Modelling storm water control operated by green roofs at the urban catchment scale

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ABSTRACT
The urban catchment of Colle Ometti, in the town of Genoa, Italy, where storm water runoff is monitored for both quantity and quality, was selected as a test site for the hydrologic modelling of greening scenarios. Although no green roof installations are now present in the area, this study modelled – using extensive green roof details – the hydrologic effects of three hypothetical roof greening scenarios at the catchment scale (conversion of 10%, 20%, and 100% impervious to green roofs).
The modelling of green roof performances was undertaken using the EPA SWMM and was calibrated and validated on a small size green roof system completed in September 2007 in the laboratory of the Department of Civil, Environmental and Architectural Engineering (DICAT – University of Genoa). Precipitation scenarios were developed based on eighteen years of high resolution (one minute) rain gauge data in Genoa (1990-2007).
Hydrologic modelling demonstrated that widespread green roof implementation can significantly reduce peak runoff rates and the lag time (7min and 15 min) runoff volume (detention effect) while after introducing the drying process operated by evapo-traspiration during the inter-event period the runoff volume reduction at the event scale (retention effect) can also be appreciated.

KEYWORDS
Green roofs; sustainable urban drainage; storm water detention; hydrologic models.

INTRODUCTION
Traditional storm water management practices mainly rely on conveyance to route storm water runoff from urban impervious surfaces into the nearby natural water bodies. Dedicated facilities are designed to reduce storm water runoff pollution and/or mitigate the effects of the increased runoff peaks, volumes, and velocity.
More recent concepts in urban storm water management, such as better site planning techniques and Sustainable Urban Drainage Systems (SUDS) or Low-Impact Development (LID) technologies – including green roofs, focus on the use of both planning techniques and micro-scale integrated landscape-based practices to prevent or reduce the impact of storm water runoff at the very point where these impacts would be initially generated.
In urbanized areas, undeveloped land is scarce and storm water management must be retrofitted into the built environment, so green roofs provide a way for roofs to be used beneficially rather than contributing to storm water problems. In the framework of the assessment of the environmental benefits of greenroof in terms of hydraulic-hydrologic performances it is necessary to extend the horizon of the investigation from the spatial scale

of the single green roof to the entire urban catchment. However few studies investigated the influence of the number and spatial distribution of green roofs throughout the watershed on the hydrologic response to quantify the reduction of the total volume entering the drainage network, the peak flow attenuation and the extended concentration times (Mentens *et al.,* 2003; Carter and Jackson, 2007; Levallius, 2005).

METHODS

Test site

The urban catchment of Colle Ometti, in the town of Genoa, Italy, where storm water runoff is monitored for both quantity and quality, was selected as a test site for the hydrologic modelling of greening scenarios. This 5.5 ha watershed, was urbanised in the eighties with 500 houses built on a previously undeveloped hill slope (cf. Figure 1). The separate sewer system consists of a main collector and eight lateral sewers.

Figure 1. A view of the urban catchment of Colle Ometti, in the town of Genoa, Italy.

As illustrated in Table 1, land uses were classified as roof, flat roof, road and parking lot, green area and farmland, and total impervious/pervious areas were calculated based on the regional cartography and aerial photographs.
The analysis of land-use data revealed that 60.3 % of the Colle Ometti watershed is covered with impervious surfaces and that roofs (flat and sloping) account for 30.9% of the total land cover and 51.3% of the impervious areas. Slightly less than 10% of the roofs are flat, with almost flat rooftops being concentrated in the upstream part of the watershed.
Although no green roof installations are now present in the area, this study modelled – using extensive green roof details – the hydrologic effects of three hypothetical roof greening scenarios (conversion of 10%, 20%, and 100% impervious to green roofs).
The detailed spatial information allowed for different scenarios to be explored across the watershed, in Table 1 the total impervious and pervious areas for each conversion scenario are summarised. The reduction in total impervious areas is evident, with the greening of all rooftops leading to about a half-size reduction.

Table 1. Land uses in the present and simulated conditions.

	Land use	Area	
	(-)	(ha)	(%)
Impervious areas			
	Sloping Roof	1.33	29.2
	Flat Roof	0.08	1.7
	Road and Parking Lot	1.28	28.1
	Other	0.06	1.3
	Total Impervious Area - existing land use	2.75	60.3
	Total Impervious Area - 10% conversion	2.61	57.2
	Total Impervious Area - 20% conversion	2.47	54.1
	Total Impervious Area - 100% conversion	1.34	29.4
Pervious areas			
	Green Area	1.28	28.1
	Farmland	0.53	11.6
	Total Pervious Area - existing land use	1.81	39.7
	Total Pervious Area - 10%conversion	1.95	42.8
	Total Pervious Area - 20%conversion	2.09	45.9
	Total Pervious Area - 100%conversion	3.22	70.6

The Modeling Structure

The Colle Ometti watershed was modelled by employing the EPA Storm Water Management Model (SWMM).The domain is simplified in 286 sub-catchments, 102 junctions and 101 conduits. The flow routing method is based on the kinematic wave model and on the Manning equation and the infiltration model is the Soil Conservation Service Curve Number method (SCS, 1972).

The model parameters, calibrated and validated on 10 events collected between February and June 2005, are summarized in Table 2. CN = 100 was assumed for rooftops, CN = 98 for roads and parking lots and other impervious areas, CN = 70 for green areas and CN = 76 for farmlands.

Table 2. Model parameters for the Colle Ometti watershed.

	Land use	CN	Depression Depth	n Manning
	(-)	(-)	(mm)	(-)
Sub-catchments	Sloping Roof	100	0.5	0.012
	Flat Roof	100	0.5	0.012
	Road and Parking Lot	98	1	0.015
	Green Area	70	5	0.41
	Farmland	76	4	0.25
Conduits		-	-	0.015

Model for the green roof. The SWMM code (Huber and Dickinson, 1992) was employed to simulate the infiltration process and the subsurface flow from green roofs. A green roof is described as a particular aquifer as thick as the substrate depth, with the water table being coincident with the bottom elevation.

The governing subsurface flow equation is the Darcy's Law under the Dupuit-Forcheimer assumption (Bouwer, 1978), while the infiltration model is the Soil Conservation Service

Curve Number method. During the simulation the deep percolation from the saturated zone to groundwater was fixed to zero and evapo-transpiration is neglected.
The green roof Model was calibrated and validated using results from a small size system realized in laboratory.
A green roof test plot was established at the laboratory of the Department of Civil, Environmental and Architectural Engineering (DICAT – University of Genoa) in September 2007 aimed at performing runoff tests in a controlled environment using rain simulators, with varying slope, depth and type of soil layers. The small size system is fully monitored: it is equipped with two cylindrical reservoirs for measuring inflow and outflow (for subsurface flows greater than 0.1 l/min) by level determination using two ultrasonic probe and with a couple of tipping buckets to measure the effluent at a lower rate.
The small size system of 2.5 m^2 uses, for this study, an engineered system "Estensivo SEIC" from Harpo SEIC – Divisioni Verde Pensile, primarily comprised of loose-laid synthetic specialized layers underneath the growing media. This growing media (total depth of 12 cm) is a blend of lapillus, crushed brickwork, pumice, sand of brickwork, and for the organic matter, a blend of peat and vegetable compost. This media has a bulk density of 1.225 g/cm^3 and a total porosity equal to 64%.
The hydraulic parameters (porosity, wilting point, field capacity, K_s and CN) required by the model for each green roof are listed in Table 3: the porosity was measured in the laboratory, CN value was assumed to have no excess infiltration; while wilting point, field capacity and K_s - saturated hydraulic conductivity [LT^{-1}] - were calibrated using specific runoff test.

Table 3. Green roof model parameters.

	Porosity	Wilting point	Field Capacity	K_s	CN
	(%)	(-)	(-)	(m/s)	(-)
Aquifer	64	0.05	0.29	0.1	10

RESULTS AND DISCUSSION

Long Period Simulation

Greening conversion scenarios. The hydrological simulation was carried out for the existing land cover and for three greening scenarios, the 10% impervious to green roof conversion, the 20% conversion and all roofs greened (100%). Spatial analysis revealed that only 6% of the rooftops were flat, so for the 10% scenario the greened roof are chosen among the flat and slightly sloping roofs, while for the 20% and 100% scenarios most of the sloping roofs are greened. In order to optimise the hydrological benefits of the greening conversion the flat roof scenario (slope equal to 1%) was assumed.

Precipitation scenarios. Storm water production was simulated based on eighteen years of high resolution (one minute) rain gauge data recorded in Genoa (1990-2007).
In order to enable the complete decrease of the hydrograph limb an inter-event equal to 24 hours was assumed.
Storm water events analysis (987 event) revealed that the rain excess for the 34 % of the events is less than 1mm and the maximum rain excess depth is 340 mm.
In Table 4 the frequency and average depth of rain excess are listed for each class of events.

Table 4. Storm event classes according to rain excess depth, relative frequency and average depth.

	Rain excess (mm)	Frequency (%)	Rain excess Avg Depth (mm)
Event class	0-1	34	0.3
	1-4	18	2.2
	4-10	15	6.4
	10-25	17	16
	25-400	16	62.8

Water quantity data

Within a urban watershed, green roofs contribute to storm water management by re-establishing the processes of the natural water cycle, including percolation, infiltration, evaporation from the soil and evapo-transpiration from vegetation, and operating a hydrologic control over storm water runoff with a derived peak flow attenuation, an increase in concentration times and the reduction of pollutant loads.

Volume detention (temporary storage and eventual slow release) determines the attenuation and delay of storm water runoff peaks at the inflow into the drainage network. Peaks attenuation is due to the storage capacity of the soil short of the field capacity, the storage capacity of the drain layer, as well as to the slope of the roof and depends on the shape of the rain hyetograph and the soil moisture conditions.
As examples, in Figure 2 and Figure 3, response hydrographs for the existing land use and for the three greening conversion scenarios are illustrated respectively for a particularly intense event (23 August 1992 event) and for a medium low event (04 April 2000 event).

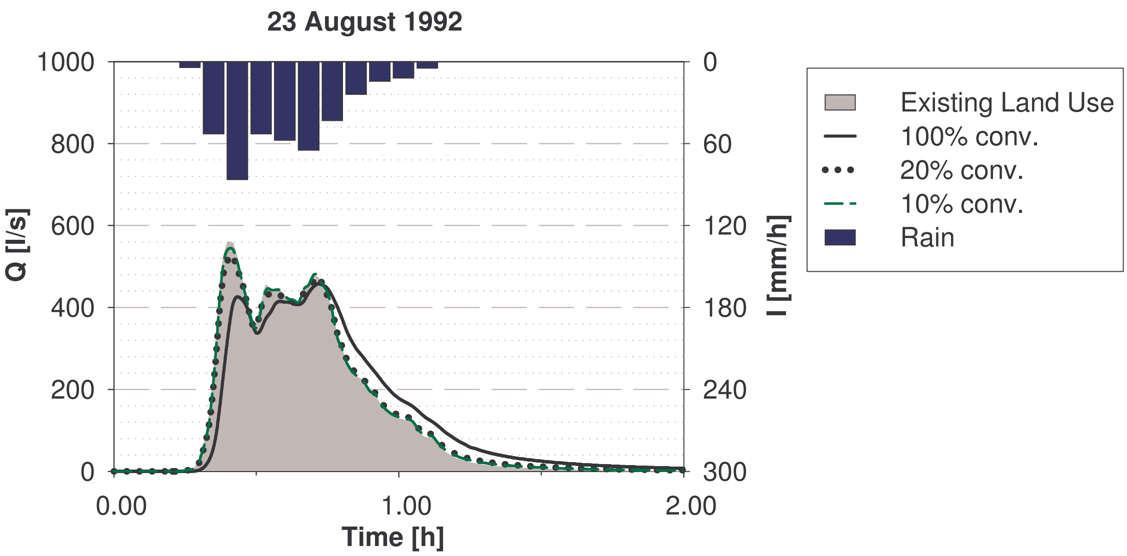

Figure 2. Comparison of existing land use condition hydrographs with the three greening conversion hydrographs for the 23 August 1992 event.

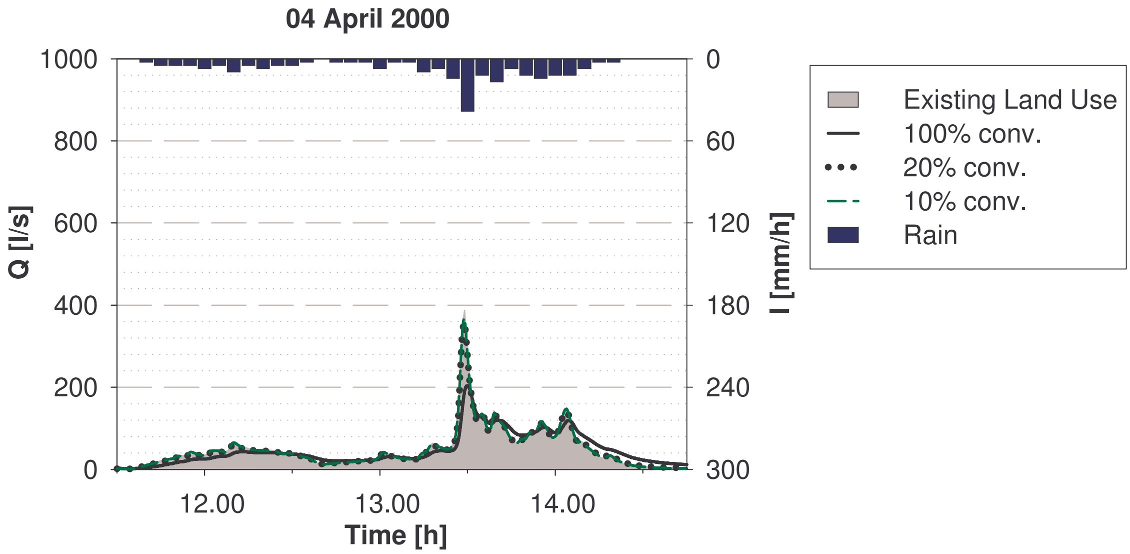

Figure 3. Comparison of existing land use condition hydrographs with the three greening conversion hydrographs for the 04 April 2000 event.

Volume retention (storage and slow dispersion in atmosphere) determines the event runoff volume reduction. The event runoff volume reduction is due to the water requirements of plants and the evapo-transpiration processes from vegetation and exposed surfaces.
Mentens *et. al* (2006) estimated a 2.7% annual runoff volume reduction for the town of Brussels in a 10% greening conversion scenario and Tillinger (2006) estimated a 2% annual runoff volume reduction in North River watershed –NY for a 10% conversion scenario.
In this simulation the evapo-transpiration and the water requirements of plants were neglected so for the greening conversion the event volume reduction is zero.

Volume Detention
The runoff coefficient calculated as the percentage ratio of the discharged volume in the first 7 minutes (equal to the lag time of Colle Ometti watershed in existing land use conditions) and 15 minutes of runoff and rainfall volume are shown in Figure 4 for the existing land use conditions and for the three greening scenarios. The average runoff coefficient for the existing land use conditions is respectively equal to 0.24 and 0.37 for 7min and 15 min of runoff; in the 100% conversion scenario the average runoff coefficient drops down to respectively 0.03 and 0.1 and in the 20% conversion scenario it reduces respectively to 0.2 and 0.3, while in the 10% conversion scenario remains respectively at 0.22 and 0.35.
The volume reduction calculated as the percentage difference between the discharged volume in existing land use conditions and the greening scenarios discharged volume in the first 7 min (lag time of Colle Ometti watershed in existing land use conditions) and 15 min of runoff are shown respectively in Figure 5 and Figure 6.The volume reduction calculated as the percentage difference between the discharged volume in existing land use conditions and the greening scenarios discharged volume in the first 7 min (lag time of Colle Ometti watershed in existing land use conditions) and 15 min of runoff are shown respectively in Figure 5 and Figure 6.
Changes in hydrology due to green roofing scenarios are clearly dependent upon the size (total depth, maximum intensity and duration) of the storm event, however for all five event classes the average value of the 7 min runoff volume reduction keeps itself constant even if, obviously for the last class (rain excess ranging between 25 mm and 400 mm) the standard deviation, bar errors in Figure 5, is bigger.

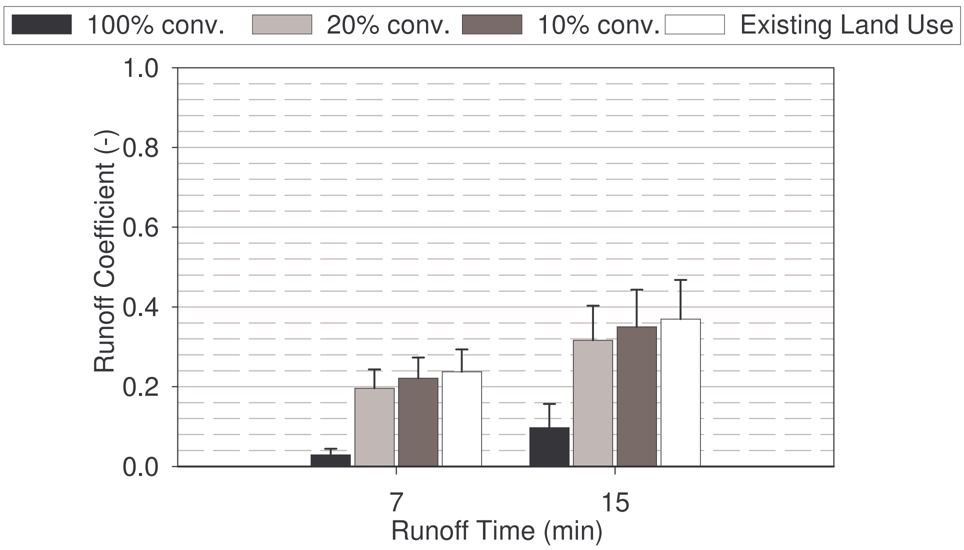

Figure 4. Comparison of the 7 min. runoff coefficient and the 15 min runoff coefficient for the three greening scenarios (10% conversion, 20% conversion and 100% conversion).

Greening all the rooftops produced a 7min volume reduction ranging between 89% for the first class (rain excess ranging between 0 mm and 1 mm) and 87% for the last classes; greening the 20% of the rooftops the 7min volume reduction is slightly under 18% and greening only the 10% is slightly under 6%.

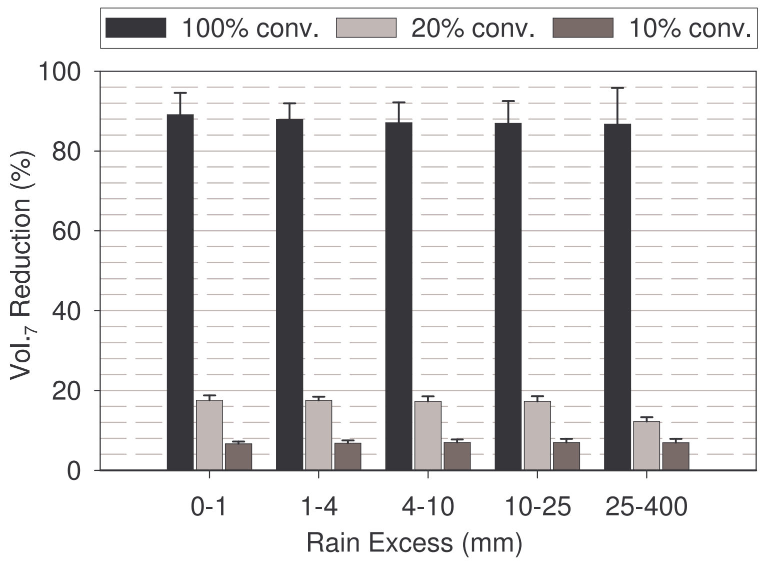

Figure 5. Comparison of the 7 min. runoff volume reduction for the three greening scenarios (10% conversion, 20% conversion and 100% conversion) according to rain excess event classes.

An analogue behaviour emerges for the 15 min. runoff volume reduction, as illustrated in Figure 6. Greening all the rooftops produced a 15 min volume reduction ranging between 79% for the first class (rain excess ranging between 0 mm and 1 mm) and 72% for the last classes; by greening 20% of the rooftops the 7min volume reduction ranging between 15% for the first class and 14% for the last classes and greening only the 10% is slightly under 5%.

Results demonstrated that greening rooftops is able to significantly detain storm water runoff with the consequent increase of concentration times and the lowering of pollutant loads associated with the early stages of rainfall.

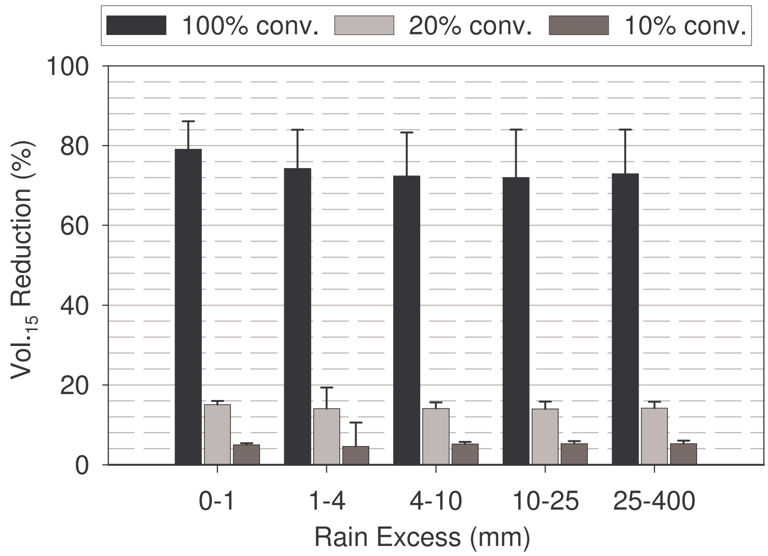

Figure 6. Comparison of the 15 min. runoff volume reduction for the three greening scenarios (10% conversion, 20% conversion and 100% conversion) according to rain excess event classes.

The peak flow reduction calculated as the percentage difference between impermeable peak flow and measured peak flow is shown in Figure 7 for the existing land use conditions and for the three greening conversion scenarios, according to the rain excess event classes.

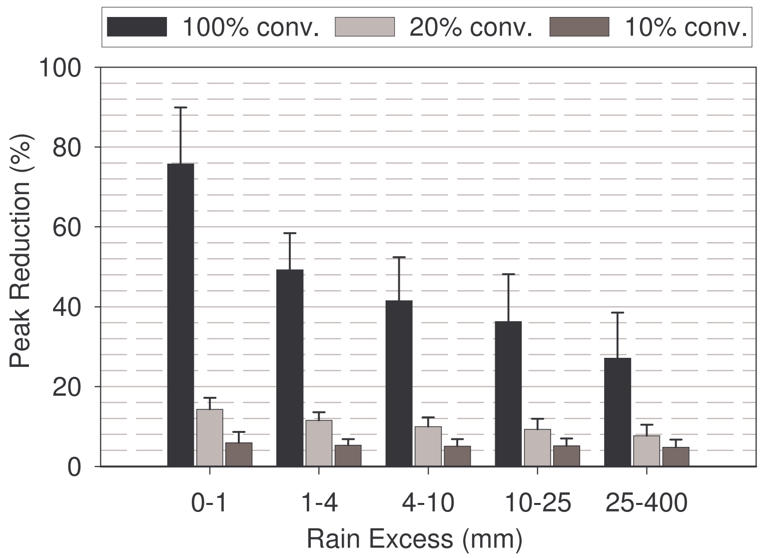

Figure 7. Comparison of the peak reduction for the three greening scenarios (10% conversion, 20% conversion and 100% conversion) according to rain excess event classes.

Changes in hydrology due to green roofing scenarios are clearly dependent upon the class of the storm event, however for all five event classes the greening of all rooftops produced a significant peak reduction ranging between 76% for the first class (rain excess between 0 mm

and 1 mm) and 27% for the last class (rain excess between 25 mm and 400 mm). In the 20% greening scenario the peak reduction ranges between 14% (for the first class) and 11% (for the last class) while for the 10% greening scenario this results between 6% and 4.8%.
From these data it clearly emerges that widespread green roof implementation (100% conversion scenario) can significantly reduce peak runoff rates. The reduction of peak runoff is able to lower the risk of localised flooding in the urban area and – in case of combined sewer systems – to reduce the number of CSOs with beneficial effect on the environment.
For future storm sewer retrofitting options, reduction in peak flows volumes from roof greening could provide economic benefit through decreasing the sizing of culverts and pipes.

Results demonstrated, according with literature experiences (Villareal *et al.*, 2004), that widespread green roof implementation became an helpful tool to prevent flooding phenomena in the urban areas and to limit the impact of storm water on waste water treatment plants. However it is clear that roof greening alone will never fully solve the urban runoff problem and it could to be combined with other runoff reduction measures (e.g. wet pond, permeable pavement, infiltration trench, etc.).

CONCLUSIONS

The hydrologic behaviour of the Colle Ometti watershed in the town of Genoa was examined over a eighteen years period on an event basis. Although no green roof installations are now present in the area, this study investigated the potential hydrologic benefits of three hypothetical rooftop greening scenarios (conversion of 10%, 20%, and 100% impervious to green roofs). The EPA SWMM 5 was used to examine the hydraulic performances of the three greening scenarios in the catchment.

The simulation demonstrates that the use of extensive green roof (15 cm total depth), even only on 10% of all roofs in a relatively green urbanized fabric, already reduce the peak flow ratio by 5%. The hydrologic performances of the 100% greening scenario with an average percent of peak flow reduction of 51% appear excellent, and it is expected, using green roof with a deeper substrate (intensive system), to enhance the detention effect. It should be noted that the depth of the substrate layer cannot be extended without consequences, while extensive system are lightweight, the intensive ones need extra load to pose construction.

The role of evapo-transpiration during the inter-event duration must be quantified to estimate the retention effect in terms of event runoff volume reduction, seasonal and annual volume retention initial and to better estimate the detention effect.

The strategy also suggests that proper land-use planning policy for the new settlements and planning restoration processes for the existing build heritage can improve the environmental benefits of green roofs at least from the hydrologic point of view.

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