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Research papers

# Evaluating performances of green roofs for stormwater runoff mitigation in a high flood risk urban catchment

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ABSTRACT

Urbanization modifies the hydrologic cycle, resulting in increased runoff rates, volumes, and peak flows in the drainage network. In this paper, the implementation of green roofs as source control solutions for mitigating the impacts of urbanization is analysed at the urban catchment scale. The hydrologic-hydraulic response of a 2 $km^2$ urban basin is investigated under various implementation scenarios and rainfall characteristics. In particular, a distributed hydrologic model is employed to assess the impact of 4 spatially homogeneous installations of green roofs (25%, 50%, 75%, 100% of roofs area converted) when forced by 6 storms differing in both duration and return period. In addition, a spatially heterogeneous configuration is tested, with green roofs concentrated where the drainage network is more prone to high degrees of filling. Results show that implementing green roofs at the urban watershed scale can be considered a valuable strategy to reduce both flow peak and volume in urban drainage networks, although the approach is more effective for frequent storms of smaller magnitude. In addition, it is found that the urban system may respond non-linearly to the extent of green roofs implementation in terms of peak flow reduction at the network outlet, and that non-linearity is mainly related to the network being close to its flow convey capability. Finally, planning redevelopment efforts on the basis of local insufficiencies in network convey capacity has the potential of increasing the effectiveness of Low Impact Development solutions.

## 1. Introduction

Urbanization is typically accompanied by expansion of impervious surfaces such as roofs and roads, compaction of soils, and modification of vegetation. These alterations may reduce rainfall infiltration, and hence increase stormwater runoff in terms of both rate and volume. As a consequence, evapotranspiration and groundwater recharge decrease, whereas erosion in streams and pollutants load to downstream ecosystems increase (Bean et al., 2007; Fassman and Blackbourn, 2010; Grebel et al., 2013), causing the well-documented decline of habitats and water quality in urban channels (Elliott and Trowsdale, 2007). To cope with the modified regime of stormwater runoff, hydraulically efficient drainage systems are usually built in the urban environment. However, traditional management approaches focusing on conveyance and detention have little to no effect on channel erosion, localized flooding, and water quality (Fry and Maxwell, 2017). Such limitations have raised the interest in nature based solutions, or green infrastructure, for achieving a more comprehensive mitigation of the impacts that urbanization has on the hydrologic cycle (Barbosa et al., 2012; Burian et al., 2000; Burns et al., 2012; Chocat et al., 2001; Delleur, 2003; Gleick, 2003). These natural systems use Low Impact Development controls (LIDs) that can mimic pre-development hydrology, and manage and treat urban stormwater in a distributed manner (Dietz, 2007; Newcomer et al., 2014; Roy et al., 2008). In particular, LID approaches implement small-scale hydrologic controls for infiltrating, filtering, storing, evaporating, and detaining runoff close to the source point (Ahiablame et al., 2012, 2013; Palla and Gnecco, 2015), thereby watersheds partially recover pre-urbanization conditions.

These sustainable runoff management measures have a prominent role in regional directives for flood protection and hydrogeological hazard prevention, especially where a high density of impervious surfaces occurs (Wilkinson et al., 2014). Indeed, currently, the urgent need to introduce “soft” mitigation measures for managing rainwater and reducing storm runoff has led many regional water agencies, in Italy and elsewhere, to increasingly promote directives addressed to the concept of “hydrologic-hydraulic invariance” (among which the Lombardy Region law n° 4 of 8 April 2016 and the Emilia-Romagna Region

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law 1860/2015), stating that the peak flow generated by any newly urbanized area has to remain unvaried after land transformation. The adoption of this concept requires the design of specific mitigation/compensatory measures as well as the definition of their appropriate allocation at the urban catchment scale in order to decrease runoff where most needed. Therefore, although urban LIDs such as bioretention systems, porous pavements, permeable patios, rain barrels/cisterns, green roofs, wet ponds, and dry ponds appear to be suitable practices to meet hydrologic-hydraulic invariance, anticipating their overall impact on the urban drainage system is not straightforward. Many model-based results confirm the role of LID solutions in restoring natural flow regime at the urban catchment scale (Lee et al., 2012a,b; Fry and Maxwell, 2017), but their effectiveness could depend on (i) the spatial location of these devices (that is often in conflict with the location of areas where redevelopment would be possible), (ii) the complexity of the urban drainage network, and (iii) the magnitude of storm events.

In this work, the SMART-GREEN software (Chiaradia et al., 2018), designed to simulate runoff formation and propagation in the urban environment and integrating LID control facilities, is used to explore the impacts of green roofs on stormwater runoff and the draining sewer system at the urban catchment scale. Performances are evaluated across a range of storm intensity and duration, for multiple degrees of implementation, and various spatial configurations. The investigation aims at offering a thorough assessment of green roofs potentialities at the urban basin scale, including the impact on both runoff generation and sewer system draining capabilities. Understanding whether and to what extent the structure of the sewer system already present in the urban catchment affects the effectiveness of redevelopment scenario is of primary importance for watershed-scale LIDs planning. The work discusses strengths and weaknesses of implementing green roofs at the urban basin scale on a real case study, attempting to evaluate the obtainable advantages for the actual drainage network, without any simplification or modification of its layout. This will enrich awareness and knowledge on the actual effectiveness of LID approaches at the urban watershed scale, and help identifying where structural measures on the sewer system appear essential to prevent excessive filling of conduits or overflow from network nodes. Furthermore, we explore the possibility of defining a rationale that could guide green roofs spatial planning at the urban watershed scale in order to enhance their effectiveness.

## 2. Materials and methods

### 2.1. SMART-GREEN software

The software is composed of two main blocks, (i) the actual modelling system, named MOBIDIC-U, and (ii) the surrounding Graphic User Interface (GUI), developed as a QGis plugin and mainly dedicated to the preparation of the input data and the analysis of the results. A full integration of a hydrological model into a QGis plugin provides the advantage of employing a comprehensive and detailed modelling approach while maintaining an easy and efficient setup of simulations, thanks to the functionalities typical of a GIS (collection and analysis of spatial data). In particular, the software allows a straightforward implementation of LID solutions in the area of study, representing a valuable tool for planners who evaluate the impact of LIDs on stormwater management at the catchment scale. More information about the SMART-GREEN framework can be found in Chiaradia et al. (2018).

#### 2.1.1. Modelling component

MOBIDIC-U (MOdello di Bilancio Idrologico DIstribuito e Continuo – aree Urbane) is a hydrologic model designed to simulate runoff formation and propagation in the urban environment, capable of including the effect of LID systems. It is a specialisation of the model MOBIDIC (MOdello di Bilancio Idrologico DIstribuito e Continuo) (Ercolani and Castelli, 2017; Yang et al., 2014a,b; Castelli et al., 2009; Campo et al., 2006), which can deal with terrains draining towards a natural channel network in accordance with the topographic slope. MOBIDIC-U shares with MOBIDIC the basic modelling features, but various algorithms have been developed to describe the peculiarities of the urban environment. Specifically, the following characteristics are in common with MOBIDIC: (i) fully distributed approach for both parameters and results (raster-based discretization of the area of study); (ii) computationally efficient and parsimonious representation of soil moisture dynamics and surface runoff formation (Castillo et al., 2015). Soil is vertically discretized into one single layer, conceptually subdivided into two non-linear interconnected reservoirs corresponding to larger pores draining water under gravity (gravitational reservoir) and smaller pores holding water through capillary forces (capillary reservoir). Accordingly, the maximum storage capacity of the two reservoirs may be parametrized as, respectively, the maximum water content above field capacity ($Wg_{max}$), and the difference between field capacity and residual water content ($Wc_{max}$). In addition, each computational cell includes three other conceptual non-linear reservoirs, i.e. the interception reservoir (characterized by a finite volumetric capability, $Wp_{max}$), the surface ponding reservoir, and the phreatic aquifer reservoir. Fig. 1 illustrates the hydrologic fluxes pertaining to the 5 compartments and their mutual connections. A detailed description of governing equations may be found in Ercolani and Castelli (2017). MOBIDIC-U combines the previous characteristics with the following ones: (i) the drainage network is described through a couple of interdependent vector layers, one polyline-type, representing conduits, and one point-type, representing network nodes. The layers should include topological, geometrical and hydraulic attributes. (ii) The flow routing through the drainage network employs the de Saint Venant equations in the conduits and mass conservation in the nodes. The algorithm is capable of dealing with a complex network topology, e.g. closed circuits (James et al., 2010). (iii) The routing of surface runoff and hypodermic flow from the production cell to the receiving node of the drainage network takes into account that the flow path in the urban environment is rarely determined by terrain slope (e.g. presence of elevated surfaces such as roofs). Furthermore, information about topography at the level of detail required to route the flow properly throughout a urban watershed is rarely available. Accordingly, the flow generated in any cell of the domain is routed to the drainage network through a linear "delay reservoir" (one

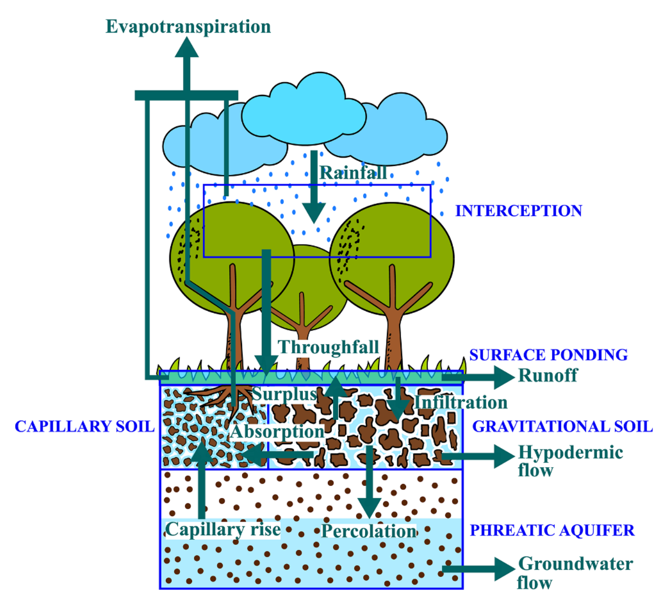


**Fig. 1.** Hydrologic volumes (blue) and fluxes (green) in the computational cell of MOBIDIC-U. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

for surface runoff and one for hypodermic flow). The delay parameter is modulated on the basis of the geometric distance between the production cell and the nearest network node, and local hydraulic properties (i.e. soil hydraulic conductivity for hypodermic flow and surface roughness characteristics for runoff). (iv) The water balance approach previously described for a generic computational cell is adapted to capture the essence of the hydrologic behaviour of LID solutions. For instance, percolation and capillary rise will be null for any cell belonging to a green roof, and no aquifer volume will be included. Drainage flow from the gravitational reservoir (corresponding to the hypodermic flow in the generic description of the balance) and surface runoff will be the only outflows during a storm event. The advantage of such approach is twofold. First, it is completely coherent with the rest of the model, adding robustness to comparisons between no-LIDs and LIDs scenarios; secondly, adopting a physically based description of LIDs functioning makes the recovering of LIDs hydrologic parameters extremely straightforward, since they are derivable directly from constructional characteristics of any single implementation (e.g., for green roofs, layers number and thickness, and media hydraulic conductivity, porosity, field capacity and residual volumetric water content). The increasing number of studies aiming at identifying values of conceptual parameters that describe properly LIDs hydrologic functioning (e.g. CN in the USDA CN method) testifies the added value of a physically based approach (e.g. Carter and Rasmussen, 2006; Getter et al., 2007; Alfredo et al., 2010; Damodaram et al., 2010; Fassman-Beck et al., 2016). Although potentially able to run continuous simulations over long periods, MOBIDIC-U is specifically designed for event based runs.

#### 2.1.2. GIS interface structure

MOBIDIC-U may be fully integrated in the GIS environment thanks to a freely downloadable QGIS (www.qgis.org) plugin, developed specifically to support model users. The general aim of the plugin is to exploit typical GIS functionalities (spatial data collection and analysis) to manage easily and efficiently both inputs and outputs of MOBIDIC-U. In particular, the plugin includes: (i) a friendly GUI to facilitate using the model; (ii) tools to import information easily from external databases; (iii) tools to check automatically the consistency of the sewer network, and to fix missing or uncoherent data (e.g. elevation of nodes bottom unknown or higher than the invert of a connected pipe); (iv) tools to view and analyse results quickly and easily. Additional details about specific functionalities and data organization are available in Chiaradia et al. (2018).

### 2.2. Study context

The area of study is the Sedriano municipality, which is located in the North-West portion of the Metropolitan city of Milan, in northern Italy (Fig. 2). The challenge that the Metropolitan city of Milan is facing is that the current stormwater infrastructure is undersized or non-existent, and will not be able to sustain the anticipated population growth and watershed modifications. Many municipalities need to address similar issues, and are looking for resilient options to mitigate the impacts on water quantity and quality (Barbosa et al., 2012; Burns et al., 2012). Sedriano municipality represents an adequate case study for multiple reasons. First, the territory consists of a mix of residential, industrial, and commercial areas, in line with many municipalities of the Metropolitan city of Milan, and emblematic of urban territories in general. Secondly, the outlet of the drainage network was monitored during late months of 2016, allowing for a basic model calibration. Third, during rainfall events inflows to the urban drainage network coincide essentially with stormwater, and possible additional inputs are neglected.

The municipality of Sedriano is 7.7 $km^2$ large (the boundary of the municipality is marked in red in Fig. 2) with a total population of about 12,000 inhabitants and a density of 1500 inhabitants per $km^2$. The topography is flat, on average 140 m a.s.l. The portion of the municipality surface considered in the study is about 1.9 $km^2$ (colored portion of the map in Fig. 2) with a total impervious area of about 0.69 $km^2$ which includes residential, commercial, and industrial buildings, roads and parking lots. Buildings roofs are around 56% of this total impervious area, i.e. 0.39 $km^2$.

The study context is characterized by a humid subtropical climate according to the Köppen classification system (Peel et al., 2007). During the year, the average temperature is about 10 °C, while total rainfall is around 800 mm.

The Sedriano urban drainage network, managed by CAP Holding spa, is about 23.5 km long and constituted by 686 conduits and 651 nodes (mainly representing manholes). The sewerage is a combined system, designed to collect both sewage and urban stormwater during rainfall events. The flow in the sewerage systems is gravity driven. Overall, conduits are designed considering rainfall whose return period ranges from 2 to 10 years, resulting in diameters between 0.1 m and 1.5 m (Fig. 3A). In this range, diameters between 0.3 and 0.5 m prevail, covering more than 50% of conduits. On the basis of diameters spatial distribution, the sewer system appears to converge the flow into a central main conduit (with a diameter enlarging from 0.8 to 1.6 m), which develops along the North-South direction of the municipality. However, the chaotic slope layout (Fig. 3B), with a considerable number of flat or almost flat conduits, does not always allow a regular delivery of water from the outermost conduits to the innermost ones. Moreover, the urban expansion in the last fifty years has increased the entanglement of conduits, and the lack of regulations requiring to map and georeference the sewer infrastructure up to 2014, made a systematic planning of conduits distribution impossible. Furthermore, the sewer system includes numerous closed circuits, which, combined with low slopes, make it impossible to know *a priori* the flow direction during a rainfall event. The significant presence of flat or almost flat conduits (about 14% of conduits with slope lower than 0.1% and 28% lower than 0.2%), and even a few improper counter-slopes, facilitates undesired backflows and overflows from nodes, as the water manager has observed in the field. The described complexity and peculiarity of the drainage network make Sedriano an interesting case study for the assessment of green roofs potential in stormwater management. Indeed, predicting the impact of a number of systems distributed over the catchment is not straightforward when a complex drainage network is involved (e.g. reducing runoff production in a certain area of the catchment may modify flow direction in some conduits, finally leading to an unexpected increment of discharge in other portions of the network).

### 2.3. Model setup

As described in Section 2.1.1, MOBIDIC-U requires a couple of interdependent shapefiles to represent the sewer system, one corresponding to conduits and one to network nodes. For Sedriano network, both layers are available from the local water manager, CAP Holding spa, complete with attributes needed by the model (i.e. for conduits, diameter, elevation of the initial and final invert, constituent material or Manning's coefficient, and for nodes, surface extension, bottom and top elevation, as well as topological information about mutual connections). Inconsistencies or missing data are detected and fixed through semi-automatic tools offered by Smart-Green QGIS plugin (see Section 2.1.2). The network is composed of 686 conduits and 651 nodes. Note that 17% of conduits and 39% of nodes have been treated to fix inconsistencies or missing information. The minimum and average conduit length is 0.5 m and 34 m respectively, for a total of about 23.5 km.

In terms of urban watershed description, MOBIDIC-U requires 4 spatially distributed physically based parameters (i.e. $Wc_{max}$, $Wg_{max}$, $Wp_{max}$ as described in Section 2.1.1, and surface layer saturated hydraulic conductivity $k_s$) and 4 lumped conceptual parameters. In particular, these latter are rate coefficients (dimensionally, inverse of a

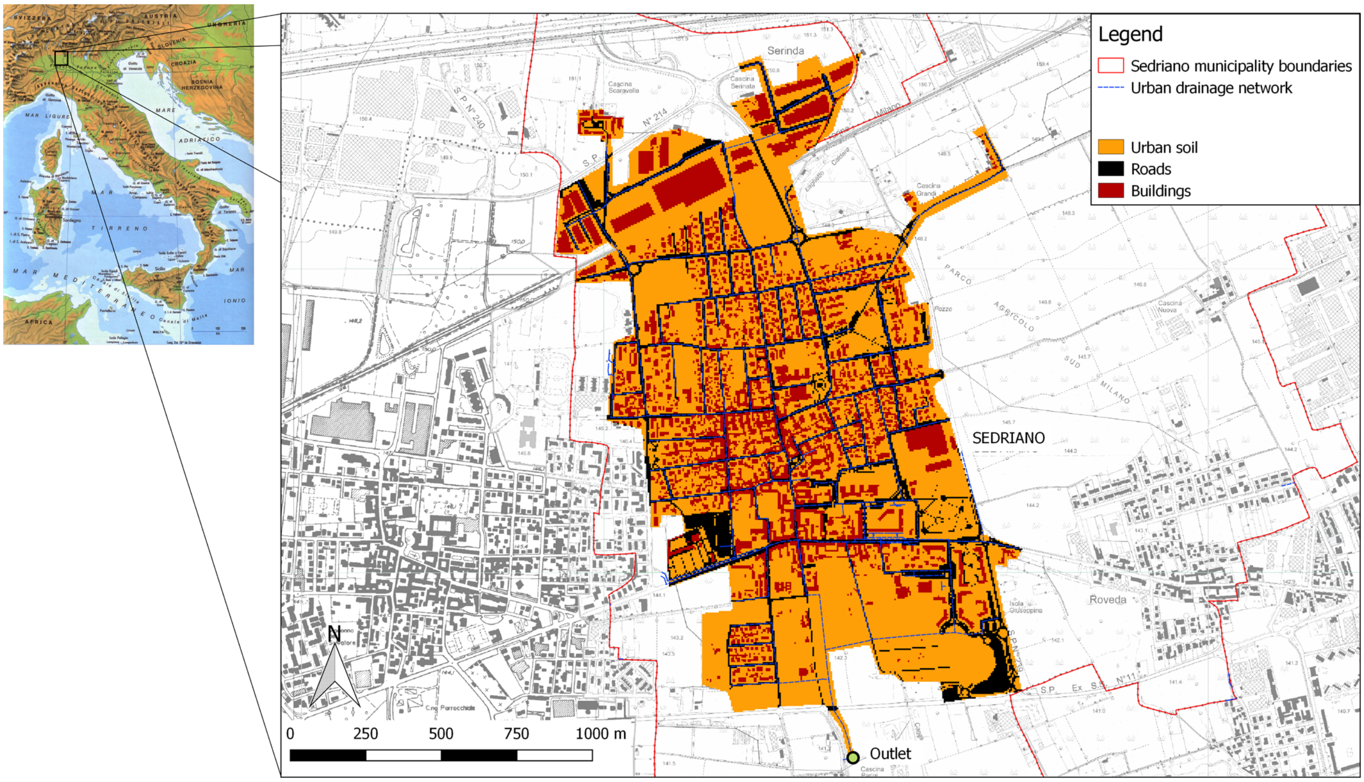


**Fig. 2.** Site position and Sedriano urban catchment as employed in the model. The thin red line indicates the boundary of the municipality. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

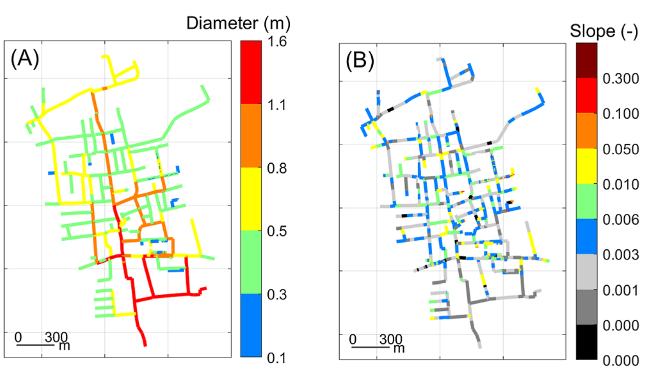


**Fig. 3.** Spatial distribution of conduits diameter (A) and slope (B) in the urban drainage network.

**Table 1**
Values selected for MOBIDIC-U parameters.

| Parameter | Roads, parking slots, impervious roofs | Urban vegetated soil | Green Roofs |
|---|---|---|---|
| $k_s$ ($m\,s^{-1}$) | 7 e-07 | 1.5 e-05 | 1.2 e-03 |
| $Wp_{max}$ (m) | 2 e-03 | 5 e-03 | 2 e-03 |
| $Wg_{max}$ (m) | 1 e-02 | 30 e-02 | 5.6 e-02 |
| $Wc_{max}$ (m) | 1 e-02 | 50 e-02 | 10.78 e-02 |
| $\alpha$ ($s^{-1}$) | 2 e-03 | | |
| $\beta$ ($s^{-1}$) | 8 e-07 | | 1 e-05 |
| $\gamma$ ($s^{-1}$) | 1 e-05 | | 0 |
| k ($s^{-1}$) | 1.82 e-06 | | |

time) regulating: (i) absorption of gravitational water by smaller pores (k); (ii) percolation of gravitational water ($\gamma$); (iii) maximum local production of hypodermic flow from gravitational water ($\beta$); (iv) maximum local production of surface runoff from surface water ($\alpha$). Details about equations involving these parameters may be found in Ercolani and Castelli (2017). The maps of the physically based parameters are derived on the basis of soil properties and land use characteristics, and refined through calibration if possible. For Sedriano municipality, the employed sources of information are Lombardy Region pedological map and topographic database, both freely available from the institutional website (www.geoportale.regione.lombardia.it). The first one offers quite a rough description of soil types spatial patterns in respect to the extension of the analysis, since our watershed is about 1.9 $km^2$ and the nominal scale of the pedological map is 1:250,000. However, it offers a support in determining model parameters directly related to soil properties, such as $Wg_{max}$ and $Wc_{max}$, which depend on porosity, field capacity and residual water content. In particular, the pedological map shows that Sedriano municipality is completely included in an area occupied by coarse-textured soils (more than 94% of sandy loam texture and less than 6% of loamy sand texture). The regional topographic database contains a series of layers representing elements constituting the territory, such as buildings, roads, agricultural fields, woods, etc. On the basis of such information, and in order to maintain a parsimonious and exportable approach, only two hydrological classes are identified in the basin, representing respectively impervious and pervious areas. Imperviousness is associated to buildings, roads and parking lots as identifiable from the regional topographic database, and shown in black (roads and parking lots) and red (buildings) in Fig. 2. The remaining areas are included in a unique class intended to represent a generic slightly vegetated coarse-textured urban soil. No information is available to further differentiate properties of pervious patches with a reasonable level of confidence. Table 1 lists the values of physically based parameters for the 2 hydrologic classes, and those of lumped conceptual parameters. The rationale employed to select the values is as follows. Physically based parameters corresponding to pervious areas are derived considering the characteristics of the predominant soil type in Sedriano municipality and a non negligible rainfall initial abstraction, due, for instance, to interception by vegetation. The same parameters for the impervious class and the conceptual parameters α and β are calibrated against one rainfall event recorded during the monitoring period. Typical average values are assumed for the remaining lumped conceptual parameters (k and γ), mainly on the basis of previous modelling experiences (e.g. Ercolani and Castelli, 2017). Finally, conduits Manning's coefficient is selected on the basis of constituent material. In particular, $0.013\ m\ s^{-1/3}$ is assumed for all the conduits, since they are plastic pipes. The whole setup is validated against the 2 remaining rainfall events that occurred during the monitoring period. Details about calibration and validation are in the following section.

The watershed is discretized with a spatial resolution of 5 m, such that singles buildings and roads are fully represented. The hydrological time step is 1 min, while flow routing through conduits in the network employs substeps of 3 s.

### 2.3.1. Calibration and validation

Sedriano sewer system was monitored from August to November 2016 by a specialized company (BM Tecnologie, Padue, Italy). Flow was measured at network outlet through a Kaptor Multi doppler device, and precipitation through a Delta Ohm HD 2013 tipping bucket rain gauge. This latter was installed in a service area in the adjacent municipality, Vittuone, about 1.9 km far from the barycentre of Sedriano urban catchment. During the monitoring period, 3 noteworthy rainfall events occurred, the first one on August, 5th, the second one on September, 21st, and the third on October 14th. All the events were moderate, with, respectively, a total rainfall depth of 19, 55.8 and 32.6 mm, a duration of about 1.25, 17.33, 7.5 h, and a maximum instantaneous intensity equal to 55.2, 36 and 31.2 mm/hour. We assume that rainfall measured by Vittuone rain gauge is representative for Sedriano urban basin and feed the model with spatially homogeneous precipitation, since no additional information is available. The event of August, 5th is employed for a trial and error calibration aimed at refining the description of impervious patches and the 2 most relevant lumped conceptual parameters. Accordingly, the calibrated parameters are $Wc_{max}$, $Wg_{max}$, $Wp_{max}$ and $k_s$ for roads, parking slots and impervious roofs, and α. The other 2 events are used to validate the whole model setup. Hydrographs of observed and modelled outflow are compared in terms of both volume and discharges. In particular, the percentage error on the peak flow ($PE_{Qmax}$) and total volume ($PE_{Vol}$) are computed, as well as the Nash-Sutchliffe Efficiency (NSE) index (Nash and Sutcliffe, 1970) to assess the instantaneous match between model and observations. Fig. 4 shows the hydrograph at Sedriano network outlet for the 3 rainfall events, with the black continuous line corresponding to modelled flows and red dots to observations. In addition, total precipitation over the urban basin is plotted in grey. Table 2 summarizes model performances for the 3 events. Overall the model can simulate properly runoff formation and propagation in the urban basin and sewer network of Sedriano. The match is excellent for the calibration event (Fig. 4A), with the NSE greater than 0.9 and only a slight underestimation of peak flow ($PE_{Qmax}$ equal to −4.88%) and overestimation of volume ($PE_{Vol}$ equal to 12.92%). The validation event of October, 14th (Fig. 4C) shows that the model is capable of describing hydrologic and hydraulic responses of Sedriano urban basin and drainage network even when triggered by more complex rainfall events (multi-peak, longer duration), with NSE equal to 0.63 and $PE_{Qmax}$ to −0.69%. For the sake of completeness, results corresponding to the last available rainfall event (September, 21st in Fig. 4B) are included. However, it is clearly visible that measured rainfall and flow are not coherent, neither in terms of quantity nor of timing. Two inconsistencies are particularly evident: (i) the first flow event (starting around 08:30) is anticipated in respect to rainfall, i.e. flow begins to rise before rainfall occurs; (ii) the system does not respond at all to the third rainfall sub-event (the one after 12:00), although intensity and total depth are comparable to those of the main sub-event of October, 14th (Fig. 4C), to which the system responds clearly. Moreover, this sub-event occurs after previous significant precipitation (i.e. the system is not dry), and a negligible flow at the outlet is unrealistic. The discrepancy between precipitation and flow observations may be due to the fact that the rain gauge is placed about 1.9 km far from Sedriano urban basin, and hence not fully representative of local precipitation. Instead, a very accurate assessment of rainfall spatio-temporal variability is required in urban hydrology, where the spatial and temporal scales are relatively small (Niemczynowicz, 1999; Fletcher et al., 2013). Accordingly, also measured and modelled flows cannot match, since they are triggered by different rainfall.

### 2.3.2. Green roofs parametrization

Green roofs are the LID devices whose implementation at the catchment scale is investigated in the present study. As described in Section 2.1.1, the parsimonious 5-compartments scheme employed by MOBIDIC and MOBIDIC-U for water balance in soil (Castillo et al., 2015; Ercolani and Castelli, 2017) can be easily specialized to represent green roof cells with ad-hoc modifications (i.e. turning off improper hydrologic fluxes, such as percolation or capillary rise). Accordingly, the hydrologic behaviour of green roof cells depends on the same 4 physically based parameters previously discussed (i.e. $Wc_{max}$, $Wg_{max}$, $Wp_{max}$, $k_s$), which can be derived from constructional characteristics of the specific implementation to represent. In the present study all the green roofs follow the design presented by Palla et al. (2009), with a total thickness of 35 cm without vegetative cover. In detail, the stratigraphy is primarily constituted by a first drainage layer of Vulcaflor (20 cm thick) and a second structural layer of Lapillus (15 cm thick). The first layer is characterized by a porosity of $0.650\ m^3\ m^{-3}$, a saturated hydraulic conductivity of $0.08\ cm\ s^{-1}$, a field capacity of $0.400\ m^3\ m^{-3}$, and a residual soil moisture of $0.165\ m^3\ m^{-3}$. Conversely, the second layer has a porosity of $0.600\ m^3\ m^{-3}$, a saturated hydraulic conductivity of $0.33\ cm\ s^{-1}$, a field capacity of $0.560\ m^3\ m^{-3}$ and a residual soil moisture of $0.155\ m^3\ m^{-3}$. These constructional characteristics correspond to the value of parameters reported in Table 1.

## 2.4. Modelling experiments

In order to assess the impact of green roofs implementation at the urban catchment scale, a series of redevelopment scenarios are simulated and compared with the current configuration, the "no conversion" scenario. This reference configuration corresponds to that employed for calibration and validation experiments, where all the roofs are impervious (see Fig. 2). A first set of simulations converts impervious roofs to green roofs homogeneously over the basin, without any preferential spatial pattern for their implementation. The impact of such spatially homogeneous conversions are assessed under different rainfall conditions. In particular, 4 percentages of rooftops conversions, 25%, 50%, 75% and 100%, are combined with 6 different hyetographs, for a total of 30 simulations (for each hyetograph the reference "no conversion" scenario is also modelled). Partial conversions (25%, 50% and 75%) are randomly distributed with the constraint of spatial homogeneity at the catchment scale. Namely, in any subcatchment contributing to a specific node of the network, the same percentage of roofs area is converted through a random selection. Hyetographs are synthetic, obtained from the Intensity–Duration Frequency relationship derived by ARPA for Sedriano area and adopting a uniform shape. In particular, 2 return periods, 2 and 10 years, and 3 rainfall durations, 35, 60 and 120 min, are considered. The selected return periods are in the range of those employed to design urban drainage systems, and, in addition, the local water management company detected small flooding in some areas of the municipality also for precipitation events corresponding to a 2 years return period or less. Table 3 shows rainfall depth and intensity for the 6 synthetic hyetographs.

In addition to the just described modelling experiments, two other simulations are included in the study. The aim is to provide a very first

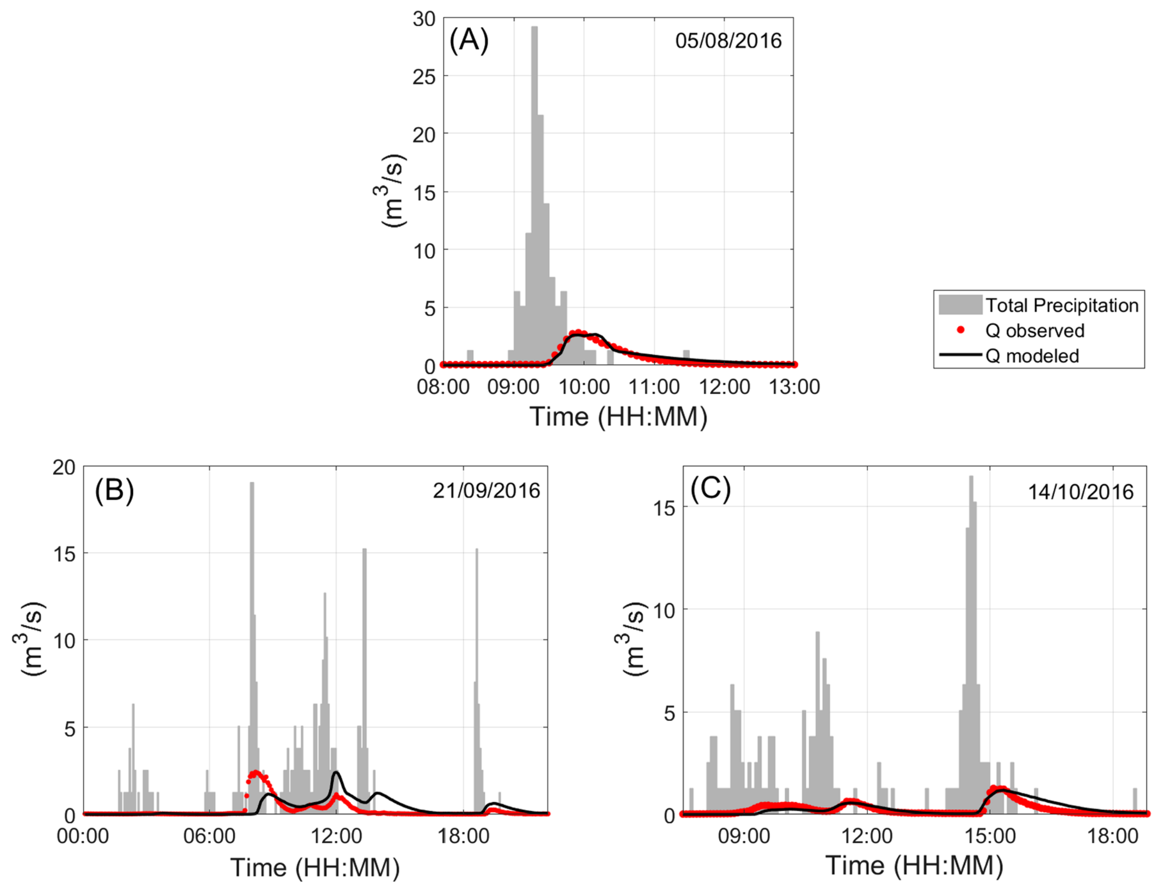


**Fig. 4.** Observed (red dots) and modelled (black continuous line) hydrographs at Sedriano network outlet for the 3 rainfall events occurred during the monitoring period. Total rainfall over the basin ($m^3/s$) is plotted in grey. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

**Table 2**
Percentage error on peak flow ($PE_{Qmax}$), percentage error on total flow volume ($PE_{Vol}$), and Nash-Sutchliffe Efficency (NSE) index for the 3 rainfall events occurred during the monitoring period.

| Rainfall event date | $PE_{Qmax}$ (%) | $PE_{Vol}$ (%) | NSE (–) |
|---|---|---|---|
| 05/08/2016 – calibration | −4.88 | 12.92 | 0.937 |
| 21/09/2016 – validation | −0.22 | 47.83 | −0.204 |
| 14/10/2016 – validation | −6.85 | 17.36 | 0.625 |

**Table 3**
Rainfall depth and intensity for the 6 synthetic uniform events employed in the analysis.

| Return Time (years) | Rainfall Duration (min) | | |
|---|---|---|---|
| | 35 | 60 | 120 |
| 2 | 19.4 mm (31.5 mm h$^{-1}$) | 28.3 mm (28.3 mm h$^{-1}$) | 35.2 mm (17.6 mm h$^{-1}$) |
| 10 | 31.5 mm (54.0 mm h$^{-1}$) | 45.9 mm (45.9 mm h$^{-1}$) | 19.4 mm (31.5 mm h$^{-1}$) |

exploratory test that could assess the possible advantages of a heterogeneous implementation of LIDs at the urban catchment scale. The two simulations share the same total percentage of green roofs over the basin (54% of the total surface occupied by impervious rooftops), but differ in terms of their spatial distribution. In one case the conversion from impervious to pervious roofs is spatially homogeneous and follows exactly the rationale employed in all the other scenarios. In the other case, green roofs are heterogeneously distributed throughout the basin. Studies have shown that spatial arrangement of LID controls on an urban watershed can influence the flow at the drainage system outlet (Bhaduri et al., 2000; Lee and Heaney, 2003; Khader and Montalto, 2008; Yao et al., 2016; Bell et al., 2016). Nevertheless, no guidance for their optimal distribution at the urban catchment scale is suggested in the literature. In our test, the heterogeneous scenario has local concentration of LIDs increasing where conduits are more prone to filling in the current condition. In particular, this "targeted" conversion of impervious roofs is guided by the results from the "no conversion" scenario when forced by 35 min of constant rainfall with a return period of 2 years. In any subcatchment contributing to a specific node of the drainage network, the area of buildings top converted to green roofs is assumed proportional to the maximum degree of filling reached by the connected conduits during the event. The "targeted" conversion is organized on the basis of a moderately frequent rainfall (return time of 2 years) coherent with the design return period of the conduits being in the range 2–10 years. Namely, 2-years events should point out which portions of the network reach their convey capability first, while more intense events (e.g. 10-years) would cause a diffused overwhelming throughout the network, preventing an appropriate discrimination between conduits behaviour. Fig. 5 shows the spatial distribution of green roofs over the basin in these two modelling experiments. Both the 54% homogeneous and "targeted" heterogeneous scenario are run with the 2-years 35-minutes constant rainfall, and the impact of the "targeted" implementation of green roofs is assessed by comparing the results from the two simulations.

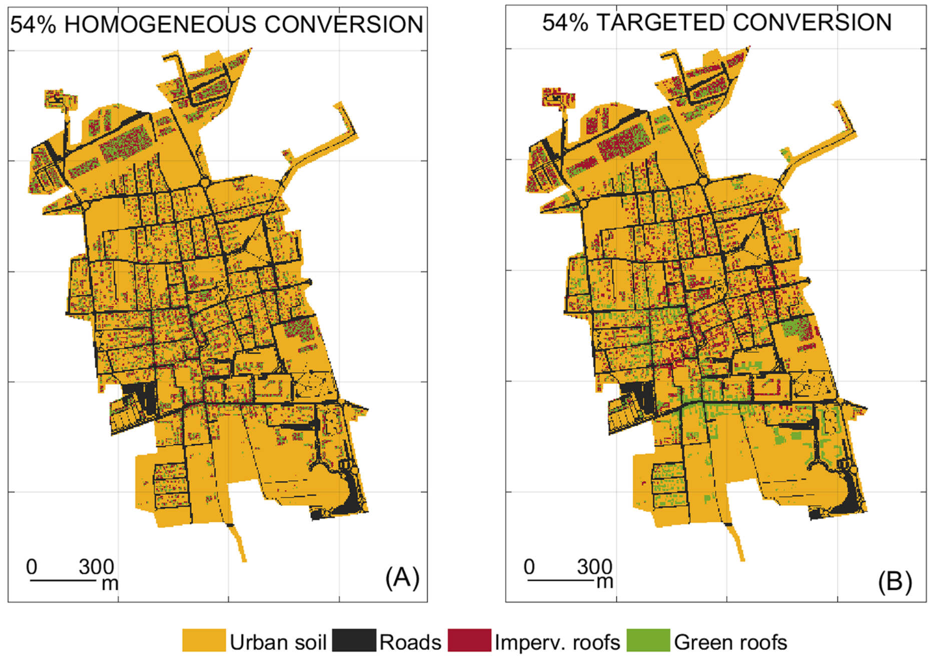


**Fig. 5.** Green roofs spatial distribution in the 54% homogeneous conversion (A) and the targeted conversion (B). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

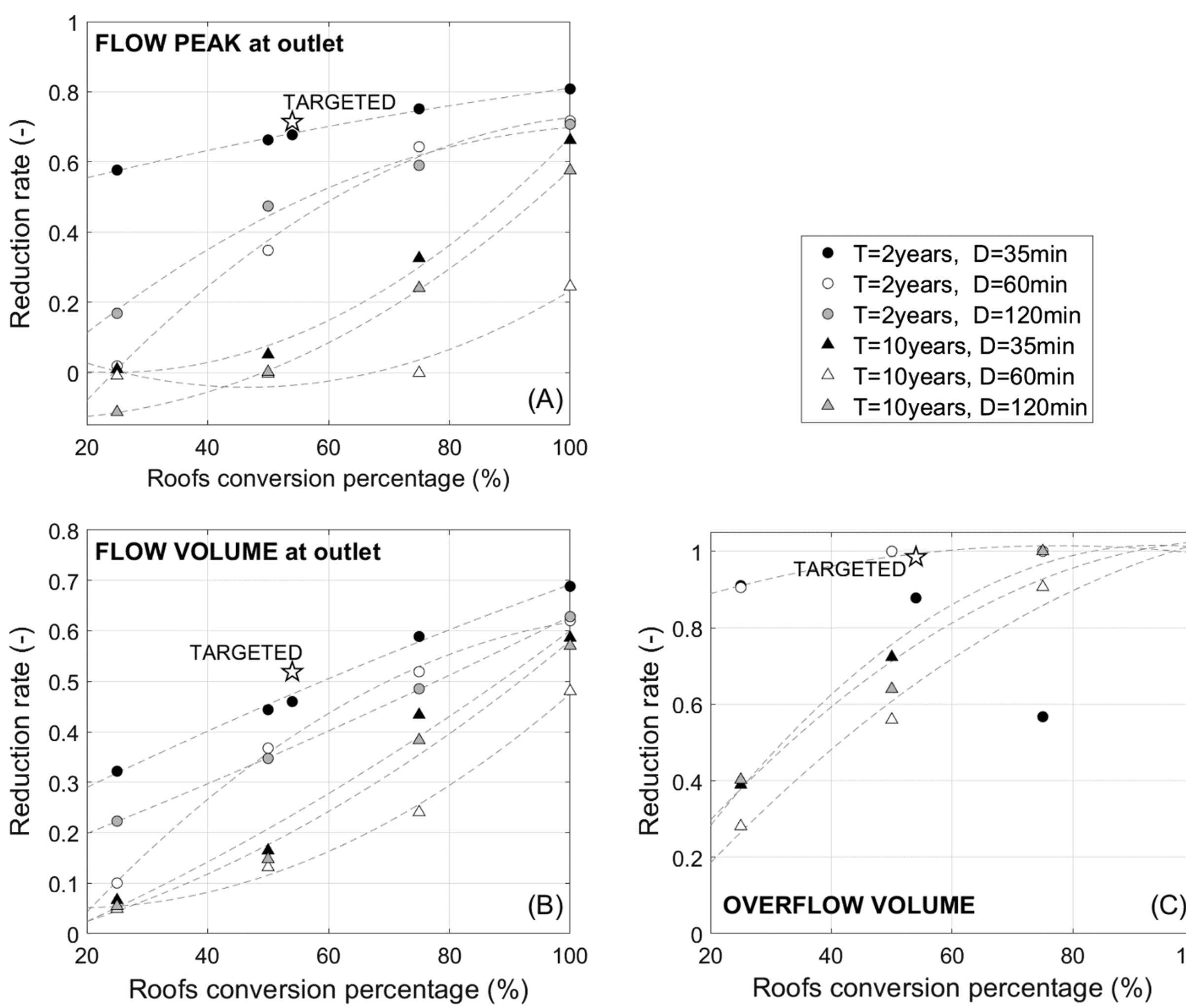


**Fig. 6.** Reduction rates of flow peak at outlet (A), flow volume at outlet (B), total overflow volume from nodes (C) for the various scenarios and rainfall events.

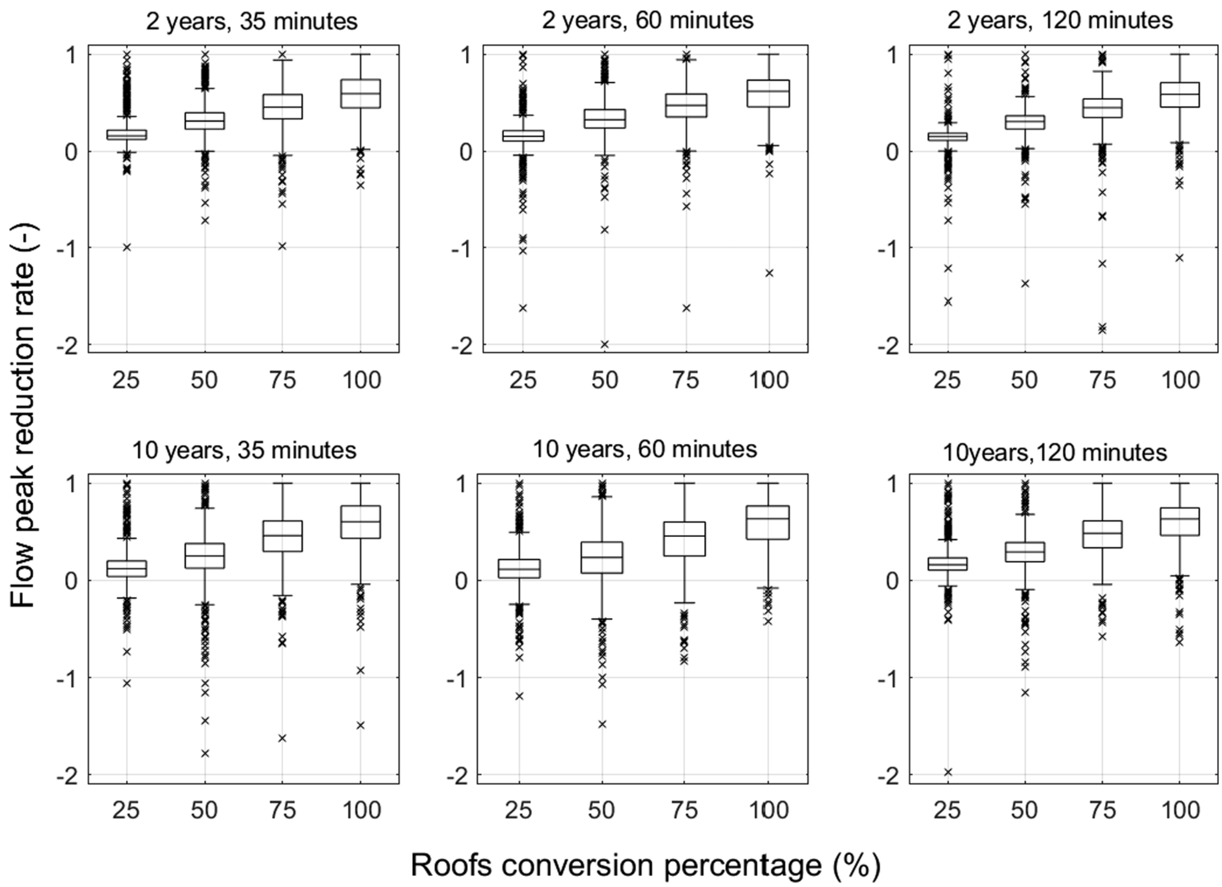


**Fig. 7.** Box plot of flow peak reduction in each conduit of the network for different conversion and rainfall scenarios.

All the simulations are initialized with a moderate dry level of soil wetness, i.e. no gravitational water and 50% of retainable capillary water in both standard soils and green roofs when present.

### 2.5. Evaluation criteria

The overall aim of the modelling experiments is to assess the impact that a diffused implementation of green roofs over a urban catchment may have on the functioning of an articulate drainage network. The focus is on aspects related to urban runoff management in presence of moderately intense rainfall. In detail, the impact of the various conversion scenarios is assessed primarily through the following hydrologic performance indexes: peak flow and volume reduction at the drainage network outlet and in each conduit. Peak flow reduction is calculated as the relative percentage difference between the flow peak in the reference run and in the conversion scenarios; volume reduction is calculated analogously. In addition, for any scenario, including the "no conversion" one, network level of stress is quantified through the percentage of conduits whose maximum degree of filling exceeds 80%, which is usually assumed as the maximum allowable filling by safety standards, and the percentage of nodes experimenting overflows, although very limited in both quantity and temporal duration. Maps showing the maximum degree of filling reached by any conduit during all the modelled events are included in the analysis as well. The aim is revealing possible portions of the network more prone to excessive filling and overflow, and investigating if green roofs implementation may reduce the tendency. Finally, when comparing results from the 54% homogeneous and targeted conversion, we examine also the full frequency distribution of the maximum degree of filling reached by the conduits during the event, in order to investigate more in detail the impact of a spatially heterogeneous implementation of green roofs throughout the urban basin.

## 3. Results and discussion

### 3.1. Current condition

In order to assess green roofs potentialities for stormwater management at the watershed scale, the response of Sedriano urban system to the various rainfall events under the "no conversion" scenario must be evaluated as well. As described in Section 2.5, the level of stress of the network during a specific event is quantified basically through the percentage of conduits exceeding the 80% of filling and of nodes experimenting overflow. Table 4 summarizes such indices for all the modelling experiments. In the "no conversion" scenario, on average, more than 25% of conduits exceed 80% of filling during storms whose return time is 2 years, and this percentage rises to 62% when the return period is 10 years. In addition, a few nodes (around 6%) may experiment overflow during these more intense storms. Considering that the design return period for these pipes ranges between 2 and 10 years, the overall response of the Sedriano drainage network to the examined events is adequate. However, the spatial distribution of the maximum degree of filling during the 2-years events (see the first line of Figs. A1 and A2 in the Appendix) reveals that conduits in the south-eastern part of the network are the most prone to reaching their maximum convey capacity, pointing out that some local deficiencies are present in the network. This fact may be explained by the presence of numerous nearly flat conduits (slope lower than 0.1%) and the proximity to the outlet (i.e. relevant flow from upstream reaching most of these conduits).

### 3.2. Impact of spatially homogeneous conversions

The impact of spatially homogeneous installations of green roofs over the urban basin is, first of all, assessed integrally in terms of flow at

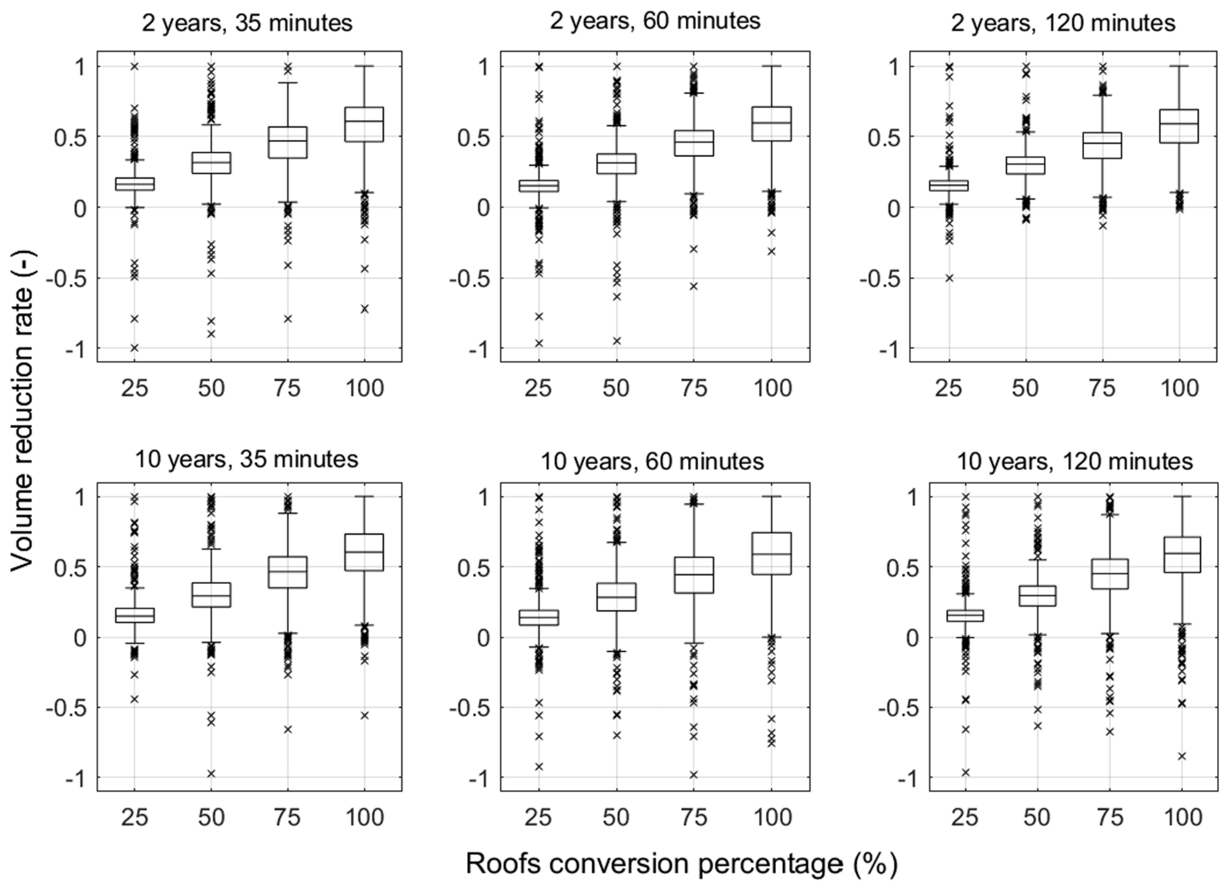


**Fig. 8.** Box plot of flow volume reduction in each conduit for different conversion and rainfall scenarios.

the network outlet through Fig. 6. However, in interpreting the results, it must be considered that dashed lines are added only to facilitate the visualization of the general trend of the various relationships, without any purpose of fitting the values. Fig. 6A and B show flow peak and volume reduction for all the conversion scenarios and rainfall events in respect to the corresponding "no conversion" scenario. Overall, the impact of green roofs decreases with precipitation magnitude, with the largest reduction rates corresponding to the 2-years 35-minutes event. This result is consistent with previous studies evaluating single or site-specific LIDs, which has shown that they are more effective for smaller storm events (Chapman and Horner, 2010; Mentens et al., 2006; Qin et al., 2013; Palla and Gnecco, 2015). Furthermore, for the 2-years events, reduction rates of peak flow range from about 10% to 80%, and volume rates from 15% to 70%, depending on the magnitude of the conversion. Hence, in our experiments, distributed implementation of green roofs is more efficient at decreasing peak flow than total volume. Regarding peak flow, Fig. 6A shows that the reduction rate is related almost linearly to roofs conversion percentage for the 2-years 35-minutes rainfall, while for the other events the trend seems to include some non-linearity. Non-linear responses to LIDs implementation has been observed also by Fry and Maxwell (2017), who tested various conversion configurations (from 15% to 50% and return period from 2 to 100 years) over an area of 26.14 ha included in Berkeley Lake watershed. Our study suggests that the non-linearity appears when convey capability of the network is the limiting factor for flow routing (i.e. when the event causes overload in a relevant number of conduits). This can be deducted by interpreting the results of Fig. 6A at the light of data in Table 4. Indeed, in cases where the baseline run ("no conversion" scenario) and some of the redevelopment configurations have more than around a quarter of conduits exceeding the 80% of filling, the relationship between peak flow reduction rate and roofs conversion percentage is not merely linear. The extreme case is that of the 10-years 60-minutes event (white triangles), for which green roofs cannot reduce the outlet peak flow up to the full conversion scenario. Data in Table 4 and maps in Fig. A3 show that this event overwhelm the system, causing nearly 75% of conduits exceeding the 80% of filling in the baseline run ("no conversion" scenario). The number of conduits above 80% of filling decreases if green roofs are implemented, but it remains still relevant (about 35% of conduits) also in the 75% scenario. Similarly, both the 10-years 35- and 120-minutes events, causing 61% and 50% of highly filled conduits in the "no conversion" scenario, experience peak flow reduction rate only in the 75% and 100% conversion scenario. Namely, during these two events, the peak flow remains almost unvaried if green roofs cover only 25% or 50% of rooftops extent. For the sake of precision, note that the negative reduction of the peak in the 25% scenario with the 10-years 120-minutes rainfall is actually a null reduction, since it is due only to the fact that the solution may oscillate slightly around the trend when the system is overwhelmed. In this specific case, a little higher oscillation occurred in the run of the 25% scenario than in the "no conversion" one, but both simulations share the same peak value if oscillations are not considered. Regarding flow volume (Fig. 6B), the non-linearity is probably related almost completely to the corresponding reduction of overflows from nodes (Fig. 6C). The previous observations lead to speculate that, when observing green roofs impact at the outlet of a sufficiently complex urban drainage network, the possible observed non-linearity is mainly related to network characteristics, and to a lesser extent to the hydrologic functioning of the single green roof. However, in our test this behaviour is probably accentuated by the fact that the network is particularly articulated (e.g. it includes closed circuits), and green roofs do not reach full saturation.

Figs. 7 and 8 summarize the impact on any conduit of the network through box-plots of local reductions of flow peak and volume respectively. Overall, reduction rates are positive (i.e. flow peak or volume is

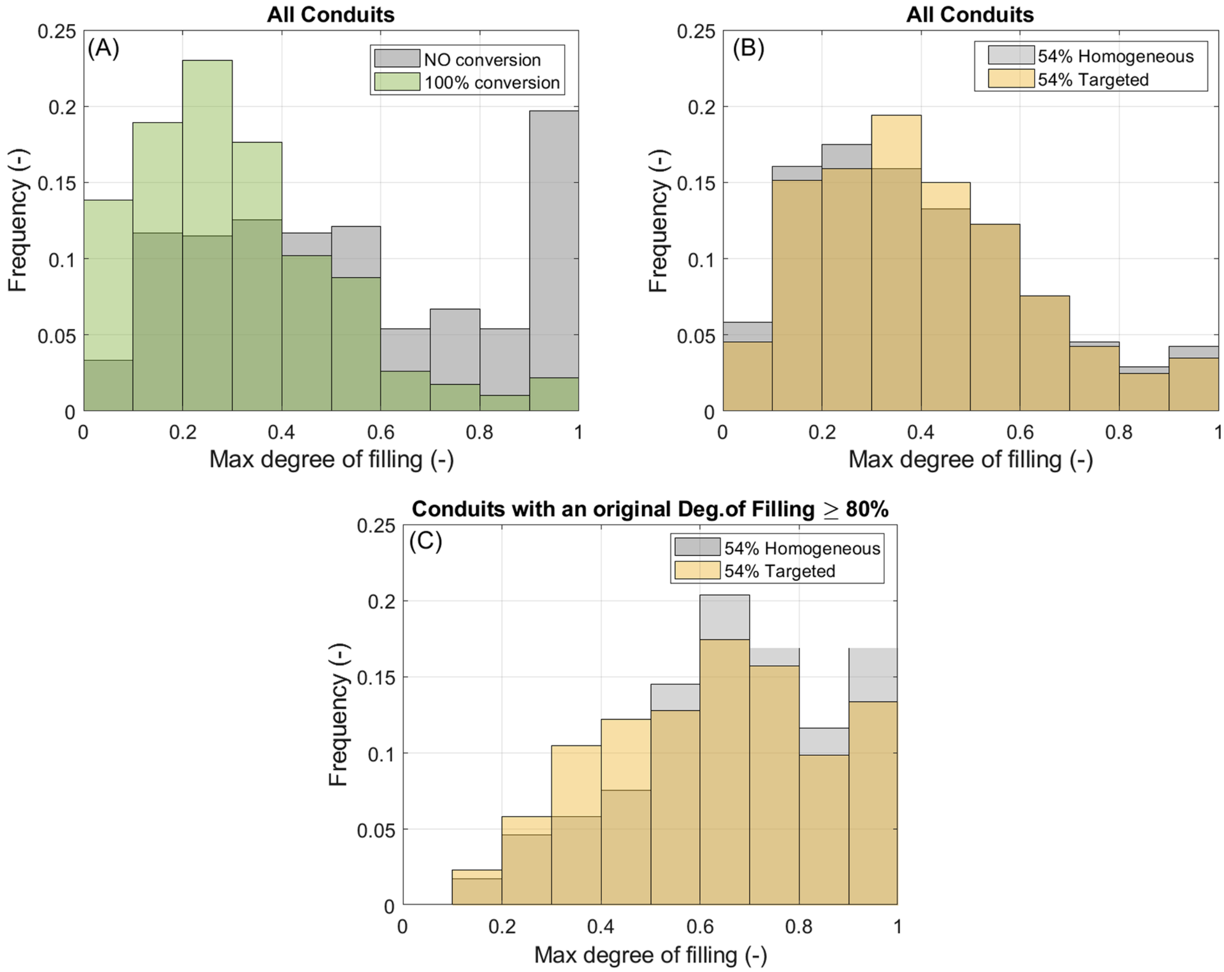


**Fig. 9.** Frequency distribution of conduits in respect to the maximum degree of filling. (A) comparison between "no conversion" and 100% conversion scenario; (B) comparison between 54% homogenous and targeted conversion; (C) comparison between 54% homogenous and targeted conversion for only the conduits with an original maximum degree of filling grater then 80%.

**Table 4**
Percentage of conduits with a maximum degree of filling greater than 80% and percentage of nodes experimenting overflow (within brackets).

| Rainfall event | Roofs conversion percentage (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 25 | 50 | 54 | 54 targeted | 75 | 100 |
| 2 years, 35 min | 25.07 (0.61) | 13.85 (0.15) | 7.43 (0) | 7.14 (0.15) | 5.98 (0.15) | 4.66 (0.15) | 3.21 (0) |
| 2 years, 60 min | 36.30 (4.15) | 26.97 (2.15) | 17.37 (0.15) | – | – | 9.91 (0.15) | 6.12 (–) |
| 2 years, 120 min | 17.20 (0) | 14.72 (0) | 11.37 (0) | – | – | 6.12 (0) | 2.92 (0) |
| 10 years, 35 min | 60.79 (8.6) | 47.52 (5.99) | 38.48 (4.45) | – | – | 22.89 (0.31) | 12.24 (0.15) |
| 10 years, 60 min | 74.78 (7.53) | 60.64 (6.30) | 49.27 (6.14) | – | – | 34.69 (1.69) | 19.24 (0) |
| 10 years, 120 min | 50.15 (4.15) | 37.46 (2.30) | 30.76 (3.07) | – | – | 18.51 (0.15) | 13.56 (0.15) |

actually decreased in the conduit), and median values increases with the conversion percentage for all the rainfall events and for both flow peak and volume. Nevertheless, this general positive impact coexists with local adverse effects. Indeed, some negative outliers occur in both flow peak and volume reduction rates (meaning increasing flow peak or volume in the conduit), and are mainly related to the complexity of the drainage system, discussed in Section 2.2. Indeed, in some conduits, green roofs implementation may cause a change of flow direction for the same rainfall event, altering flow paths through the network. Accordingly, the effect of a conversion scenario is not straightforward to predict.

In terms of network stress, Table 4 shows that the average percentage of conduits whose maximum filling exceeds 80% reduces from more than 25% to 4% for 2-years events, and from 62% to 15% for 10-years events. Furthermore, in both cases overflows almost nullify. However, if for the 2-years events a satisfactory stress reduction is obtained also with partial conversions (starting from 50% of buildings), 10-years events correspond, on average, to more than 25% of conduits exceeding 80% of filling even with the 75% scenario. Maps of the maximum degree of filling for any conduit in any experiment (Appendix A) suggest that the south-eastern portion of the network reaches excessive filling (greater than 90%) in the majority of scenarios, and reveal structural inefficiencies in the drainage network that cannot be balanced only through green roofs.

### 3.3. Impact of targeted conversion

In the following, we present results from the second set of modelling experiments described in Section 2.4. The aim is investigating possible advantages of a targeted implementation of green roofs which concentrates the efforts where conduits are more prone to filling. In particular, Fig. 5 shows that, in our case study, the degree of conversion is greater in the south-eastern portion of the urban basin, and this is coherent with the discussion of Section 3.1 about drainage network behaviour in the current condition.

The comparison between the 54% homogeneous and “targeted” scenario shows that the latter provides better results in terms of both number of conduits exceeding the 80% of filling and reduction rates of peak flow and volume at the network outlet. As reported in Table 4, results for the 54% homogeneous scenario are in line with expectations, with 7.14% of conduits exceeding 80% of filling, a percentage very close to the 7.43% obtained in the 50% scenario. Apparently similar, the 5.98% of the “targeted” conversion should be interpreted considering that this value lies in the middle between the percentages corresponding to the 50% and 75% scenario, although still corresponding to a total conversion of 54%. Furthermore, in Fig. 6A and B it is visible that reduction rates for the 54% homogenous scenario are completely coherent with the trend of the other homogeneous runs, while the rates of the “targeted” conversion (marked by a star in the plots) are clearly shifted. All of the above, suggests that, for the tested event, concentrating implementation efforts in specific locations leads to an improvement of performances. Note that results regarding overflow, in terms of both total volume and number of nodes experimenting it, are not significant for any of the simulations forced by the 35-minutes 2-years rainfall, including the 54% homogeneous and “targeted” scenario. Indeed, overflow barely occurs in the “no conversion” run, and affects only one single node in only some of the others.

In order to evaluate more in detail the effects of a spatially heterogeneous implementation of green roofs over the basin, we compare also the frequency distribution of conduits maximum degree of filling for the 54% homogeneous and “targeted” scenario (Fig. 9B). In interpreting the results, we consider the distribution for the current condition and the total conversion (Fig. 9A), which represent the extreme responses of Sedriano system to the rainfall event under examination. Both 54% homogeneous and “targeted” scenario are able to reduce the highest fillings significantly, with less than 5% of conduits over 90% of filling, starting from the 20% of the current condition and with the lower bound of 2% in the total conversion. However, the implementation effort seems to be spent better with the “targeted” conversion. Namely, the results show a more balanced network, with less underexploited conduits (maximum filling below 30%) and less exceeding 80% of filling. In addition, Fig. 9C reports the frequency distribution of only those conduits whose filling is over 80% in the “no conversion” scenario for the homogeneous and targeted conversion, and shows that the targeted approach leads to more effective reductions. Finally, the impact of the two 54% conversions may be appreciated in Fig. A3 in the Appendix in terms of spatial distribution of the maximum filling.

## 4. Concluding remarks

This work explores the effects of green roofs implementation at the urban watershed scale using a high-resolution, distributed hydrologic model (MOBIDIC-U) equipped with a QGIS plugin interface (SMART-GREEN). We find that a diffused installation of green roofs over the basin results in a reduction of both flow peak and volume at the outlet of the drainage network, variable with storm intensity and duration. Peak flows are reduced more effectively for frequent storms of smaller magnitude than for infrequent storms of larger magnitude, a finding consistent with previously published studies (Chapman and Horner, 2010; Mentens et al., 2006; Qin et al., 2013). In addition, we detect that peak flow reduction at network outlet may be both almost linearly and non-linearly related to green roofs implementation extent, and non-linearity is related to convey capability of the network being the limiting factor for flow routing. Namely, in our experience, the majority of non-linearity is due to network characteristics rather than to the hydrologic functioning of the single green roof. In the context of exploring possible criteria to maximize LIDs effectiveness at the watershed scale, our results indicate that: (i) green roofs spatial distribution has a non-negligible impact on system response; (ii) mitigation effects may be improved by concentrating implementation sites in proximity of network portions more prone to high degree of filling. Lastly, despite the results in general confirm green roofs capability of restoring a natural flow regime at urban catchment scale, their effectiveness is strongly related to sewer infrastructure characteristics. Indeed, in some cases green roofs alone are not able to reduce significantly the discharge or the degree of filling in the conduits. Therefore, for these situations it will be necessary to include structural measures such as sewer relining, enlargement of the diameters, or simplifying network layout. Future work should evaluate the performances of multiple LID systems (e.g. permeable pavements, rainfall barrels, etc.), as well as performing continuous simulations of multiple storms under varying soil moisture conditions.

## Acknowledgements

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## Appendix A

Figs. A1 and A2 show the maximum degree of filling reached by each conduit for the various scenarios of homogeneous conversions when responding to events with return period of 2- and 10-respectively. In particular, in both Figs. A1 and A2, each line corresponds to a specific scenario, and each column to a rainfall duration. Hence, the percentage of standard roofs transformed into green roofs increases when moving from top to bottom along a column, and rainfall duration passes from 35 to 60 and 120 min when going from the left- to the right-side. In addition, Fig. A3 refers to the 54% homogeneous (panel A) and targeted (panel B) conversion.

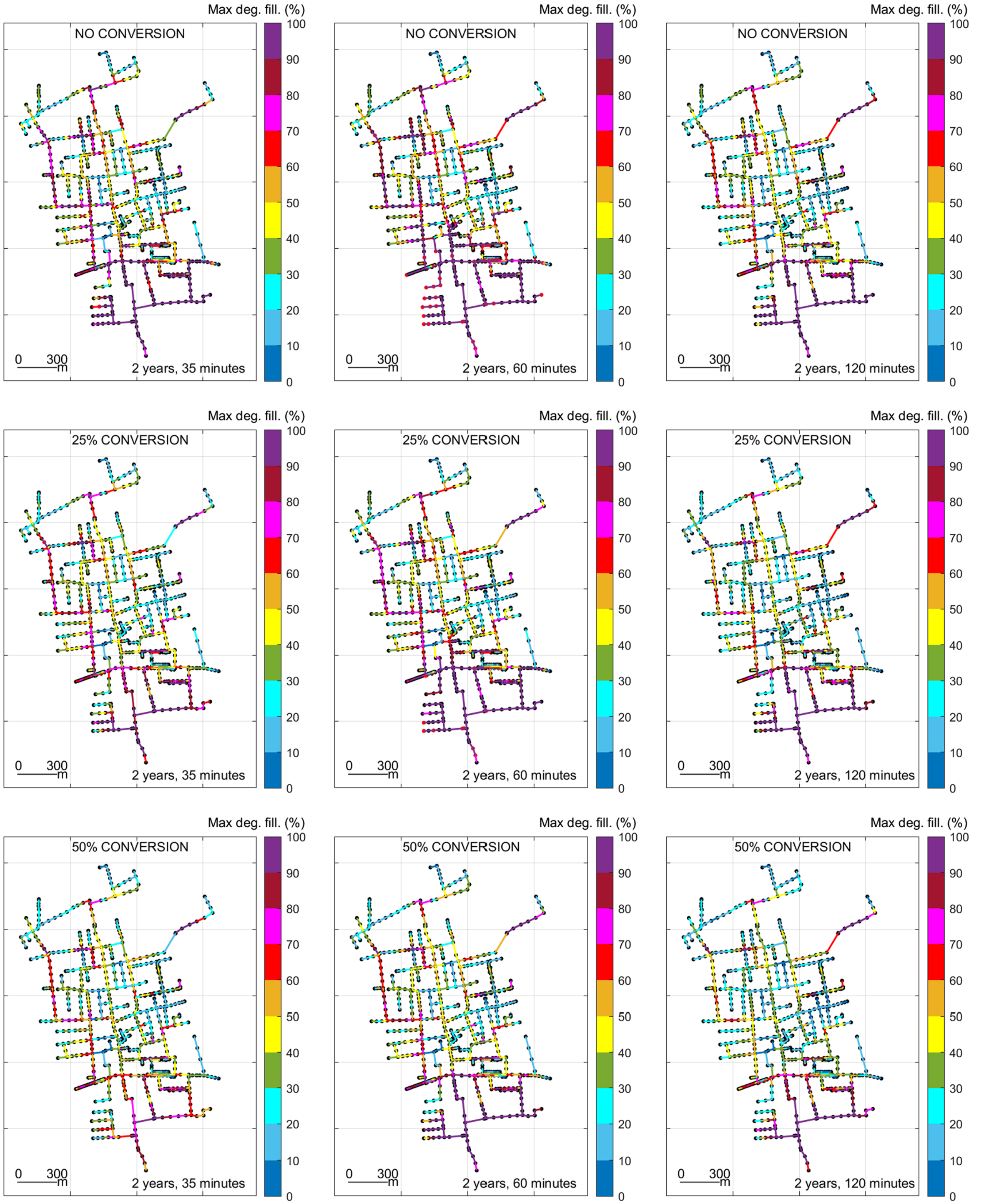


**Fig. A1.** Maximum degree of filling (%) reached in each conduit for the various conversion scenarios during rainfall events whose return period is 2 years. Red points are nodes experimenting overflow for at least one instant during the simulation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

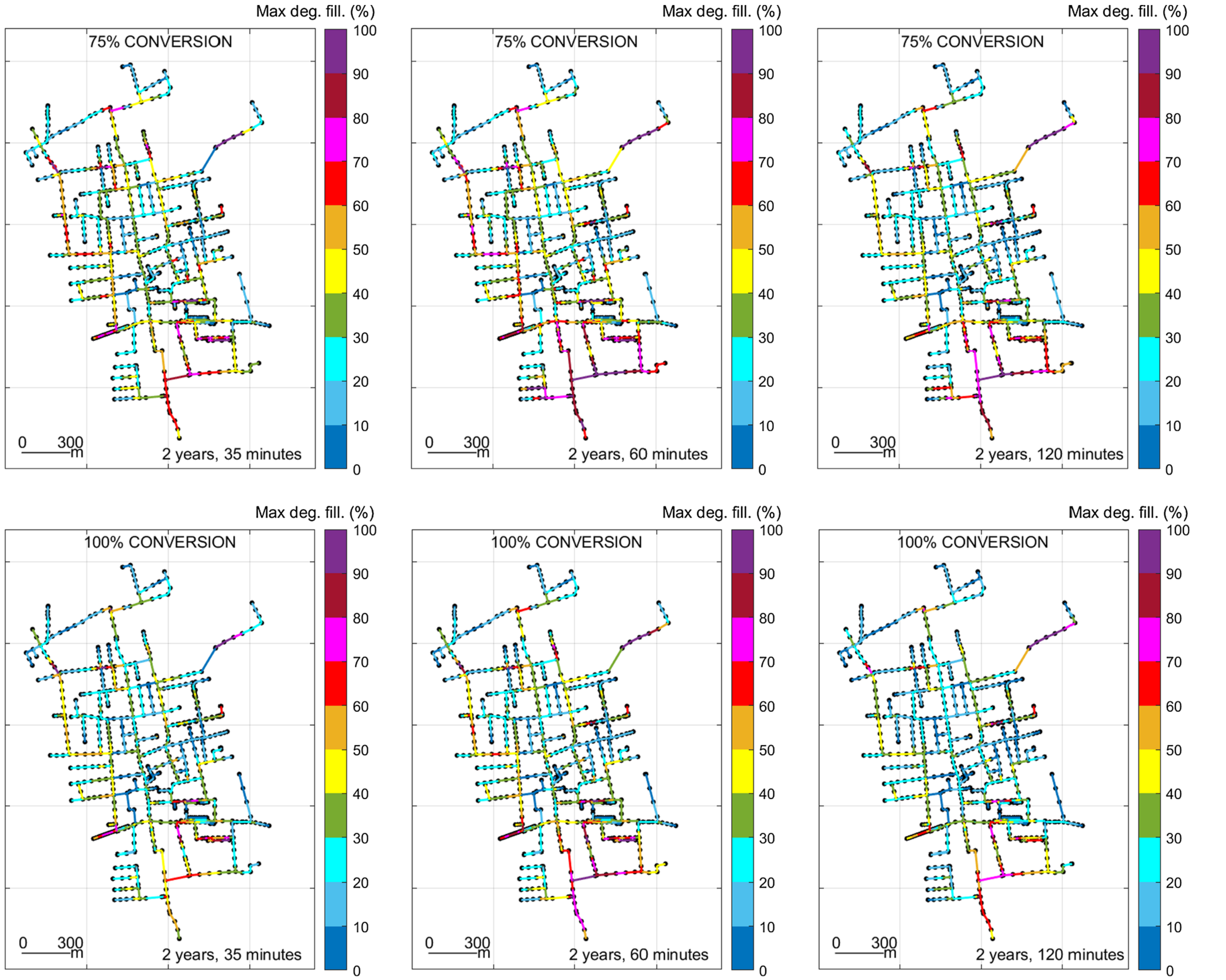


**Fig. A1.** (*continued*)

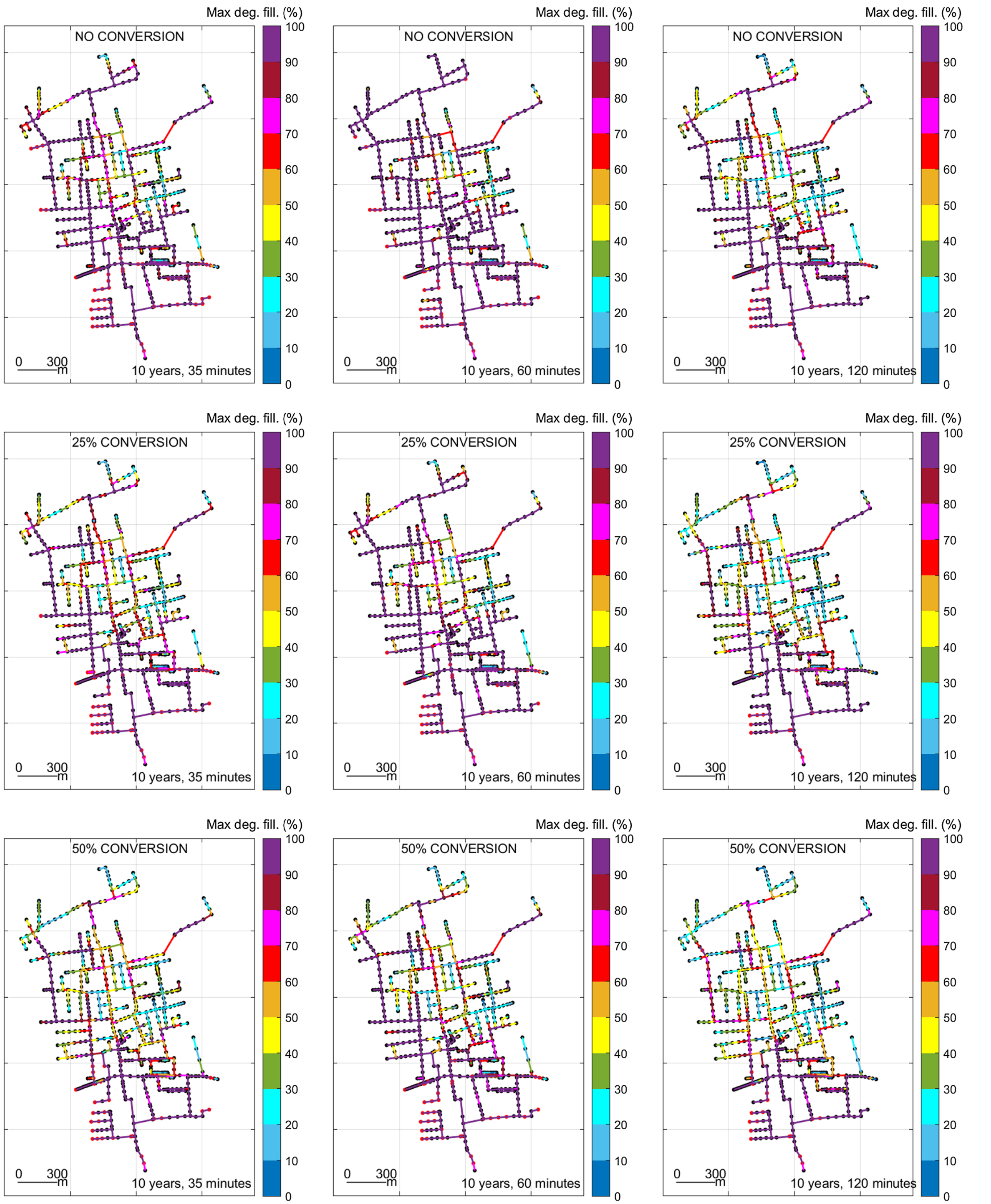


**Fig. A2.** Maximum degree of filling (%) reached in each conduit for the various conversion scenarios during rainfall events whose return period is 10 years. Red points are nodes experimenting overflow for at least one instant during the simulation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

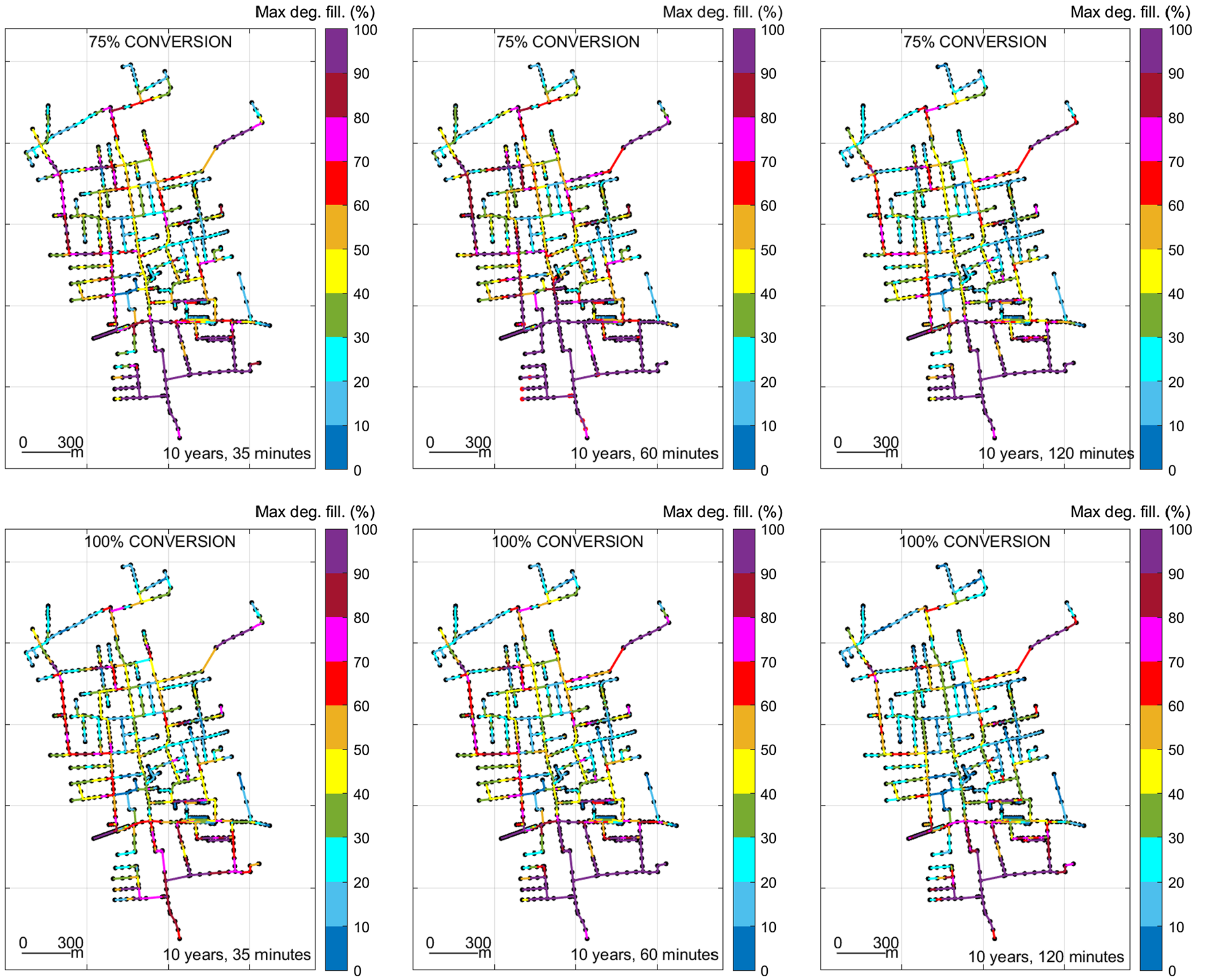


**Fig. A2.** (*continued*)

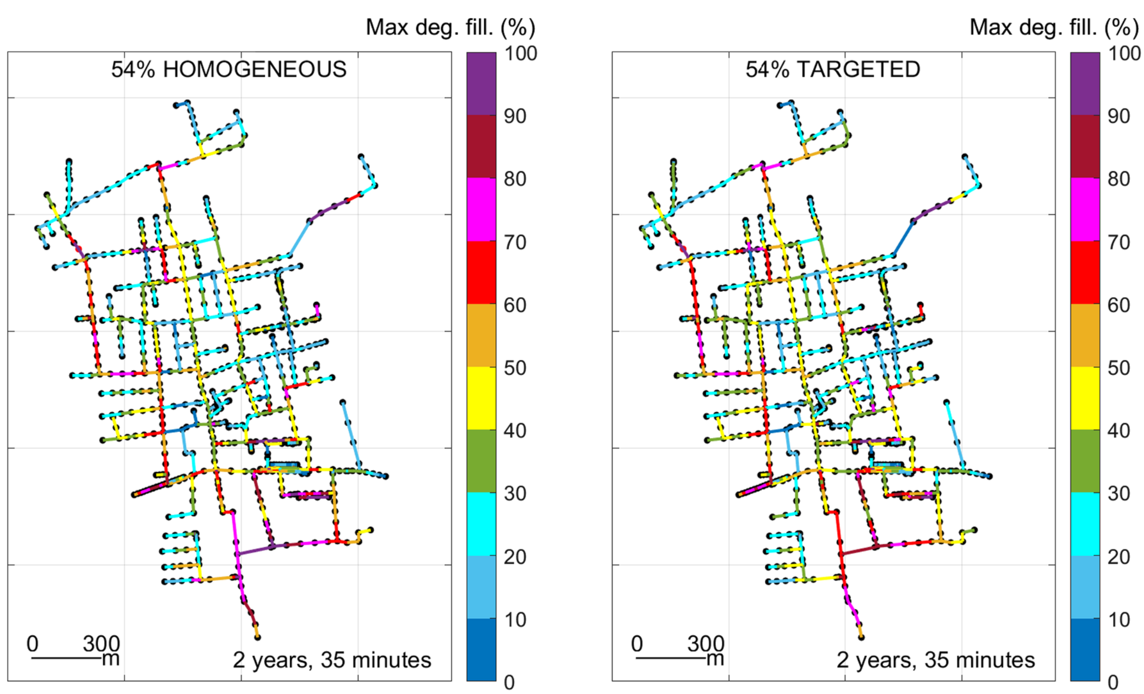


**Fig. A3.** Maximum degree of filling (%) during a 2-year 35-minutes rainfall event for a 54% homogeneous conversion (A) and a 54% targeted conversion (B).

## References


Ahiablame, L.M., Engel, B.A., Chaubey, I., 2012. Effectiveness of low impact development practices: literature review and suggestions for future research. Water Air Soil Pollut. 223 (7), 4253–4273. https://doi.org/10.1007/s11270- 012-1189-2.

Ahiablame, L.M., Engel, B.A., Chaubey, I., 2013. Effectiveness of low impact development practices in two urbanized watersheds: retrofitting with rain barrel/cistern and porous pavement. J. Environ. Manage. 119, 151–161. https://doi.org/10.1016/j.jenvman.2013.01.019.

Alfredo, K., Montalto, F., Goldstein, A., 2010. Observed and modeled performances of prototype green roof test plots subjected to simulated low-and high-intensity precipitations in a laboratory experiment. J. Hydrol. Eng. 15 (6), 444–457. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000135.

Barbosa, A.E., Fernandes, J.N., David, L.M., 2012. Key issues for sustainable urban stormwater management. Water Res. 46, 6787–6798. https://doi.org/10.1016/j.watres.2012.05.029.

Bean, E.Z., Hunt, W.F., Bidelspach, D., 2007. Field survey of permeable pavement surface infiltration rates. J. Irrig. Drain. Eng., ASCE 133 (3), 249–255. https://doi.org/10.1061/(ASCE)0733-9437(2007) 133:3(249).

Bell, C.D., McMillan, S.K., Clinton, S.M., Jefferson, A.J., 2016. Hydrologic response to stormwater control measures in urban watersheds. J. Hydrol. 541, 1488–1500. https://doi.org/10.1016/j.jhydrol.2016.08.049.

Bhaduri, B., Harbor, J., Engel, B., Grove, M., 2000. Assessing watershed scale long-term hydrologic impacts of land-use change using GIS-NPS model. Environ. Manage. 26 (6), 643–658. https://doi.org/10.1007/s002670010122.

Burian, S.J., Nix, S.J., Pitt, R.E., Durrans, S.R., 2000. Urban wastewater management in the United States: past, present, and future. J. Urban Technol. 7, 33–62. https://doi.org/10.1080/713684134.

Burns, M.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Hatt, B.E., 2012. Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform. Landsc. Urban Plan. 105, 230–240. https://doi.org/10.1016/j.landurbplan.2011.12.012.

Campo, L., Caparrini, F., Castelli, F., 2006. Use of multi-platform, multi-temporal remote-sensing data for calibration of a distributed hydrological model: an application in the Arno basin, Italy. Hydrol. Process. 20 (13), 2693–2712. https://doi.org/10.1002/hyp.6061.

Carter, T.L., Rasmussen, T.C., 2006. Hydrologic behavior of vegetated roofs. J. Am. Water Resour. Assoc. 42 (5), 1261–1274. https://doi.org/10.1111/j.1752-1688.2006.tb05299.x.

Castelli, F., Menduni, G., Mazzanti, B., 2009. A distributed package for sustainable water management: a case study in the Arno Basin. Int. Assoc. Hydrol. Sci., IAHS Publ. 327, 52–61.

Castillo, A., Castelli, F., Entekhabi, D., 2015. Gravitational and capillary soil moisture dynamics for distributed hydrologic models. Hydrol. Earth Syst. Sci. 19, 1857–1869. https://doi.org/10.5194/hess-19-1857-2015.

Chapman, C., Horner, R.R., 2010. Performance assessment of a street drainage bioretention system. Water Environ. Res. 82 (2), 109–119. https://www.jstor.org/stable/40575462.

Chiaradia, E.A., Ercolani, G., Bischetti, G.B., Gandolfi, C., Castelli, F., Masseroni, D., 2018. A Customized GIS-based Model for Stormwater Mitigation by LID Controls. In: La Loggia, G., Freni, G., Puleo, V., De Marchis, M. (Eds.), HIC 2018. 13th International Conference on Hydroinformatics. EPiC Series in Engineering, vol. 3. EasyChair, pp. 438–446. https://doi.org/10.29007/dmjh. ISSN: 2516–2330.

Chocat, B., Krebs, P., Marsalek, J., Rauch, W., Schilling, W., 2001. Urban drainage redefined: from stormwater removal to integrated management. Water Sci. Technol. 43, 61–68. https://doi.org/10.2166/wst.2001.0251.

Damodaram, C., Giacomoni, M.H., Prakash Khedun, C., Holmes, H., Ryan, A., Saour, W., Zechman, E.M., 2010. Simulation of combined best management practices and low impact development for sustainable stormwater management. J. Am. Water Resour. Assoc. 46 (5), 907–918. https://doi.org/10.1111/j.1752-1688.2010.00462.x.

Delleur, J.W., 2003. The evolution of urban hydrology: past, present, and future. J. Hydraul. Eng. 129, 563–573. https://doi.org/10.1061/(ASCE)0733-9429(2003) 129:8(563).

Dietz, M.E., 2007. Low impact development practices: a review of current research and recommendations for future directions. Water Air Soil Pollut. 186 (1–4), 351–363. https://doi.org/10.1007/s11270-007-9484-z.

Elliott, A.H., Trowsdale, S.A., 2007. A review of models for low impact urban stormwater drainage. Environ. Modell. Softw. 22 (3), 394–405. https://doi.org/10.1016/j.envsoft.2005.12.005.

Ercolani, G., Castelli, F., 2017. Variational assimilation of streamflow data in distributed flood forecasting. Water Resour. Res. 53, 158–183. https://doi.org/10.1002/2016WR019208.

Fassman, E.A., Blackbourn, S., 2010. Urban runoff mitigation by a permeable pavement system over impermeable soils. J. Hydrol. Eng., ASCE 15 (6), 475–485. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000238.

Fassman-Beck, E., Hunt, W., Berghage, R., Carpenter, D., Kurtz, T., Stovin, V., Wadzuk, B., 2016. Curve number and runoff coefficients for extensive living roofs. J. Hydrol. Eng. 21 (3), 04015073. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001318.

Fletcher, T.D., Andrieu, H., Hamel, P., 2013. Understanding, management and modelling of urban hydrology and its consequences for receiving waters: a state of the art. Adv. Water Resour. 51, 261–279. https://doi.org/10.1016/j.advwatres.2012.09.001.

Fry, T.J., Maxwell, R., 2017. Evaluation of distributed BMPs in an urban watershed-high resolution modeling for stormwater management. Hydrol. Process. 31 (15), 2700–2712. https://doi.org/10.1002/hyp.11177.

Getter, K.L., Rowe, D.B., Andresen, J.A., 2007. Quantifying the effect of slope on extensive green roof stormwater retention. Ecol. Eng. 31 (4), 225–231. https://doi.org/10.1016/j.ecoleng.2007.06.004.

Gleick, P.H., 2003. Global freshwater resources: soft-path solutions for the 21st century. Science 302 (5650), 1524–1528. https://doi.org/10.1126/science.1089967.

Grebel, J.E., Mohanty, S.K., Torkelson, A.A., Boehm, A.B., Higgins, C.P., Maxwell, R.M., Sedlak, D.L., 2013. Engineered infiltration systems for urban stormwater reclamation. Environ. Eng. Sci. 30 (8), 437–454. https://doi.org/10.1089/ees.2012.0312.

James, W., Rossman, L.E., James, W.R., 2010. User's Guide to SWMM 5, 13th ed. CHI Press Publication.

Khader, O., Montalto, F.A., 2008. Development and calibration of a high resolution SWMM model for simulating the effects of LID retrofits on the outflow hydrograph of a dense urban watershed. International Low Impact Development Conference.

Lee, G.L., Heaney, J.P., 2003. Estimation of urban imperviousness and its impacts on stormwater system. J. Water Resour. Plan. Manage. 129 (5), 419–428. https://doi.org/10.1061/(ASCE)0733-9496(2003) 129:5(419).

Lee, J.G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J.X., Shoemaker, L., Lai, F.H., 2012a. A watershed-scale design optimization model for stormwater best management practices. Environ. Modell. Softw. 37, 6–18. https://doi.org/10.1016/j.envsoft.2012.04.011.

Lee, J.M., Hyun, K.H., Choi, J.S., Yoon, Y.J., Geronimo, F.K.F., 2012b. Flood reduction analysis on watershed of LID design demonstration district using SWMM5. Desalin. Water Treat. 38, 255e261. https://doi.org/10.1080/19443994.2012.664377.

Mentens, J., Raes, D., Hermy, M., 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landsc. Urban Plan. 77 (3), 217–226. https://doi.org/10.1016/j.landurbplan.2005.02.010.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—a discussion of principles. J. Hydrol. 10 (3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6.

Newcomer, M.E., Gurdak, J.J., Sklar, L.S., Nanus, L., 2014. Urban recharge beneath low impact development and effects of climate variability and change. Water Resour. Res. 50 (2), 1716–1734. https://doi.org/10.1002/2013WR014282.

Niemczynowicz, J., 1999. Urban hydrology and water management: present and future challenges. Urban Water 1, 1–14. https://doi.org/10.1016/S1462-0758(99)00009-6.

Palla, A., Gnecco, I., 2015. Hydrologic modeling of low impact development systems at the urban catchment scale. J. Hydrol. 528, 361–368. https://doi.org/10.1016/j.jhydrol.2015.06.050.

Palla, A., Gnecco, I., Lanza, L.G., 2009. Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof. J. Hydrol. 379 (1–2), 193–204. https://doi.org/10.1016/j.jhydrol.2009.10.008.

Peel, M.C., Finlayson, B.L., McMahon, T.A., 2007. Updated world map of Köppen-Geiger climate classification. Hydrol. Heart Syst. Sci. 11, 1633–1644. https://doi.org/10.5194/hess-11-1633-2007.

Qin, H.-P., Li, Z.-X., Fu, G., 2013. The effects of low impact development on urban flooding under different rainfall characteristics. J. Environ. Manage. 129, 577–585. https://doi.org/10.1016/j.jenvman.2013.08.026.

Roy, A.H., Wenger, S.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R., Shuster, W.D., Thurston, H.W., Brown, R.R., 2008. Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. J. Environ. Manage. 42, 344–359. https://doi.org/10.1007/s00267-008-9119-1.

Wilkinson, M.E., Quinn, P.F., Barber, N.J., Jonczyk, J., 2014. A framework for managing runoff and pollution in the rural landscape using a catchment systems engineering approach. Sci. Total Environ. 468, 1245–1254. https://doi.org/10.1016/j.scitotenv.2013.07.055.

Yang, J., Castelli, F., Chen, Y., 2014a. Multiobjective sensitivity analysis and optimization of distributed hydrologic model MOBIDIC. Hydrol. Earth Syst. Sci. 18 (10), 4101–4112. https://doi.org/10.5194/hess-18-4101-2014.

Yang, J., Entekhabi, D., Castelli, F., Chua, L., 2014b. Hydrologic response of a tropical watershed to urbanization. J. Hydrol. 517, 538–546. https://doi.org/10.1016/j.jhydrol.2014.05.053.

Yao, L., Wei, W., Chen, L., 2016. How does imperviousness impact the urban rainfall-runoff process under various storm cases? Ecol. Indic. 60, 893–905. https://doi.org/10.1016/j.ecolind.2015.08.041.