On the Effectiveness of Domestic Rainwater Harvesting Systems to Support Urban Flood Resilience

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Abstract

The effectiveness of domestic rainwater harvesting (DRWH) systems to support urban flood resilience is analysed at the sub-catchment scale, according to a specific DRWH conversion scenario, under 4 degrees of urbanization, 3 drainage network configurations, 4 precipitation regimes and 3 return periods of the rainfall event. At this aim, a suitable modelling framework is implemented: the semi-distributed hydrologic-hydraulic model is undertaken using EPASWMM 5.1.007 where specific tools are developed to simulate DRWH systems at high spatial resolution. The effectiveness of the DRWH systems simulated for the 144 different cases, is analysed at the event scale by using the Volume and Peak Reduction indexes to measure the hydrologic performance. The dimensionless variable, namely the event storage fraction, is defined in order to easily describe the DRWH effectiveness. The event storage fraction is defined as the ratio between the event runoff volume resulting from the impervious surface of the urban catchment in the reference scenario and the storage capacity of the DRWH systems. Modelling results confirm that DRWH catchment-scale applications allow to support specific stormwater control requirements based on peak-flow or volume regulations strategies. Findings of the elaboration reveal for a typical residential catchment in the Italy-France cross-border coastal area, that DRWH effectiveness in supporting the urban flood management becomes significant (i.e. Volume and Peak Reduction indexes greater than 0.2) starting from a storage event fraction of 0.4 that means realizing storage tanks able to contain at least the 40% of runoff volume generated by the targeted event at the sub-catchment scale.

Keywords Hydrologic performance · Rainwater harvesting · Storm water management · SWMM · Tank sizing · Urban drainage network

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1 Introduction

Urban flooding has become one of the most frequent natural disasters in recent years and Low-Impact Development (LID) approach is nowadays recognised as a sustainable and economic alternative to traditional grey infrastructures to mitigate the negative impact of urbanization on hydrological processes (e.g. Singh et al. 2020). LID is an increasingly popular strategy to manage urban stormwater for individual properties, but the aggregate effect on runoff control (both peak flow rate and volume reduction) at the urban catchment scale is nowadays an open issue among researchers (e.g. De Paola et al. 2018; Ghodsi et al. 2021; Cristiano et al. 2021).

Recently domestic rainwater harvesting systems (DRWH) have been included among LID solutions since they simultaneously provide the dual benefit of water supply augmentation and stormwater detention as documented in the literature through both modelling and experimental studies (e.g. Deitch and Feirer 2019; Jing et al. 2018; Teston et al. 2018).

In urban catchments, the extensive installation of DRWH is nowadays recognized as a support in stormwater detention for reducing the frequency and peak of stormwater flood. In the residential district in Nanjing (China), Zhang et al. (2012) found that the installed tanks have satisfactory performance in mitigating stormwater waterlogging problems, reducing flood volume by 13.9%, 30.2% and 57.7% in the cases of maximum daily rainfall, annual average maximum daily rainfall and critical rainfall, respectively. Steffen et al. (2013) evaluated the DRWH benefits through the application of rainwater harvesting systems in 23 cities located in seven different regions of the United States of America and the results indicate that rainwater harvesting can reduce the drained volume from 1 to 17%. In Italy, Freni and Liuzzo (2019) analysed the hydrologic response of a residential district in Sicily to the maximum rainfall depth recorded over the 2002–2008 period and the critical rainfall event of the 5-year return period: results showed that the contribution of the DRWH tanks to flood volume reduction is weak due to the shortage of capacity to store rainfall peak events. Indeed, the retention of stormwater during critical or heavy rainfall events requires the introduction of specific mitigation measures, such as detention tanks or bigger pipes, which can significantly reduce peak flows or the installation of DRWH tanks with a larger capacity. The researches quoted above show very different results from each other because the efficiency of the DRWH systems depends on several internal factors (such as tank size, water use, spatial allocation of the systems) and external ones (such as precipitation regimes, land use characteristics of the catchment).

A knowledge gap exists with respect to DRWH catchment-scale application (Jamali et al. 2020) and targeted hydrologic metrics (Quinn et al. 2021). New approaches to focus on how to best represent the impact of DRWH at larger scales need to be tested in different countries with different climatic and land use conditions (Campisano et al. 2017). Targeted hydrologic metrics should overcome classic retention metric that have a main drawback: they tend to focus on long-term volumetric performance rather than performance within specific, extreme events. Furthermore, the lack of monitoring data remains a crucial issue for catchment-scale studies; in particular to reduce the modelling uncertainties extensive data records (long-term hydrologic data along with detailed records of urbanizations) are required to carry out suitable calibration and validation procedures (Li et al. 2017).

In this framework the main objective of the present research is to develop a modelling framework to assess the effectiveness of DRWH in supporting urban flood resilience at

the sub-catchment scale. The first specific objective is to assess and compare the impact of DRWH systems in favouring stormwater detention by means of event-based hydrologic metrics - for different urban sub-catchments in terms of precipitation regimes and catchment configurations. The second specific objective is to analyse the influence of the rainfall characteristics and catchment urbanization (total impervious area) on the DRWH effectiveness in order to identify those variables that most significantly affect urban flood resilience. The third specific objective is to define a dimensionless variable able to describe the hydrologic performance of DRWH for the different urban system configurations and the investigated precipitation regimes. These three specific objectives represent the original contributions of the research to address the above-mentioned knowledge gap. Furthermore, its implications for engineering practice concern the preliminary siting and sizing of DRWH tanks at the sub-catchment scale for a required flood mitigation target or vice versa the assessment of the DRWH effectiveness based on the available storage volume.

2 Methodology

In the present study the effectiveness of the DRWH systems is investigated by means of a Decision Support Tool (DST) implemented in the web-GIS application namely TRIG Eau platform recently developed within the homonymous INTERREG IT-FR Maritime Programme project (Palla and Gnecco 2021). The web-GIS application is available online (http://www.trigeau.servergis.it/, accessed in September 2021) in Italian and French languages.

A suitable semi-distributed hydrologic-hydraulic model (Palla et al. 2017) is implemented in the TRIG Eau DST page (http://www.trigeau.servergis.it/it/mappa_ipotetico) to assess the impact of DRWH systems on the hydrologic response of a non-specific urban sub-catchment. The hydrologic-hydraulic modelling is undertaken using EPASWMM 5.1.007 (Rossman 2010) according to the following simulation options: the Soil Conservation Service Curve Number Method is employed to estimate infiltration losses; runoff is calculated using Manning's equation and, as for flow routing computation, the dynamic wave theory is used. Specific details on DRWH modelling are reported in Palla et al. (2017). The modelling analysis refers to the sub-catchment scale indeed the hydrologic-hydraulic variables are predicted at the discharge outlet of the main conduit, upstream of the receiving water body (Li et al. 2017). Numerical simulations are performed at the event scale including one initial conditions of the system corresponding to empty or full tanks (Palla and Gnecco 2021).

Modelling scenarios include four degrees of urbanization, four precipitation regimes, three drainage network configurations, and a specific DRWH conversion scenario. Furthermore, for each precipitation regime, three return periods of the rainfall event are investigated.

The effectiveness of the DRWH systems is analysed at the sub-catchment scale by using the well-known hydrologic performance, Volume and Peak Reduction indexes (namely VR and PR, respectively). The performance indexes indicate respectively the relative differences of the total outflow volume and the maximum flow rate observed at the outlet section of the catchment in the reference and the DRWH scenarios (Palla et al. 2017).

2.1 Urban Catchment Outline

The outline of the urban catchment refers to a non-specific urban area of 2 ha. The urban area is simplified into two typologies of sub-catchments: streets and residential areas. The area of main roads and residential areas are assigned respectively equal to 0.54 and 1.46 ha, respectively the 27 and 73 percentages of the total area, thus complying with the most common residential settlement characteristics (Ferri et al. 2017). The two typologies of sub-catchments are characterised 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). The percentage of imperviousness of the streets is assigned equal to 100% while the one of the residential areas is selectable between 30%, 45%, 75% and 90% thus describing different urbanization degrees. The main hydrologic and hydraulic parameters (CN values and n-Manning values) are assumed as follows: CN value is assigned 90 for streets while it is assigned 72 for residential areas; Manning coefficient is assumed equal to 0.1 $m^{1/3}/s$ and equal to 0.01 $m^{1/3}/s$ for the pervious and impervious areas, respectively.

2.2 Modelling Scenarios

2.2.1 Precipitation Regimes

Four precipitation regimes, namely Humid Temperate (HuT), Mediterranean Continental (MeC), Hot Temperate (HoT) and Sublitoral (Sub), are implemented in the TRIG Eau platform according to the cross-border area of the Interreg Maritime Italy-France programme with the exception of the Corse island. The HuT precipitation regime refers to the Liguria Region (IT), the MeC area to the Provence-Alpes-Côte d'Azur -PACA Region (FR), the Hot to the Sardinia Region (IT) while the Sub area to the coastal area of Tuscany Region (IT).

The synthetic design storm events are computed for the HuT, MeC, HoT and Sub precipitation regimes referring respectively to the regional studies on the extreme precipitations of Liguria (DGR 359/2008), France (http://services.meteofrance.com/e-boutique/climatologie/coefficient-montana-detail.html accessed on September 2021), Sardinia (Deidda and Sechi 2000) and Tuscany (DGRT 1133/2012). In particular for each precipitation regime, the estimation of the parameters of the Depth–Duration–Frequency (DDF) curve was carried out based on regional frequency analysis of rainfall extremes. Based on the aforementioned DDF relationship, the synthetic design storm events are computed using the Chicago method for three return periods: namely 2, 5, and 10 years. Note that the Chicago method was selected in order to generate a synthetic rainfall event that shows the maximum intensity over each sub-event duration (Keifer and Chu 1957). The rainfall duration is assumed to be 30 min and the time-to-peak ratio is equal to 0.5. By comparing the maximum intensity over 5 min, it is possible to define two rainfall design cases namely the Heavy (corresponding to the Humid Temperate and Sublitoral precipitation regimes) and Light (corresponding to the Hot Temperate and Mediterranean Continental precipitation regimes) cases.

2.2.2 Drainage Network Configurations

The urban area is served by a stormwater drainage network consisting of 13 junctions (including the terminal node that defines the final downstream boundary) and 12 conduits located below the streets network. Three different drainage network configurations, namely coastal, medium-slope and high-slope are implemented in the TRIG Eau platform in order to cover the main plane-altimetric profiles. The three drainage network configurations are consistent in terms of specific drained areas (expressed as a number of nodes and conduits) while differing in terms of conduits slope and lengths. The drainage systems are sized according to the 30%-degree of urbanization and the diameters are calculated in order to convey the 10-year, 0.5-hr design storm without any flooding occurrence.

2.2.3 DRWH Scenarios

The DRWH scenario is conceived according to the following operational and management rules. In each DRWH system, rainwater is assumed to be collected only from rooftops; 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 an active DRWH configurations is foreseen (Xu et al. 2020). The areal distribution of the DRWH systems is assumed to be uniform across the urban catchment, in particular no assumptions on the favourable locations for the DRWH systems are formulated (Fry and Maxwell 2017). Furthermore, the water demand to be supplied by rainwater is limited to toilet flushing and is assumed to occur at a constant daily rate with three different supplied periods (Campisano and Modica 2016; Palla et al. 2017).

In particular, the DRWH scenario is designed for the urban catchment characterised by the 30%-degree of urbanization that corresponds to a percentage of rooftops of 30% in the residential area. Therefore, the area of the overall collected rooftops is equal to 0.4386 ha for all the different degrees of urbanization. The number of inhabitants for a medium density-residential zone where condominiums and/or multi-floors buildings are foreseen is evaluated based on the following empirical relationship: 1 inhabitant for 22 square meters (e.g. Munafò and Tombolini 2014). According to above mentioned empirical relationships and the overall rooftop area, the total number of inhabitants served by the DRWH systems is 200, thus corresponding to the annual rainwater demand of 2920 m^3 per year.

The tanks are designed according to the simplified method as indicated in the Italian guideline UNI/TS 11445 (2012): the storage volume of the tank is then assumed as the 6% of the minimum value between the inflow and the rainwater demand on an annual basis. The tank sizing criterion is consistent with the French guidelines (MSS 2009; JORF 2008). The annual inflow is evaluated by multiplying the rooftop area with the annual rainfall depth and the discharge coefficient of 0.8. The annual rainfall depths are assigned equal to 1145 mm and 650 mm respectively for the Heavy (corresponding to the Humid Temperate and Sub-litoral precipitation regimes) and Light (corresponding to the Hot Temperate and Mediterranean Continental precipitation regimes) cases. The demand fraction (indicated as D/Q) is defined as the ratio between the annual rainwater 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.

Note that the DRWH sizing criterion implies in two different cases namely the Heavy and Light cases, corresponding to the above-mentioned precipitation regimes. The Heavy case is characterized by the D/Q and S/Q values of 0.74 and 0.04 while in the Light case D/Q and S/Q are equal to 1.3 and 0.06 respectively.

Specific details on DRWH modelling are reported in Palla et al. (2017). The geometry of each tank is designed according to 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 weir is accordingly defined; in particular, the inlet offset is placed to a 2-m depth and the weir section is schematised as a transverse rectangular element able to properly convey to the drainage network all the excess water. For a reliable and conservative evaluation of the hydrologic performance, no additional water storage is then foreseen in the tanks.

As for the initial condition of the tank, the initial empty tank is assumed as reference condition. Note that the empty tank's initial condition implies the following management rule: each DRWH is equipped with a Real-Time Control (RTC) technology that allows the emptying of the tank when a severe weather warning is expected (Xu et al. 2020).

2.3 The Statistical Analysis

Hydrologic performance index values evaluated with respect to the different simulation scenarios are represented by means of box plots providing statistical results on a sample basis. The lower and upper boundary of each box indicate respectively the 25th and 75th percentiles, while the continuous line within the box marks the mean values; whiskers above and below each box indicate the 90th and 10th percentiles; individual dots showed in the plot represent the 5th and 95th percentiles.

The Kruskal–Wallis test (H-Test) for Oneway Analysis of Variance (ANOVA) by Ranks (Vargha and Delaney 1998) is used to determine if there are statistically significant differences for comparisons of the hydrologic performance index values evaluated with respect to the different simulation scenarios. The comparison among the different groups is undertaken by considering a single factor affecting the simulation results including the drainage network typology, the precipitation regime and the DRWH sizing criterion. The Kruskal–Wallis Test being a nonparametric test does not require any normality assumption. Similarly, the Mann–Whitney (M-W) test is adopted for the pairwise comparisons. Note that the statistical tests are assumed successful when the p value is larger than 0.05.

3 Results and Discussion

Model simulation results consist of the paired values of the total outflow volume and the maximum flow rate predicted for the selected reference and the corresponding DRWH scenarios. The selected reference scenario corresponds to the ''do nothing'' scenario while the corresponding DRWH scenario is characterised by the collection of 30% of the residential area irrespective to the selected percentage of urbanization. In detail, the simulation results refer to 4 degrees of urbanization, 4 precipitation regimes, 3 return periods of the rainfall event and 3 drainage network configurations thus forming 144 different cases in total. The Volume and Peak Reduction indexes are then evaluated for the 144 cases and analysed in

order to assess the effectiveness of the DRWH system in supporting urban flood resilience at the sub-catchment scale.

3.1 The hydrologic performance analysis

The VR and PR indexes evaluated from the modelling results are clustered according to the specific precipitation regime and drainage network configurations thus resulting in 12 groups including 12 simulation results. Within each results group 3 different return period of the rainfall events and 4 urbanization degrees are represented.

Figure 1 illustrates the non-parametric distribution of the hydrologic performance indexes (VR and PR respectively) with respect to the drainage network configuration for the four precipitation regimes. Results show a wider range of variation for PR with respect to VR although the mean PR value reveals fairly constant across the different groups.

Aiming at pointing out the impact of the DRWH system, the H-test for ANOVA by ranks is performed by comparing at first the VR indexes with respect to the drainage network configuration observed in a given precipitation regime and characterized by a consistent DRWH criterion. Statistical results are synthetically described in Table 1.

In particular, for each precipitation regime the results of the normality and the equal of variance tests (success/failure) are reported, the latter is performed only if the normality test is passed; the H and p values of the H-test are then reported. Note that looking at the different precipitation regimes, two different sizing cases (respectively the Heavy and Light) emerge by means of the DRWH storage fraction, S/Q. Since the H-test is passed in each precipitation regime, results demonstrate that the drainage network does not represent an affecting factor for the investigated scenarios. It has to be noticed that the 2-ha urban catchment area, although it can be considered representative of the hydrologic response of an urban catchment unit, may not enough large to reveal the impact of the drainage network typology.

Based on the previous statistical results, the H-test is then performed by considering the VR indexes evaluated for each group of precipitation regimes and pairwise comparing the precipitation regime characterised by the same DRWH storage fraction. As an example, the VR indexes resulting from the HuT precipitation regime are compared with the ones resulting from the Sub precipitation regime both corresponding to a S/Q value equal to 0.04; similarly, the VR indexes resulting from the HoT and MeC precipitation regimes characterised by an S/Q value equal to 0.06 are compared. Results of the Mann-Whitney test are described in Table 2 where the results of the normality and equality of variance tests are reported together with the T and p values. Since the test confirms that the groups are not statistically different, the test is performed to evaluate if the VR values resulting from the Light sizing case (S/Q=0.06) are statistically different from the ones resulting from the Heavy sizing case (S/Q=0.04); the results are reported at the bottom of Table 2. The latter statistical test failed thus confirming a statistical difference between the two groups. Excluding from the analysis different tank sizes and water uses (e.g. outdoor usage) Steffen et al. (2013) showed similar results indicating that regions with higher precipitation tend to have lower stormwater control potential than semiarid regions.

Likewise, the VR indexes, Tables 3 and 4 describe the results of the statistical analysis performed for the PR indexes to figure out if the drainage network configuration and the precipitation regime represent factors affecting the hydrologic performance in the inves-
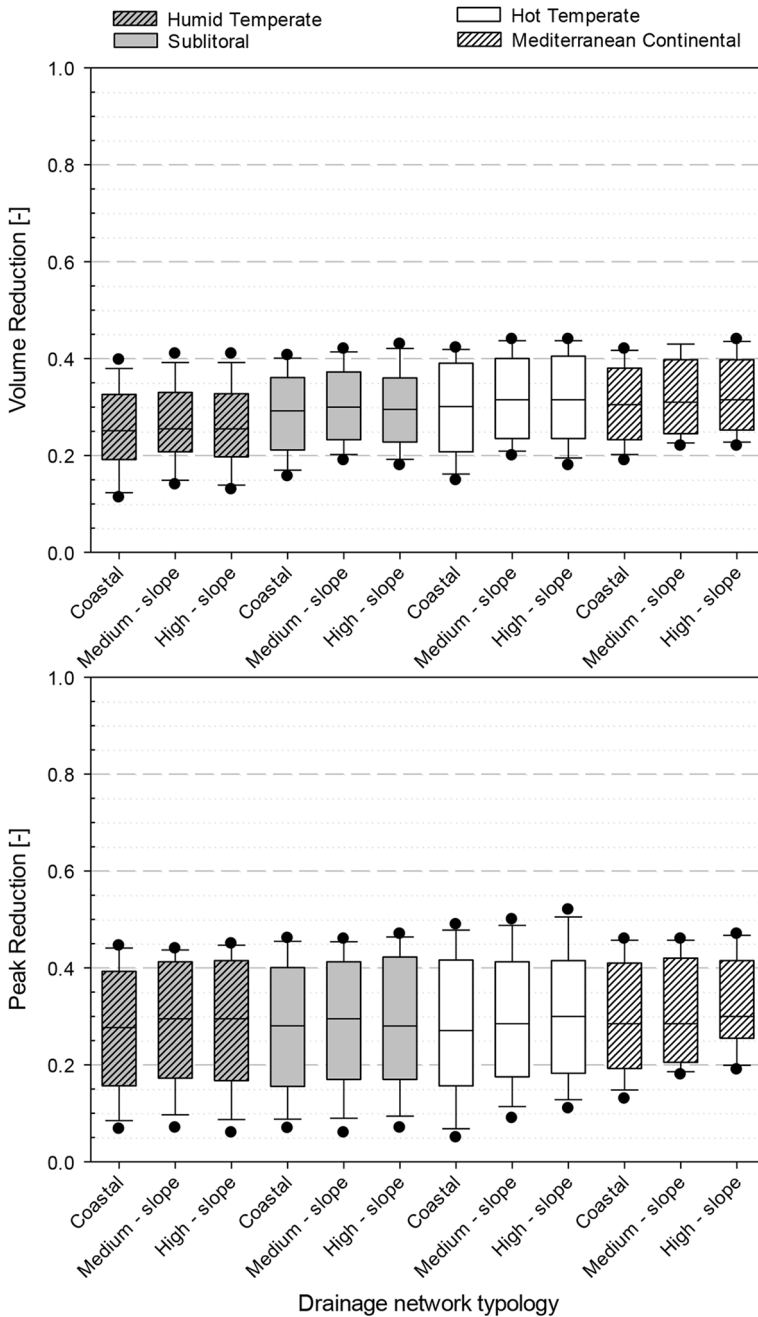
Fig. 1 Non-parametric distribution of Volume Reduction (top) and Peak Reduction (bottom) indexes with respect to the drainage network typology (Coastal, Medium–slope, High–slope) for the different precipitation regimes (Humid temperate, Hot temperate, Sublitoral and Mediterranean continental)

Table 1 ANOVA on ranks of the volume reduction index by comparing the network typology groups for different DRWH storage fractions and precipitation regimes (Humid Temperate, HuT; Mediterranean Continental, MeC; Hot Temperate, HoT and Sublitoral, Sub). Results of the normality, the constant variance and the Kruskal – Wallis (H and p values) tests are reported. Note that the black dot indicates a passed test and the white dot indicates a failed test

Storage fraction	Precipitation regime	Network typology	Volume Reduction - VR		
			Norm.	Equal Var.	H
0.04	HuT	Costal	●	●	0.155 (p=0.926)
		Medium-slope			
		High-slope			
0.06	HoT	Costal	○	-	0.712 (p=0.701)
		Medium-slope			
		High-slope			
0.04	Sub	Costal	●	●	0.194 (p=0.908)
		Medium-slope			
		High-slope			
0.06	MeC	Costal	○	-	0.848 (p=0.654)
		Medium-slope			
		High-slope			

Table 2 ANOVA on ranks of the volume reduction index by comparing two groups of precipitation regimes (Humid Temperate, HuT; Mediterranean Continental, MeC; Hot Temperate, HoT and Sublitoral, Sub) for different DRWH storage fractions. Results of the normality, the constant variance and the Mann – Whitney (T and p values) tests are reported. Note that the black dot indicates a passed test and the white dot indicates a failed test

Storage fraction	Precipitation regime	Volume Reduction - VR		
		Norm.	*Equal Var.*	*T*
0.04	HuT	●	●	1150.5 (p=0.066)
	Sub			
0.06	HoT	○	-	1295.5 (p=0.839)
	MeC			
ALL	HuT and Sub	○	-	4578.5 (p=0.010)
	HoT and MeC			

tigated scenarios. As observed for VR, results reported in Table 3 confirm that the drainage network does not represent an affecting factor for the PR indexes, indeed p values are greater than 0.05. The statistical analysis is then performed by pairwise comparing the PR indexes resulting from the simulation carried on in the precipitation regime characterised by the same DRWH storage fraction. Again, results of the Mann-Whitney test reported in Table 4 confirm that the groups are not statistically different. On the contrary to statistical findings related to VR, the test performed to compare the PR values resulting from the Light sizing case (S/Q=0.06) and the ones resulting from the Heavy sizing case (S/Q=0.04) is successful thus confirming no statistical difference among the simulated scenarios. It has to be noticed that the simulations are performed assuming the DRWH tanks initially empty therefore considering the form of the design rainfall events (i.e. symmetric Chicago hyetographs) it is reasonable that the PR value reveals on average irrespective of the specific simulation scenario. As highlighted by Di Matteo et al. (2021), the runoff peak reduction can be enhanced by operating the tank as a smart system thus managing several tanks as an inte-

Table 3 ANOVA on ranks of the peak reduction index by comparing the network typology groups for different DRWH storage fractions and precipitation regimes (Humid Temperate, HuT; Mediterranean Continental, MeC; Hot Temperate, HoT and Sublitoral, Sub). Results of the normality, the constant variance and the Kruskal – Wallis (H and p values) tests are reported. Note that the black dot indicates a passed test and the white dot indicates a failed test

Storage fraction	Precipitation regime	Network typology	Peak Reduction - PR		
			Norm.	*Equal Var.*	*H*
0.04	HuT	Costal	○	-	0.328
		Medium-slope			(p=0.849)
		High-slope			
0.06	HoT	Costal	●	●	0.126
		Medium-slope			(p=0.938)
		High-slope			
0.04	Sub	Costal	○	-	0.091
		Medium-slope			(p=0.955)
		High-slope			
0.06	MeC	Costal	○	-	0.572
		Medium-slope			(p=0.751)
		High-slope			

Table 4 ANOVA on ranks of the peak reduction index by comparing two groups of precipitation regimes (Humid Temperate, HuT; Mediterranean Continental, MeC; Hot Temperate, HoT and Sublitoral, Sub) for different DRWH storage fractions. Results of the normality, the constant variance and the Mann – Whitney (T and p values) tests are reported. Note that the black dot indicates a passed test and the white dot indicates a failed test

Storage fraction	Precipitation regime	Peak Reduction - PR		
		Norm.	Equal Var.	T
0.04	HuT	○	-	1304.5
	Sub			(p=0.919)
0.06	HoT	○	-	1240.5
	MeC			(p=0.411)
ALL	HuT and Sub	○	-	5068.5
	HoT and MeC			(p=0.545)

grated system. Through an adaptative control technology, tanks can be managed to store or release water to maximize both stormwater control and rainwater demand (Xu et al. 2020).

3.2 Impact of rainfall characteristics and impervious area conditions

The impact of the different factors including the rainfall characteristics (i.e. the total rainfall depth and maximum rainfall intensity of the design storm) and the percentage of imperviousness of the catchment are statistically investigated to point out the effectiveness of the DRWH systems. In the present analysis, the external factors are examined while the internal factors (e.g. tank sizing criteria) are neglected since the focus is to provide suggestions for management policies rather than specific implications to the system optimization (Li et al. 2017).

Figure 2 illustrates the mean and standard deviation values of the volume and peak reduction indexes resulting from the 12 investigated cases (4 urbanization degrees for 3 network
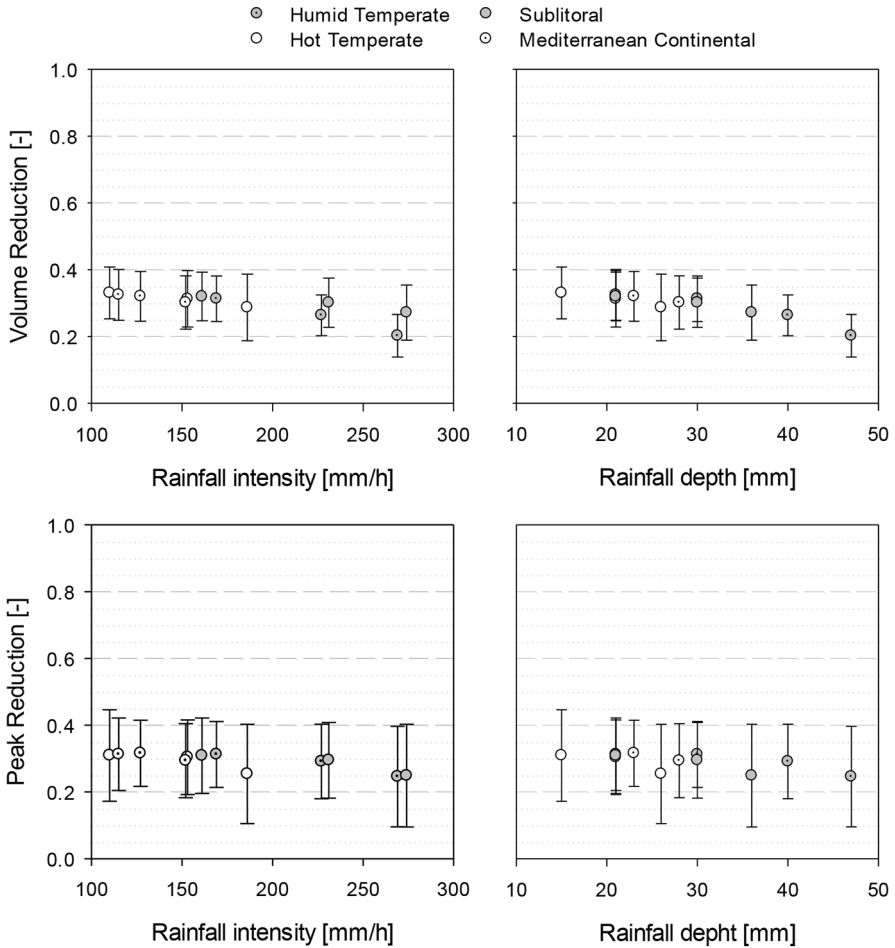
Fig. 2 Mean values of the volume reduction (top) and peak reduction (bottom) indexes plotted versus the maximum rainfall intensity evaluated over 5 min (left) and the rainfall depth (right) for the different precipitation regimes (Humid temperate, Hot temperate, Sublitoral and Mediterranean continental). Note that the error bars represent the standard deviations

typologies) plotted versus the twelve simulated maximum rainfall intensities and depths (3 return periods for 4 precipitation regimes). Looking at the results reported in Fig. 2, it emerges that both the maximum rainfall intensity and the rainfall depth slightly impacts on the two hydrologic performance indexes: indeed the mean value of VR and PR slightly decreases increasing the rainfall characteristics while standard deviation values observed for VR and PR are consistent in both cases. It has to be noticed that the impact on the VR indexes is more noticeable with respect to the PR ones, as expected. Indeed, the effectiveness of DRWH in reducing the runoff volume is proportional to the available volume in the tank (Deitch and Feirer 2019). For example, Zhang et al. (2012) found that for an urban catchment in Nanjing city (China) rainwater harvesting effectiveness does not increase in
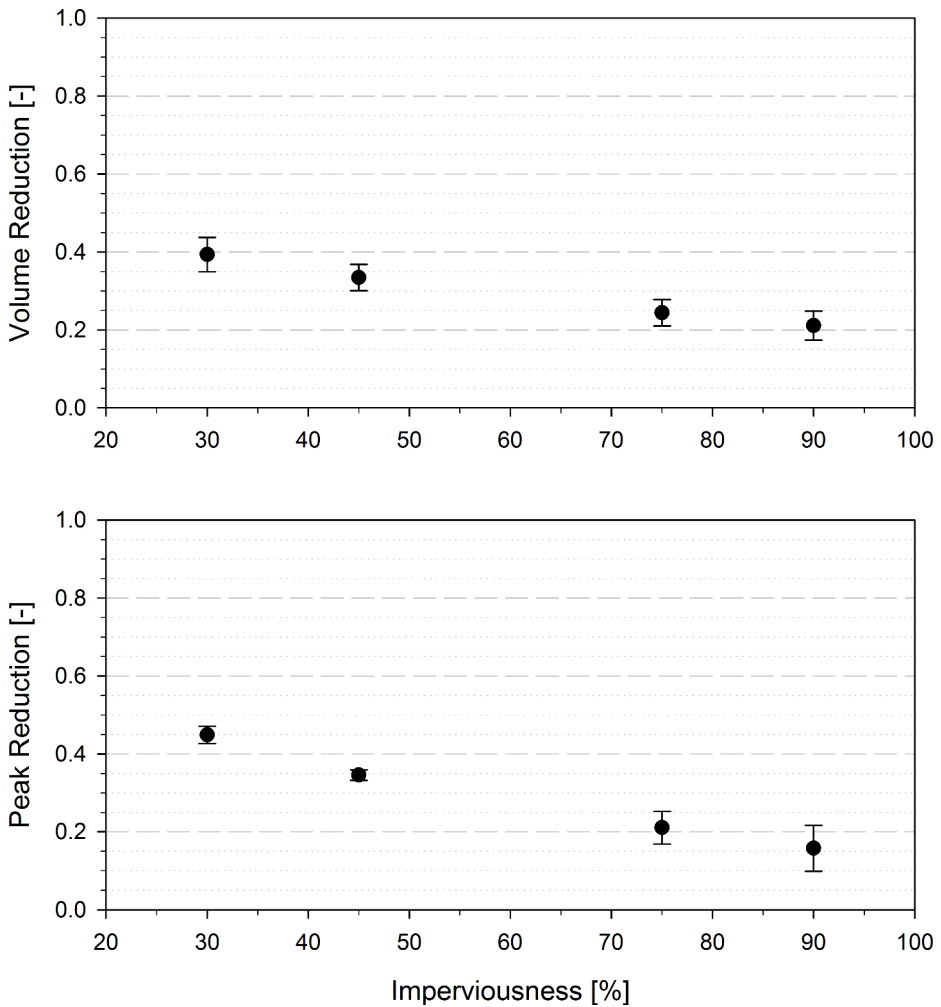
Fig. 3 Mean values of the volume reduction (top) and peak reduction (bottom) indexes plotted versus the percentage of sub-catchment imperviousness. Note that the error bars represent the standard deviations

proportion to the increase in implementation areas while it is mainly influenced by the precipitation depth and consequently by the available storage.

Figure 3 illustrates the mean and standard deviation values of the volume and peak reduction indexes resulting from the 36 investigated cases (4 precipitation regimes for 3 return periods and 3 network typologies) plotted versus the 4 degrees of urbanizations.

Looking at the results reported in Fig. 3, it clearly emerges that the imperviousness rate significantly impacts on the two hydrologic performance indexes, indeed the mean value of VR and PR linearly decreases increasing the imperviousness and the standard deviations of VR and PR at assigned imperviousness is minimal.

Results indicate that the percentage of imperviousness reveals the limiting factor of the DRWH effectiveness in the urban contest of concern; in particular, for an imperviousness

rate of the residential areas equal to 30%, the average VR and PR are respectively equal to 0.4 and 0.45 regardless the precipitation regime and the network typology. On the contrary, it can be assessed that for an imperviousness rate of 90% the average values of VR and PR are significantly reduced even if remain still detectable and equal to 0.21 and 0.15, respectively. The role of imperviousness is therefore predominant with respect to the rainfall event characteristics thus confirming that DRWH as other source control measures by directly modifying the effective impervious areas can potentially increase the resilience of communities to changing the precipitation patterns (Pyke et al. 2011).

Since the sizing of the drainage network refers to the 30% imperviousness (corresponding to the reference scenario where flooding does not occur), the scenarios characterised by the higher urbanization degree may represent the actual scenarios where the design of the drainage network was not properly upgraded as well as the future urbanization scenarios. In addition, the DRWH systems is conceived for the urban catchment characterised by 30% imperviousness thus resulting in an assigned impervious area to be collected to the DRWH tanks. In case of larger imperviousness degrees, it has to be noticed that the DRWH conversion scenarios correspond to different effective impervious area reductions (Palla and Gnecco 2015). In this framework the preliminary assessment of the DRWH impact on stormwater control provides a measure of urban flood resilience.

3.3 The DWRH effectiveness

Based on the result of the statistical analysis, the DRWH effectiveness is examined for all the 144 cases by using a dimensionless variable simultaneously accounting for both the investigated external factors: the magnitude of the rainfall-runoff event and the degree of urbanization.

The proposed dimensionless variable namely "event storage fraction" is evaluated as the ratio between the event runoff volume resulting from the impervious surface of the urban catchment in the reference scenario and the storage capacity of the DRWH system.

Figure 4 illustrates the behaviour of the VR and PR versus the event storage fraction for the 144 simulated cases. The event storage fraction allows to describe the DRWH effectiveness by pointing out the trend of the hydrologic performance revealing an almost linear relationship in the case of the VR index as illustrated in Fig. 4. Results related to the VR index are consistent with previous studies: Walsh et al. (2014) indicated a linear relationship between runoff reductions and the DRWH available capacity.

Furthermore, results plotted in Fig. 4 show that a minimum storage fraction value of 0.4 is required to obtain on average VR and PR greater than 0.2. Therefore, it can be argued that, for a typical residential catchment in the investigated area, the DRWH effectiveness in supporting the urban flood resilience becomes relevant starting from a storage event fraction of 0.4 that means realizing storage tanks able to contain at least the 40% of runoff volume generated by the targeted rainfall event.

On the other hand, the maximum modelled hydrologic performance VR and PR equal to 0.44 and 0.5 are consistent with the analytical evaluations. In particular, the maximum performance rates can be analytically evaluated by assuming that no overflow occurs from the tanks and by referring to the lower rainfall magnitude when the pervious areas do not contribute to the outflow peak.
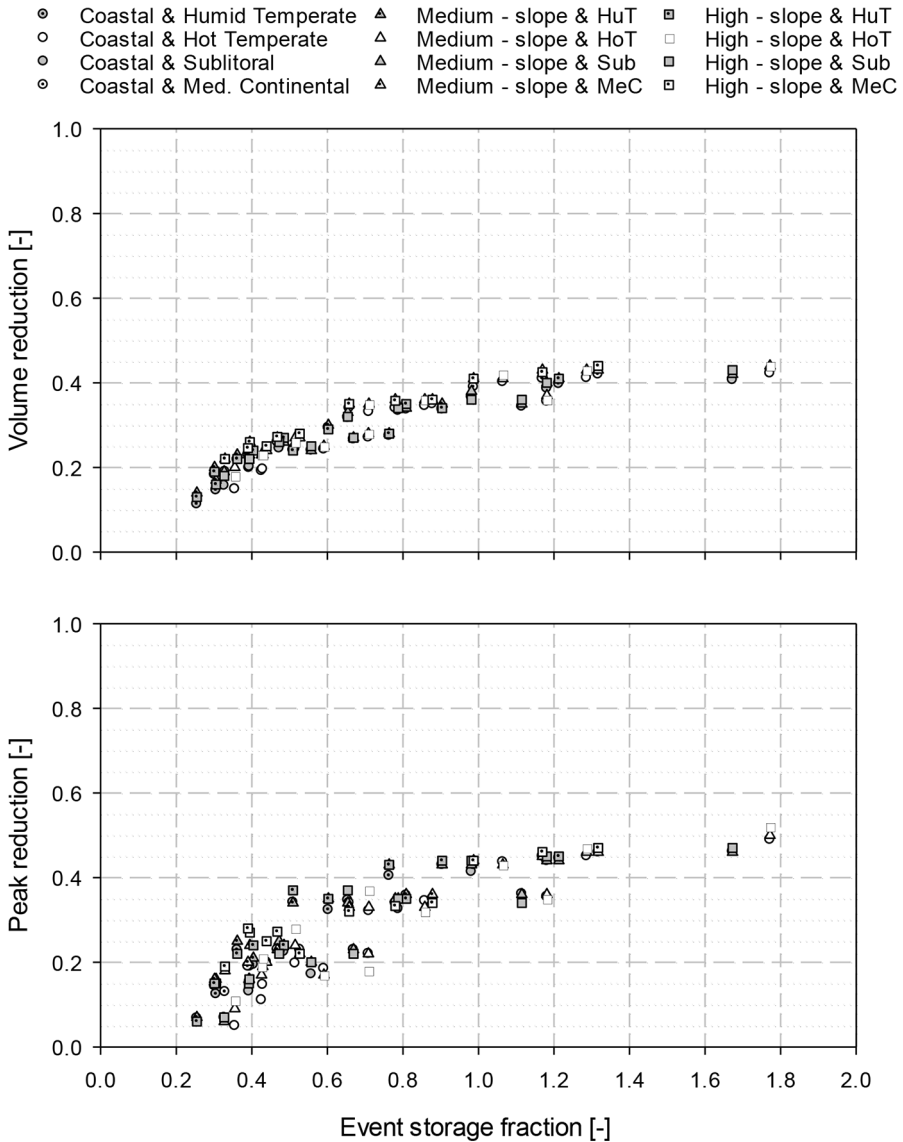
Fig. 4 Volume and Peak reduction indexes plotted versus the event storage fraction simulated for the three drainage network catchment typologies (Coastal, Medium–slope; High–slope) according to the four precipitation regimes (Humid Temperate, HuT; Mediterranean Continental, MeC; Hot Temperate, HoT and Sublitoral, Sub)

The findings of the present research overcome the limitations of the modelling approaches of a specific case study by improving our understanding of the DRWH performance and the corresponding dynamic variations due to different precipitation regimes, rainfall magnitudes and network configurations.

Future modelling research should integrate innovative smart operating schemes of DRWH tanks (Di Matteo et al. 2021; Quinn et al. 2021; Maiolo et al. 2020) in order to minimize the storage volume required to obtain the desired hydrologic performance.

4 Conclusion

The DRWH effectiveness at the sub-catchment scale is analysed according to a specific DRWH conversion scenario under 4 degrees of urbanization, 3 drainage network configurations, 4 precipitation regimes and 3 return periods of the rainfall event. At this aim, a suitable modelling framework is implemented in the TRIG Eau DST page (http://www.trigeau.servergis.it/it/mappa_ipotetico). The semi-distributed hydrologic-hydraulic model is undertaken using EPASWMM 5.1.007 where specific tools are developed to simulate DRWH systems at high spatial resolution. The DRWH scenario is designed for the urban catchment characterised by the 30%-degree of urbanization assuming a uniform areal distribution of the DRWH systems across the urban catchment. The effectiveness of the DRWH systems simulated for the 144 different cases, is analysed at the event scale by using the hydrologic performance Volume and Peak Reduction indexes.

The hydrologic performance analysis shows the following results for the urban contest of concern:

- DRWH catchment-scale applications are effective in stormwater detention for reducing both volume and peak of the runoff;
- the drainage network typology does not represent an affecting factor of the DRWH effectiveness;
- the total depth and the maximum intensity of the rainfall event slightly impacts the two hydrologic performance indexes;
- the percentage of imperviousness reveals the predominant limiting factors of the DRWH effectiveness.

Based on the results analysis, the dimensionless variable, namely the event storage fraction, is defined to easily describe the DRWH effectiveness. The event storage fraction can be used by water engineers to develop easy-to-use equations to carry out the preliminary sizing of DRWH tanks or vice-versa to quantitatively assess the hydrologic performance based on the available storage volume. In the present research, for a typical residential catchment in the Italy-France cross-border coastal area, the DRWH effectiveness in supporting urban flood management becomes greater than 0.2 starting from a storage event fraction of 0.4 which means realizing storage tanks able to contain at least the 40% of runoff volume generated by the targeted event.

The main result of the present research, according to an engineering perspective, confirm that DRWH catchment-scale applications allow to support specific stormwater control requirement based on peak-flow or volume regulations strategies. Furthermore, improving the actual knowledge on the effectiveness of DRWH catchment-scale applications, these research findings contribute to include these solutions in government policy and regulations.

Data Availability Not applicable.

Code Availability Not applicable.

Declarations

Ethical Approval: Not applicable.

Consent to Participate: Not applicable.

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