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Research article

# The impact of domestic rainwater harvesting systems in storm water runoff mitigation at the urban block scale

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A B S T R A C T

In the framework of storm water management, Domestic Rainwater Harvesting (DRWH) systems are recently recognized as source control solutions according to LID principles. In order to assess the impact of these systems in storm water runoff control, a simple methodological approach is proposed. The hydrologic-hydraulic modelling is undertaken using EPA SWMM; the DRWH is implemented in the model by using a storage unit linked to the building water supply system and to the drainage network. The proposed methodology has been implemented for a residential urban block located in Genoa (Italy). Continuous simulations are performed by using the high-resolution rainfall data series for the "do nothing" and DRWH scenarios. The latter includes the installation of a DRWH system for each building of the urban block. Referring to the test site, the peak and volume reduction rate evaluated for the 2125 rainfall events are respectively equal to 33 and 26 percent, on average (with maximum values of 65 percent for peak and 51 percent for volume). In general, the adopted methodology indicates that the hydrologic performance of the storm water drainage network equipped with DRWH systems is noticeable even for the design storm event (T = 10 years) and the rainfall depth seems to affect the hydrologic performance at least when the total depth exceeds 20 mm.



## 1. Introduction

Domestic rainwater harvesting (DRWH) systems is a complementary water supply method supporting the potable water saving in urban areas facing water scarcity and demographic pressure (Campisano et al., 2013). DRWHs have been recently recognized as one of the tools of Low Impact Development (LID) solutions which aim at restoring the natural hydrologic cycle in the urban environment. DRWH limits the demand for potable water and, at the same time, contributes to control storm water runoff at the source by providing distributed retention storage throughout the catchment (e.g. Petrucci et al., 2012; Zhang et al., 2009; Burns et al., 2015). Although the hydrologic performance of DRWH is nowadays recognized, the effectiveness of DRWH implementation at the urban catchment scale is still scarcely investigated by means of both experimental and numerical studies. Burns et al. (2015) assessed the DRWH retention capability in a peri-urban catchment in South-Eastern Australia; results indicated that the increasing in the retention capability can be achieved by increasing the demand and/or conveying the overflow to infiltration systems. Petrucci et al. (2012) found similar results for a suburban catchment of Paris where the hydrologic response was affected by the DRWH systems only for small rainfall events. The experimental results, available in the literature, are specific to the study locations hence additional research is required to understand how the climatic factors may impact the ability of DRWH to retain and detain storm water.

The retention performance of DRWH has been studied using numerical models that are generally able to predict only the system variables (behavioural models) without taking into account neither the runoff of the non-connected areas nor the flow routing inside the drainage network. In the framework of the behavioural models, Campisano and Modica (2015) investigated the appropriate time-scale resolution to simulate the water saving efficiency and the retention potential of DRWH at a household scale. In particular it is shown that at least hourly time step resolution is required for a reliable evaluation of the tank volumetric retention efficiency while high time resolution (sub-hourly time step) becomes mandatory if the analysis is related to the storm water peak reduction. Other research studies (Petrucci et al., 2012; Walsh et al., 2014; Huang

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et al., 2015) simulated the DRWH by using the EPA Storm Water Management Model (SWMM); however the implementation of the DRWH is carried out by means of simplified approaches. Petrucci et al. (2012) did not include the tanks in the model but transposed their effect by means of a modified equivalent initial loss. Walsh et al. (2014) and Huang et al. (2015) implemented the DRWH by using the rain barrel control unit provided in SWMM 5.0 in order to simulate the hydraulic failure of the drainage systems for several rainfall events. However, the rain barrel unit does not properly describe the hydraulic behaviour of DRWH systems since the overflow and the yield volume are not separately computed.

The main focus of this paper is to assess the impact of DRWH systems on the hydrologic response of a residential urban block. With this aim, the first specific objective is to define a methodology including a hydrologic-hydraulic model able to predict the outflow hydrographs together with the hydraulic behaviour of the DRWH at high time resolution. The second specific objective is to assess the performance of the DRWH systems in terms of water-saving efficiency and overflow ratio; the performance reliability is based on continuous simulation results over at least 20years of precipitation records. The final specific objective is to identify the hydrologic variables that significantly affect the storm water runoff mitigation provided by DRWH systems. To support this investigation, the proposed methodological approach has been implemented for a specific urban block located in Genoa (Italy).

## 2. Material and methods

In order to assess the impact of DRWH systems on the hydrologic response of a residential urban area a simple methodological approach is here defined. The proposed approach allows assessing the hydrologic performance of DRWH systems as source control solutions in case of existing plants (in order to verify the actual systems – i.e. verification purpose) or in case of foreseen installations (in order to predict the impact of hypothetic scenarios – i.e. planning and design purposes).

In this framework, the analysis of the DRWH potential is performed according with the following methodological scheme:

1. Urban area analysis;
2. Simplified criteria for tank design and setting rules for DRWH management;
3. Hydrologic-hydraulic modelling;
4. Performance analysis.

The urban area analysis includes outlining the residential urban block in terms of land use categories; the collection of rainfall data at high time resolution and the characterization of the main storm water drainage network (in terms of plano-altimetric layout and geometric data).

In case of planning and/or design purposes, the simplified criteria for tank design and setting rules for DRWH management refers to the national standard (if available) otherwise, the use of the most common standard (e.g. DIN, 2004) is suggested.

### 2.1. The hydrologic-hydraulic modelling

The hydrologic-hydraulic modelling is undertaken using EPA SWMM 5.1.007 (Rossman, 2010). Regarding the hydrologic response of the urban block, SWMM allows simulating the hydrologic and hydraulic processes at sub-hourly time resolution. The urban catchment consists of a collection of subcatchment areas that receive rainfall and generate different hydrologic components including surface runoff, infiltration and evaporation. Each subcatchment area should be characterized by single land use type and homogenous properties in order to reliably simulate the catchment hydrologic response (Krebs et al., 2014) and to precisely define the source control scenarios (Palla and Gnecco, 2015).

In the present study, the DRWH system is simulated in SWMM as a hydraulic node using the *storage unit* object instead of the *rain barrel* control unit since the overflow and the yield volume have to be separately computed in order to suitably assess the performance. The inflow of the storage unit is the subcatchment outflow connected to the DRWH system. The storage outflows consist in the rainwater supply and the overflow that are implemented respectively as a pump linked to the building water supply and a weir section linked to the drainage network. Note that the building water supply system is schematized by an outfall section. In order to reproduce the daily rainwater-demand pattern, specific control rules (clock time rules) are defined to activate the pumps.

### 2.2. Perfomance analysis

Simulation results are analysed by means of both system and hydrologic performance. The configuration which corresponds to the “do nothing” scenario, is assumed as the reference scenario in order to measure the impact of the DRWH installation.

#### 2.2.1. The system performance

The system performance is investigated by means of two non-dimensional indices: the water saving efficiency and the rainwater overflow ratio. The system performance indexes are evaluated with respect to the entire simulation period. The water-saving efficiency, $E$, is obtained as:

$$E = \frac{\sum_{t=1}^{N} Y_t}{\sum_{t=1}^{N} D_t} \quad (1)$$

where $Y_t$ [$L^3$] represents the rainwater supply (yield) at each time step $t$, $D_t$ [$L^3$] is the rainwater demand at each time step, and $N$ is the total number of simulation time steps (see e.g. Dixon et al., 1999).

The rainwater overflow ratio, $O$, is obtained as:

$$O = \frac{\sum_{t=1}^{N} O_t}{\sum_{t=1}^{N} Q_t} \quad (2)$$

where $O_t$ [$L^3$] represents the rainwater exceeding the system capacity at each time step $t$, $Q_t$ [$L^3$] is the system inflow at each time step, and $N$ is the total number of simulation time steps. The analysis of system performance is carried out as a function of two non-dimensional parameters, namely the demand fraction and the storage fraction as already discussed in Palla et al. (2011) since the adoption of non-dimensional parameters permits to suitably compare the performance under different system conditions. The demand fraction (indicated as $D/Q$) is defined as the ratio between the annual water demand and the annual inflow while the storage fraction (indicated as $S/Q$) is defined as the ratio between the storage capacity of the tank and the annual inflow.

#### 2.2.2. The hydrologic performance

The hydrologic performance of the DRWH systems installed at the urban block scale is assessed through two indexes: the peak and volume reduction rates, namely $PR$ and $VR$, respectively. The hydrologic performance indexes are evaluated at the event scale. For each rainfall event, the peak reduction is calculated as the relative percentage difference between the outflow peaks of the “do nothing” and DRWH scenarios; the volume reduction is similarly evaluated.

In order to assess the behaviour of the hydrologic performance indexes as a function of the rainfall event characteristics, rainfall events are classified based on both the rainfall depth and maximum rainfall intensity on event basis. In particular, five classes characterized by a constant frequency of about 0.2 are defined. The hydrologic performance is then statistically examined by means of a non-parametric distribution: with respect to each class of rainfall depth/intensity, the median and mean values as well as the different percentiles (5th, 10th, 25th, 75th, 90th and 95th) are evaluated.

### 2.3. Test site

The methodology proposed to assess the impact of DRWH systems in storm water runoff control has been applied to a selected urban block located in the town of Genoa (Italy) thus being included as a study case representative of the Mediterranean climate.

The study area is located in the neighbourhood of Albaro in the eastern part of the town centre. Fig. 1 provides an overview of the study area: it corresponds to an urban block limited on the four sides by the small road network leading into the internal lots and two/three-story buildings. The block area is about 0.6 ha and includes 4 buildings and a private green area. As illustrated in Table 1, land uses are classified as rooftop, road and parking lot, other impervious and green area; total impervious/pervious areas are calculated based on the aerial photographs. The analysis of land use data reveals that 57% of the urban block is covered with impervious surfaces and that rooftops account for 33% of the total areas.

The management of storm water is separated from the sewer system and addressed according to the traditional approach; in particular the separate sewer system consists of three pipes located below the street network without any LID source control solutions (such as green roofs, permeable pavements, rainwater harvesting systems) installed in the area.

**Table 1**
Land use characteristics of the urban block.

| Land use | Area (ha) | Area ratio (-) |
|---|---|---|
| Rooftop | 0.19 | 0.33 |
| Road and Parking Lot | 0.10 | 0.17 |
| Other impervious | 0.05 | 0.08 |
| Green Area | 0.25 | 0.43 |
| Total Area | 0.59 | 1.00 |
| Total Impervious | 0.34 | 0.57 |
| Total Pervious | 0.25 | 0.43 |

The installation of a DRWH system for each building of the urban block is here assumed as hypothetic scenario for planning and design purposes according to an integrated storm water mitigation strategy.

#### 2.3.1. The precipitation regime

The precipitation regime of the study area is analysed based on rain data collected at the raingauge station of Villa Cambiaso (44.3986N; 8.9633E) located in the vicinity. Rainfall data are available since 1990 with 1-min resolution.

Throughout the investigated period (from 1990 to 2015), 2125 rainfall events are selected using a threshold filter able to extract events with total depth and antecedent dry weather period respectively exceeding 1.8 mm and 1 h.

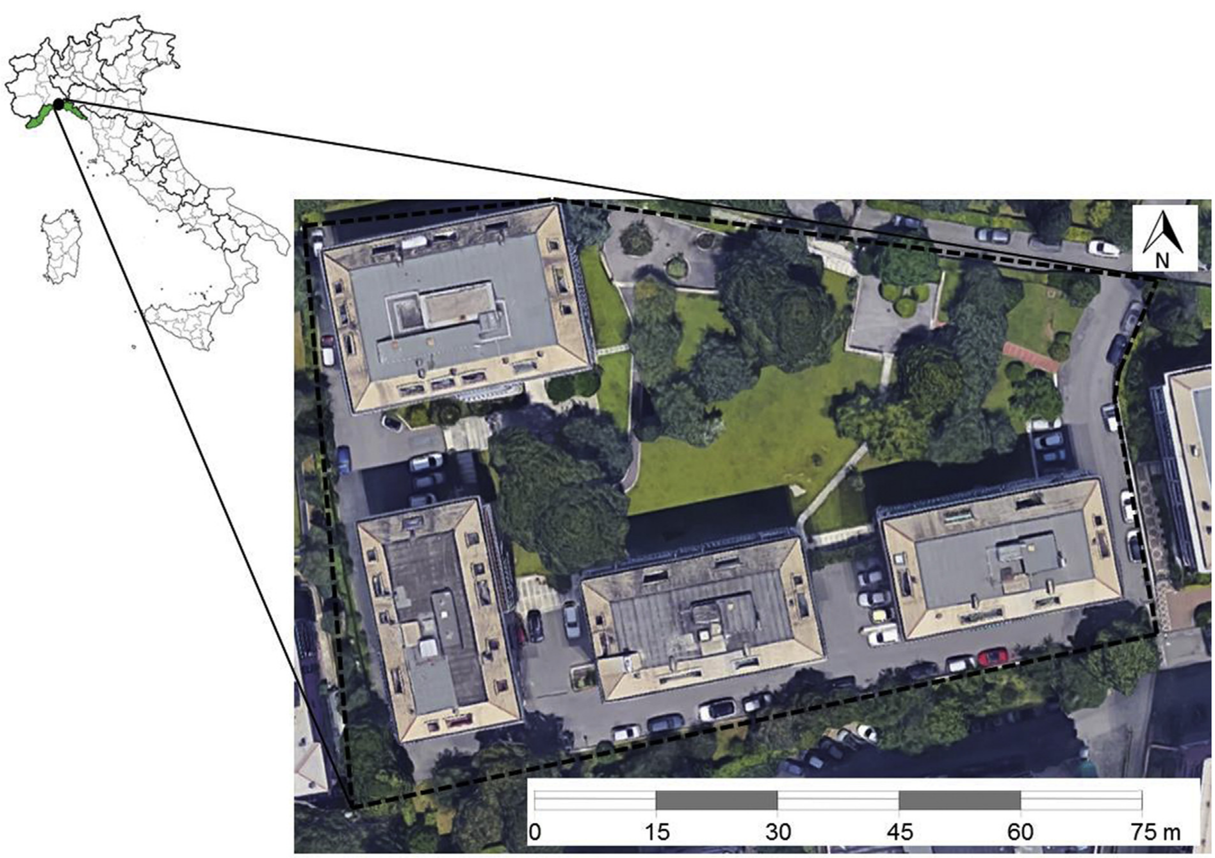


**Fig. 1.** Overview of the study area located in Albaro neighbourhood, Genova (Italy).

**Table 2**
Rainfall characteristics for the time series climate records (1990–2015) of Villa Cambiaso (Genoa, IT). ADWP is the Antecedent Dry Weather Period and the maximum intensity is evaluated over 10 min.

| Statistical data | Annual Depth (mm) | Depth (mm) | Duration (h) | ADWP (d) | Max. Intensity (mm/h) |
|---|---|---|---|---|---|
| Maximum | 2320 | 410.8 | 45.12 | 62.7 | 234 |
| Minimum | 714 | 2.0 | 0.03 | 0.04 | 1 |
| Mean | 1340 | 14.8 | 4.03 | 1.5 | 19 |
| Standard deviation | 372 | 23.6 | 4.49 | 3.5 | 24 |

Table 2 summarizes the rainfall characteristics for the time series climate records of Villa Cambiaso: the mean annual precipitation and the rainfall-event characteristics in terms of depth, duration, antecedent dry weather period (ADWP) and maximum intensity over 10 min are reported. The statistics of the annual rainfall depth as well as the rainfall-event characteristics are typical of the Mediterranean area: the average and standard deviation values of the annual rainfall depth are respectively 1340 mm and 372 mm, the rainfall-event depth and ADWP are higher than 14 mm and 1.5 days, on average.

### 2.3.2. Operational conditions of the DRWH systems

In each DRWH system, rainwater is assumed only collected from rooftops therefore the occurrence of the first flush phenomenon is neglected. The roof runoff is collected in the corresponding storage tank and pumped directly to the point of use while the overflow is directly conveyed to the downstream drainage network.

Furthermore, the water demand to be supplied by rainwater is limited to the toilet flushing and is assumed to occur at a constant daily rate. This assumption is reasonable because the demand time series generated by WC usage do not exhibit excessive daily variances (Fewkes, 2000; Silva and Ghisi, 2016). The daily rainwater-demand diagram with three different supplied periods is defined in order to reproduce the typical water consumption with well-defined peaks: two noticeable peaks occurring in the morning (between 7:00 and 9:00) and in the evening (between 19:00 and 21:00) and a lower one at the lunch time (between 13:00 and 15:00). Such assumption complies with experimental results on sub-daily pattern of toilet flushing reported in the literature (Mun and Han, 2012). The toilet flushing demand per person is assumed as 40 l/d (UNI/TS 11445, 2012).

A survey was carried out in May 2016 to investigate the actual number of inhabitants for each building. Based on the survey, the four buildings are classified as 4-flat house (2 units), 6-flat house (1 unit) and condominium (1 unit) characterized, respectively, by the following numbers of inhabitants of 16, 24 and 32. In Table 3, the main characteristics of each building in terms of roof area and number of inhabitants are reported together with the annual rain water demand.

### 2.3.3. The tank-sizing criteria

The tanks are designed according to the simplified method as indicated in the Italian guideline UNI/TS 11445 (2012). This method is based on the evaluation of two terms: the annual inflow, Q, and the annual water demand, D. In particular, the annual inflow is evaluated by multiplying the collected area with the annual runoff depth and the latter is determined by multiplying the annual rainfall depth with the discharge coefficient of the corresponding collected area. The annual water demand for toilet flushing is evaluated by assuming a constant daily rate per person. The storage volume of the tank is then assumed as the 6% of the minimum value between the inflow and the water demand on annual basis. In Table 4 the main characteristics (including storage capacity, demand fraction and storage fraction) of the DRWH systems are listed for the investigated buildings. The $D/Q$ is lower than one for all the building typologies being affected by the precipitation regime of the site, the number of inhabitants and the rainwater demand use (see also Tables 2 and 3). Therefore, the sizing variable affecting the tank capacity is the annual water demand in all cases. The resulting storage fractions are larger than 0.04 thus the systems can be suitably simulated with behavioural model at a daily temporal resolution (Fewkes and Butler, 2000). Further $S/Q$ is lower than 0.1 thus limiting the detention time (<30 days) even at low demand fraction ($D/Q < 0.5$) (Palla et al., 2011).

### 2.3.4. The model implementation

The study area in the current configuration ("do nothing scenario") is simplified in 12 subcatchments, 6 junctions, 6 conduits and 1 outfall. The subcatchments are characterized by single land use type and homogenous properties according to the required high-spatial discretization. The Soil Conservation Service Curve Number Method is here used to estimate the infiltration losses and runoff is calculated using the Manning's equation. CN value equal to 85 is assumed for rooftops, roads and parking lots and other impervious areas while CN value equal to 70 is assumed for green areas; n-Manning value equal to 0.01 is assumed for the rooftops, roads and parking lots while n-Manning value equal to 0.013 is assumed for the conduits. As for flow routing computation, the cinematic wave theory is used.

Compared to the current condition, the DRWH scenario includes

**Table 4**
The demand fraction, tank capacity and the corresponding storage fraction for the three typologies of residential buildings.

| Residential buildings | Demand Fraction (-) | Tank Capacity ($m^3$) | Storage Fraction (-) |
|---|---|---|---|
| 4-flat house | 0.51 | 14 | 0.03 |
| 6-flat house | 0.77 | 21 | 0.05 |
| Condominium | 0.64 | 28 | 0.04 |

**Table 3**
Number of inhabitants, roof area and annual rainwater demand for the three typologies of residential buildings.

| Residential buildings | Inhabitants (-) | Roof area ($m^2$) | Annual water demand ($m^3$/y) |
|---|---|---|---|
| 4-flat house | 16 | 420 | 233.6 |
| 6-flat house | 24 | 420 | 350.4 |
| Condominium | 32 | 680 | 467.2 |

4 storage units (1 for each building), 4 weirs (1 for each tank), 8 pumps (2 for each DRWH), and 4 outfalls representing the water-supply system in the buildings. The geometry of each tank is designed according with the available surface area in the vicinity of the building and by considering an effective water depth in the tank of 2 m. The design of the weirs is accordingly defined; in particular, the inlet offset is placed to a 2-m depth and the weir section is schematized as a transverse rectangular element. For each pump is

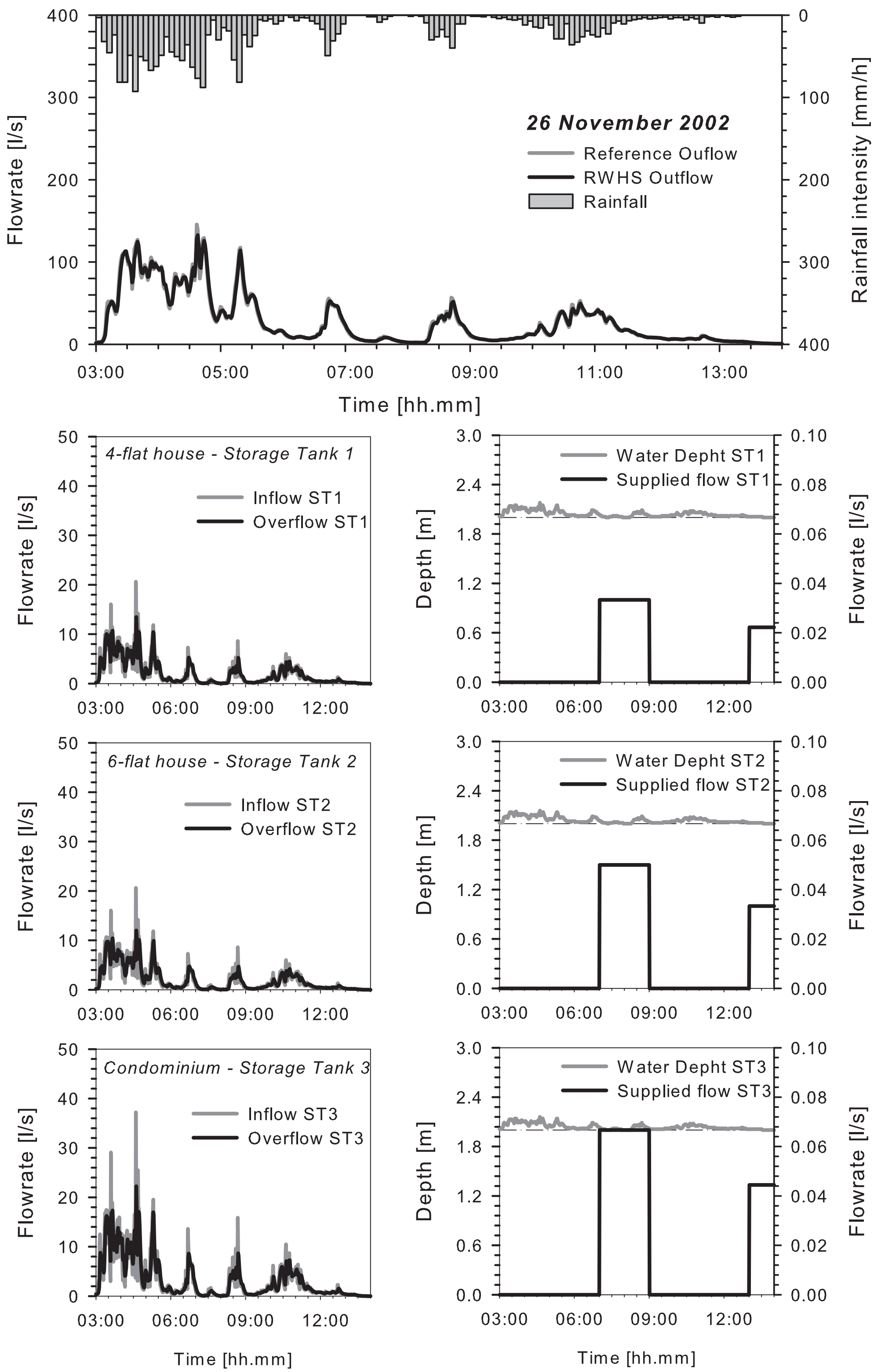


**Fig. 2.** The 26 November 2002 rainfall event: the hyetograph, the corresponding hydrographs simulated for the reference and the DRWH scenarios (graph at the top); comparison between the inflow and outflow at each storage tank (graphs at the left side); the storage depth and the yield flow together with the effective water depth (dash-dot line) at each storage tank (graphs at the right side). The reference scenario indicates the "do nothing" scenario.

assumed constant flow with inlet node depth, in particular the single flow rate is evaluated based on the duration of the three supply-period of the rain water demand daily diagram.

Finally, continuous simulation are performed over 26-years at 1-min time interval; as for the initial condition of the DRWH systems, the tanks are assumed initially empty as generally recommended (Mitchell, 2007).

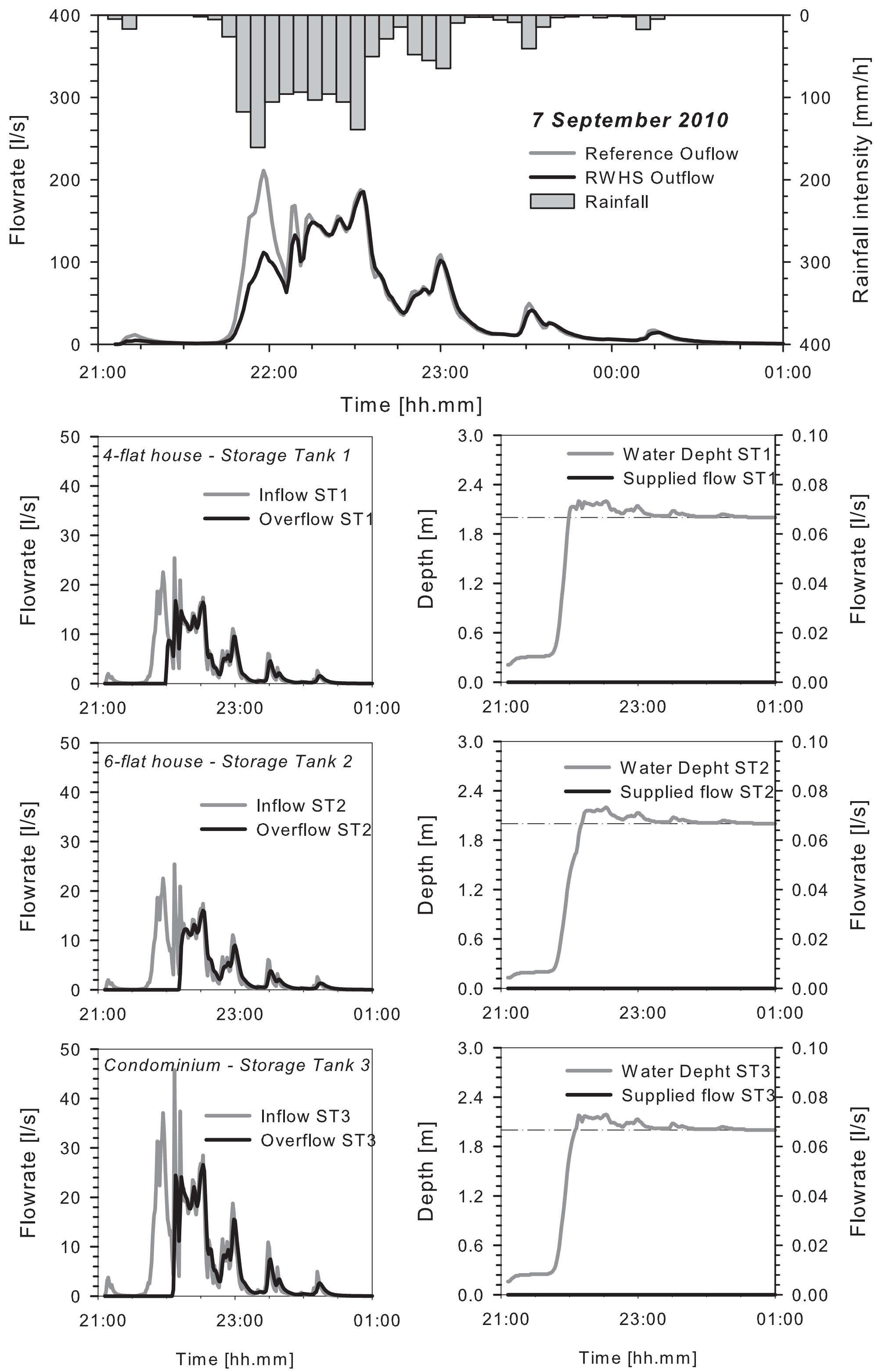


**Fig. 3.** The 7 September 2010 rainfall event: the hyetograph, the corresponding hydrographs simulated for the reference and the DRWH scenarios (graph at the top); comparison between the inflow and outflow at each storage tank (graphs at the left side); the storage depth and the yield flow together with the effective water depth (dash-dot line) at each storage tank (graphs at the right side). The reference scenario indicates the "do nothing" scenario.

## 3. Results and discussion

In the following section the modelling results together with the system and hydrological performance are evaluated and discussed for the test site of concern.

### 3.1. The simulation results

Model simulation results consist of the outflow hydrographs at 1-min time interval for the reference and DRWH scenarios over 26-years. The reference scenario corresponds to the “do nothing” scenario while the DRWH scenario includes the installation of a DRWH system for each building of the urban block. Furthermore, simulation results include 1-min time series of the DRWH system variables including the water depth in the tank, the supplied rainwater discharges, the inflow and the overflow rates for each system.

Fig. 2 illustrates the hydrologic response of the urban block and the hydraulic behaviour of the rainwater harvesting systems simulated for the 26 November 2002 rainfall event. The graph at the top reports the hyetograph and the corresponding hydrographs simulated for the reference and the DRWH scenarios. The three graphs at the left side show the comparison between the inflow and outflow with respect to the storage tank installed at the 4-flat, 6-flat and condominium buildings. The three graphs at the right side show the water depth and the rainwater supply flow together with the effective water depth (dash-dot line) at each storage tank. Similarly, Fig. 3 illustrates the hydrologic response of the urban block and the hydraulic behaviour of each storage tank simulated for the 7 September 2010 rainfall event.

Figs. 2 and 3 provide an example of the hydraulic behaviour of the storm water drainage network equipped with DRWH systems under different rainfall conditions and statuses of the tank. The 26 November 2002 rainfall event (see Fig. 2) is characterized by the total rainfall depth and duration respectively of 208.7 mm and 12.5 h, thus corresponding to the 10-years return period rainfall event according to the Depth-Duration-Frequency curves of Villa Cambiaso rainfall series. As for the DRWH systems, all tanks are full at the beginning of the event; this status of the tanks complies with the occurrence of the rainfall event during the rainy season (Palla

**Table 5**
The water saving efficiency and overflow ratio for the three typologies of residential buildings. The demand fraction and the storage fraction are also indicated.

| Residential buildings | Demand Fraction (-) | Storage Fraction (-) | Efficiency (-) | Overflow ratio (-) |
|---|---|---|---|---|
| 4-flat house | 0.51 | 0.03 | 0.83 | 0.66 |
| Condominium | 0.64 | 0.04 | 0.79 | 0.59 |
| 6-flat house | 0.77 | 0.05 | 0.76 | 0.53 |

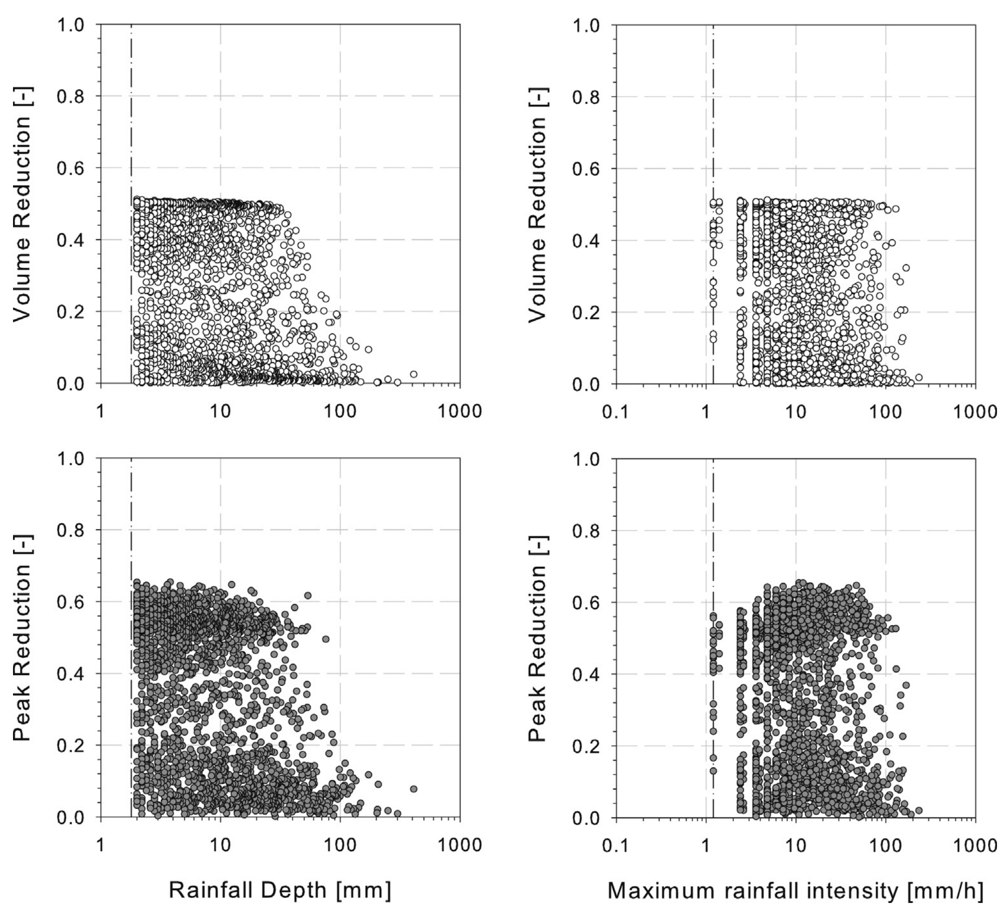


**Fig. 4.** The volume and peak reduction rates plotted vs. the rainfall depth and intensity, respectively. The vertical reference lines indicate the threshold value for the rainfall depth and intensity. The rainfall intensity refers to the maximum value calculated over 10 min.

et al., 2011). Based on such conditions, it emerges that the water demand is fully satisfied and the volume reduction is negligible ($VR = 0.002$), as expected. On the contrary, the storage tanks are effective on the peak reduction ($PR = 0.09$).

The 7 September 2010 rainfall event (see Fig. 3) is characterized by a total rainfall depth and duration respectively of 121 mm and 3.2 h (7-years return period event); it can be included among typical Mediterranean summer storms with high rainfall depth and short duration. Being during the dry season, all tanks are almost empty, thus the DRWH systems are able to contribute to the volume and peak reductions (equal to 0.12 for both indexes) in spite of the rainfall event characteristics.

### 3.2. The analysis of system performance

The system performance is assessed at the entire simulation period (26-year long) for each DRWH system in the urban block. Table 5 reports the water saving efficiency and overflow ratio for the three typologies of residential buildings.

The water saving efficiency and overflow ratio slightly decrease with the increasing demand fractions (or storage fractions), in particular demand fractions in the [0.51, 0.77] range affect the corresponding efficiency decreasing from 0.83 to 0.79 as well as the overflow ratio decreasing from 0.66 to 0.59. The analysis of the system performance as a function of the storage fractions reveals a similar behaviour; indeed in these cases the storage fractions could be calculated as the 6% of the demand fraction in accordance with the adopted sizing criterion (simplified method of the Italian guidelines, UNI/TS 11445:2012). Results demonstrate that the demand fraction can be effectively used to maximize the water-saving efficiency: for all cases the water saving efficiency is almost equal to 0.8 thus confirming that the sizing criterion - based on the demand fraction - has been effectively applied.

### 3.3. The analysis of hydrologic performance

Simulation results confirm the impact of DRWH systems on storm water runoff mitigation: the mean values of peak and volume reduction rates, evaluated for the 2125 rainfall events, are respectively equal to 0.33 and 0.26, while the maximum values are 0.65 for peak and 0.51 for volume. The hydrologic performance observed for the site of concern refers to a DRWH scenario where each rooftop is connected to its storage tank; such hypothesis is suitable for a high-income residential district while at the urban catchment scale DRWH systems collecting at least 50% of rooftops seems more reasonable (see e.g. Zhang et al., 2012).

Fig. 4 shows the volume and peak reduction rates plotted vs. the rainfall depth and the rainfall intensity, respectively; in each graph the vertical reference lines indicate the threshold value for the rainfall depth (1.8 mm) and intensity (1.2 mm/h). Note that the rainfall intensity refers to the maximum value calculated over 10-min duration. Looking at results reported in Fig. 4, the hydrologic performance of the DRWH system seems to be irrespective of the rainfall characteristics. Similarly to findings from other research studies (e.g. Walsh et al., 2014), it can be noticed that the volume reduction rate is upper bounded by the percentage of impervious area connected to the rainwater harvesting system, corresponding to the rooftop areas in the present simulation.

In order to point out any influence of the precipitation regime on the hydrologic performance, the 2125 rainfall events are classified in terms of both rainfall depth and intensity classes characterized by constant frequency distribution. Fig. 5 shows the non-parametric distribution of the volume (hatched box) and peak (grey box) reduction rates for each rainfall depth class; the frequency distribution of the rainfall depth is also reported. Results confirm (see also Fig. 4) that for rainfall events with total depth below 20 mm, the peak and volume reductions slightly decrease on

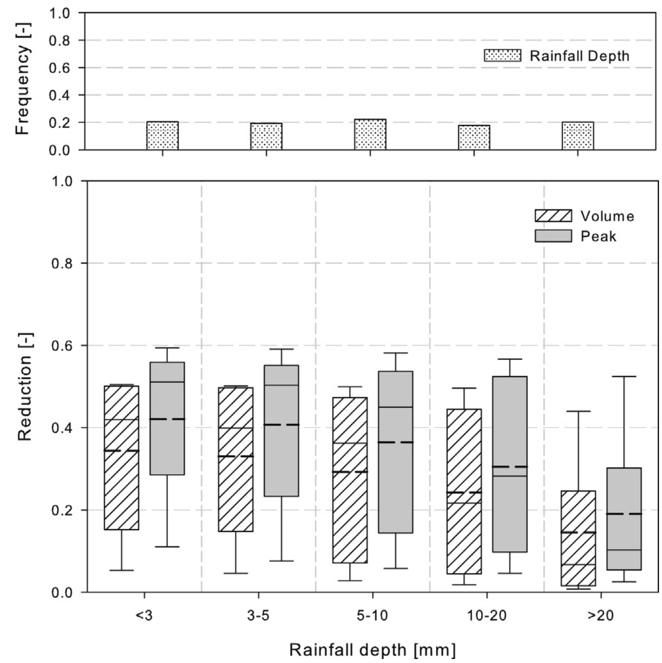


**Fig. 5.** Non-parametric distribution of the volume (hatched box) and peak (grey box) reduction rates for each rainfall depth class and the frequency distribution of the rainfall depth. The lower and upper boundary of each box indicate respectively the 25th and 75th percentiles, while the solid and dashed lines within the box mark the median and mean values respectively. Whiskers above and below each box indicate the 90th and 10th percentiles.

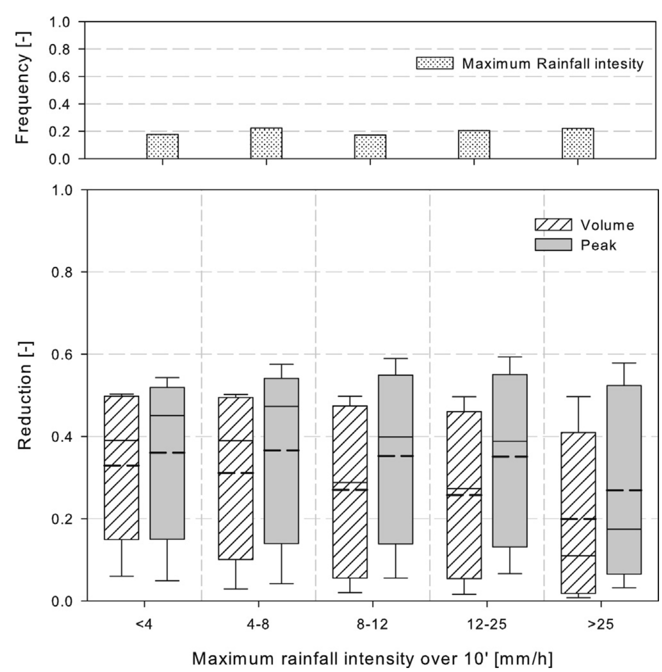


**Fig. 6.** Non-parametric distribution of the volume (hatched box) and peak (grey box) reduction rates for each rainfall intensity class and the frequency distribution of the rainfall intensity. The rainfall intensity refers to the maximum value calculated over 10 min. The lower and upper boundary of each box indicate respectively the 25th and 75th percentiles, while the solid and dashed lines within the box mark the median and mean values respectively. Whiskers above and below each box indicate the 90th and 10th percentiles.

average (being fairly constant for depth lower than 5 mm); while for rainfall events with total depth exceeding 20 mm, the hydrologic performance decreases below 0.2 (in terms of both the median and mean values).

Similarly to Figs. 5 and 6 reports the non-parametric distribution of the hydrologic performance indexes with respect to the maximum rainfall intensity calculated over 10 min. For rainfall intensity under 25 mm/h, the hydrologic performance ranges between 0.25 and 0.35 and slightly decreases for high-intensity event.

## 4. Conclusions

The present study aims at the assessment of the impact of DRWH systems in storm water runoff control at the urban catchment scale. The modelling results refer to the specific test site, however they can be extended at the urban catchment scale and the methodological approach can be easily replicated.

The hydrologic behaviour of the investigated urban block equipped with DRWH systems has been continuously simulated over 26-years of rainfall records using the EPA SWMM model. In order to quantify the impact of the DRWH systems on improving the hydrologic performance of the urban block, the peak and volume reduction are evaluated on event-basis with respect to the "do nothing" scenario:

- the peak and volume reduction rate evaluated for the 2125 rainfall events are respectively equal to 0.33 and 0.26, on average (with maximum values of 0.65 for peak and 0.51 for volume);
- the rainfall depth seems to affect the hydrologic performance at least when the total depth exceeds 20 mm;

The observed hydrologic performance can be transferred to a residential urban block characterized by similar precipitation regime and DRWH intervention percentage. With regard to a generic urban block modelling results allow drawing the following conclusions:

- the tank sizing criteria based on water demand and runoff volume as key parameters guarantee satisfactory system performance (i.e. water-saving efficiency), even in simplified approaches;
- the hydrologic performance in terms of volume reduction rate is strongly affected by the specific features of the urban catchment (such as land use characteristics, percentage of imperious surfaces potentially connected to DRWH systems, etc.);
- regarding the peak reduction, the drainage system characteristics as well as the management rules of the DRWH system and the hydraulic outfall device have a direct implication on the hydrologic performance of the urban catchment.

Although the hydrologic performance is limited for exceedance rainfall events (high-intensity and short-duration), the installation of DRWH systems at the urban catchment scale contributes to satisfactorily increase the hydrologic performance of the storm water drainage network even for the design storm event ($T = 10$ years).

As the findings of the research study focused on the LID performance (Palla and Gnecco, 2015), the present results point out that the widespread implementation of rainwater harvesting systems at the urban catchment scale noticeably affects the quali-quantity aspects of urban water management. In detail, the DRWH systems operate as source control solutions thus contributing to limit overflow discharges and drainage system failures; reducing the amount of runoff volume that need to be treated before discharging into the receiving water bodies and finally diminishing the use of potable water.

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