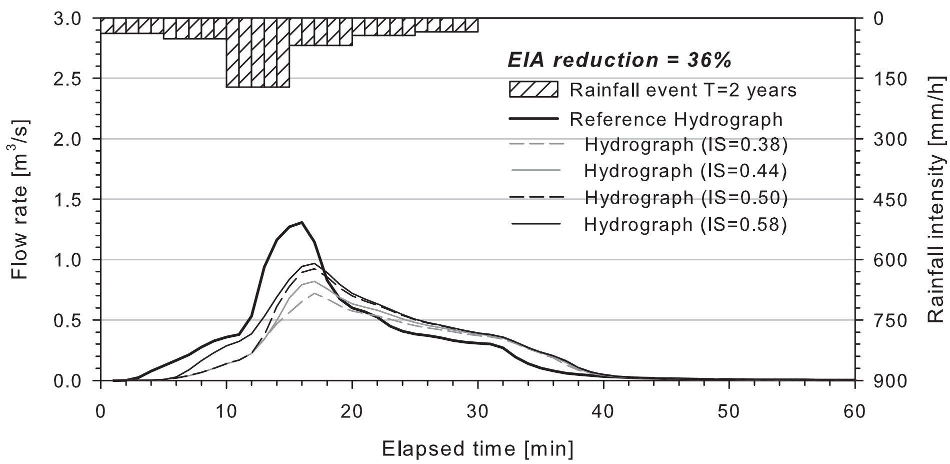

Fig. 7. Comparison between the reference hydrograph and the hydrographs simulated at different Initial Saturation (IS) of the green roofs. The simulation is referred to the rainfall event return period $T = 2$ years and EIA reduction scenario 36%. The reference scenario indicates the "do nothing" scenario.

Regarding the hydrograph peak and timing (see also Fig. 4), the peak reduction is affected by the detention capability of the catchment (connected to the rainfall-runoff process modified by the LIDs) while the hydrograph delay is fairly constant since the time-to peak is independent by the rainfall intensity for the investigated low-frequency events.

Fig. 6 shows the hydrologic performance vs. the rainfall event return period at the EIA reduction scenario of 36% (corresponding to the whole conversion of rooftops and parking lot areas). Findings of the analysis clearly confirm the influence of the rainfall event return period on the reduction of the peak and volume. Moving from the 2-year to the 10-year return period event, the performance decreases by 0.14 out of 0.45 for the peak reduction and by 0.09 out of 0.23 for the volume reduction; in addition the peak reduction decrease is fairly linear whereas the variation of the volume reduction is pronounced between 2-year and 5-year return period.

3.3. Sensitivity analysis of the LID initial saturation

The sensitivity analysis of the initial saturation condition of the LIDs is performed referring to the 2-year rainfall event return period and the EIA reduction scenario of 36%. As the simulations are performed on an event basis, the initial saturation accounts for the retention recovery that occurs during the inter-event periods (Lucas and Sample, 2015). In particular the initial saturation conditions are assumed in the range of variation between 0.38 and 0.62 in steps of 0.04. With specific reference to the green roof solution adopted in the present study, the Initial Saturation (IS) of 0.38 and 0.62 corresponds to a Soil Water Content (SWC) of 0.30 and 0.43 respectively. Therefore the sensitivity analysis concerns the water content ranging between average moisture conditions and the field capacity (see also Table 5).

Fig. 7 reports the comparison between the reference hydrograph and the hydrographs simulated at different initial saturation conditions of the green roofs. Simulation results demonstrate that the rising limb is delayed even if the initial saturation is closer to the field capacity (i.e. IS = 0.58 or SWC = 0.42); when the IS decreases, the hydrographs reveal a slower rising limb thus resulting in decreasing peak flow rate. Note that the peak flow is fairly constant for IS ranging from 0.50 to 0.58 and the time-to-peak is constant across the whole range of variation.

In Fig. 8 the hydrologic performance is plotted vs. the initial saturation conditions of the green roof. The peak reduction shows two different trends: as IS rises up to 0.50, the peak reduction is linearly reduced while for IS greater than 0.50 the curve rapidly tends to a constant value. The volume reduction is linearly reduced by increasing IS conditions, as expected. The hydrograph delay slowly

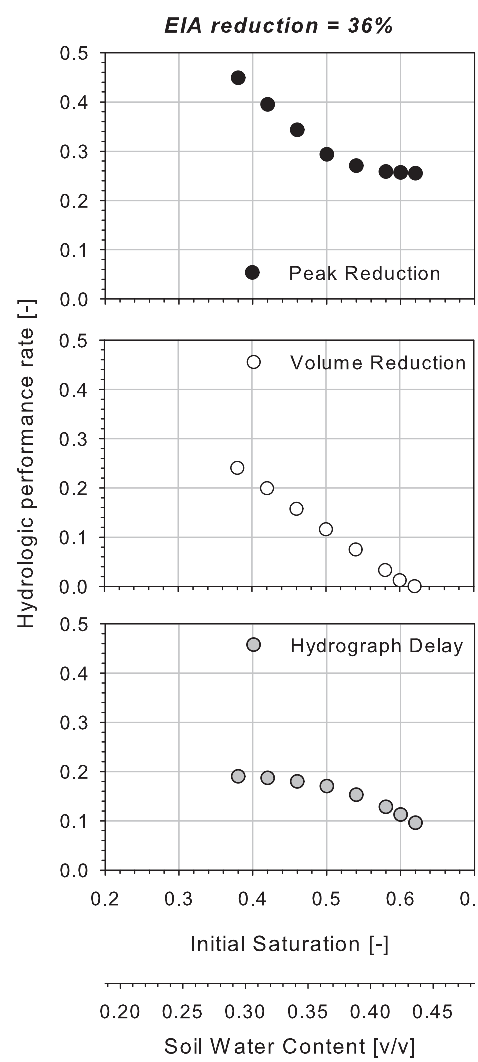

Fig. 8. Hydrologic performance vs. Initial Saturation of the green roofs at a rainfall event return period $T = 2$ years and EIA reduction scenario of 36%.

decreases when IS increases, as confirmed by the similar shape and timing of the hydrographs (see also Fig. 7).

4. Conclusions

The hydrologic response of a small urban catchment has been simulated under different rainfall event return periods implementing various land use conversion scenarios. At this aim, the EPA SWMM including the LID control modules has been implemented at high spatial resolution. The urban catchment of 5.5 ha has been subdivided into 286 subcatchments with homogenous surface properties. The detailed disaggregation of the catchment land uses (i.e. the definition of subcatchments characterized by single land use) is needed to suitably implement the LID solutions and assess their performance. The reference scenario and the LID modules have been calibrated using respectively field and laboratory test measurements.

Modeling results confirm the role of LID solutions in restoring the critical components of the natural flow regime at the urban catchment scale. The environmental benefits are estimated based on the following hydrologic performance indexes: the peak flow reduction, the volume reduction and the hydrograph delay.

The hydrologic performance analysis shows the following results

- the effectiveness of LID solutions requires a minimum land use conversion area (EIA reduction threshold value of 5%);
- the hydrologic performance linearly increases with increasing the EIA reduction percentages. At 36% EIA reduction, the peak and volume reductions rise till 0.45 and 0.23 respectively while the hydrograph delay increases till 0.19;
- the peak reduction diminishes by 0.14 out of 0.45 and the volume reduction diminishes by 0.09 out of 0.23 with increasing the rainfall event return periods from 2 to 10 years.

Findings of the present research reveal a noticeable hydrologic performance even for the design storm event ($T = 10$ years) thus confirming the effectiveness of LID practices in storm water control.

The EIA reduction strategy suggests that proper land use planning policy, including LID installations, achieves the sustainability objectives of storm water management thus limiting overflow discharges and drainage system failures. The proposed modeling approach demonstrates that SWMM can be suitably used to assess the LID performance and consequently to support their widespread implementation at the urban catchment scale.

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