A procedure for designing natural water retention measures in new development areas under hydraulic-hydrologic invariance constraints

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ABSTRACT

In recent years, in Italy and elsewhere, regional regulations based on Hydraulic-Hydrologic Invariance (HHI) principles have taken hold, especially for new development areas. Natural Water Retention Measures (NWRMs) are among the most interesting options to provide the storage and infiltration capacities that are needed to achieve the HHI objectives. A procedure for the design of NWRMs in new development areas under HHI constraints is presented and is based on a simple combination of CN-SCS method for determining rainfall excess and lag-time method for simulating runoff propagation. Three types of NWRMs can be considered: rain barrels, drainage wells and drainage trenches, and five types of synthetic hyetographs can be selected and three different approaches for the determination of critical storm duration applied. The results obtained by applying the procedure in a new development area located in northern Italy are illustrated and some general remarks are drawn. It clearly emerges that practitioners should pay particular attention to the correct determination of design storm duration in order to avoid large underestimations of NWRMs size. Moreover, different combinations of the three NWRMs can provide the required reduction of peak of runoff after the transformation, but it appears that drainage trenches are more effective with respect to harvesting systems in reducing the peak runoff value.

Key words | CN-SCS method, critical storm duration, hydraulic-hydrology invariance, natural water retention measures, sustainable drainage systems, time of concentration

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INTRODUCTION

The increasing urbanization that many cities in the world are experiencing causes adverse effects on water quantity and quality, such as augmented runoff volume and rates, decreased runoff lag-time and groundwater recharge, and impaired water quality (Chiaradia *et al.* 2018). Hence, the need to manage rainwater and reduce runoff in the urban context (especially starting from new development areas) has led many regions and water management companies to increasingly promote acts addressed to the concept of Hydraulic-Hydrologic Invariance – HHI (e.g. Sustainable Development Goals (SDGs) in Europe, Water Management Act 2,000 of NSW government in Australia, Clean Water Act in USA). Specifically, the HHI principle requires that the runoff in the outlet from the transformed area remains unchanged or does not exceed a given threshold (generally both in terms of peak of runoff and volume). A storage volume therefore needs to be implemented in the area in order to achieve a partial or total disconnection from the downstream drainage system.

In Italy the need to define methods that guarantee the principle of HHI in urban planning interventions has been prompted by frequent and sudden flooding events due to the

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climate and to the high anthropization of the territory (Sofia et al. 2017). If, on one hand, imperviousness and urban sprawling highly contributed to these events, on the other, the existing drainage systems were often designed with inadequate return times and currently they are unable to safely collect rainfalls from extreme events (Masi et al. 2018). Therefore, national and regional authorities have introduced, since the beginning of this millennium, HHI principles in the context of urban transformation projects (Botticelli et al. 2018). Concerning this matter, Italy appears a pioneer at international level, with effective and concrete regulation to make operative HHI principles at regional scales (Pappalardo et al. 2017). One of the first efforts to produce a mathematical method to identify when a land use change can be considered 'invariant' in terms of water discharge was by Pistocchi (2001) and applied in Emilia Romagna region. This author proposed a simplified approach based on the design of water storage devices through a constant 'udometric' coefficient (i.e. the contribution of the basin unitary area to the formation of peak discharge) in order to cut down the increased runoff coefficient after the transformation. However, this approach does not consider the possibility that once the maximum allowed flow rate after the transformation has been defined, there may be longer rain durations for which the ante-operam peak discharge is exceeded and then a larger storage volume could be required. Conversely, Veneto region provides two methods based on reservoir flood routing: the linear reservoir method and the direct rainfall method. Both the approaches evaluate the maximum volume that exceeds the peak discharge of *ante-operam* conditions. They are still based on simple rainfall-runoff conceptual models, and they use the runoff coefficient as the only parameter to treat infiltration losses. Moreover, runoff coefficient values that can be found in technical literature usually focus on differences between types of land cover, there is no adequate classification based on soil and subsoil textural and granular properties.

Other Italian regions or river basin authorities have followed similar approaches based either on udometric coefficients or on simplified flood routing schemes. In 2017, the Lombardy region authority (through regional directive n°7 of 23 November 2017) classified the regional territory in three different hydraulic-hydrologic criticality levels, each of which corresponds a specific peak of runoff and a minimum storage volume to apply when a new development area is designed . The storage volume can be achieved through traditional storage tanks or exploiting soil infiltration capacity, the latter attained by natural water retention measures (NWRMs) or sustainable drainage system practices (SuDSs).

In many cases HHI directives establish a hierarchy of rainwater management modalities, putting infiltration and percolation first (compatibly with the soil and subsoil characteristics) and connection to the sewerage last. The adoption of the HHI concept, therefore, needs to design appropriate mitigation or compensatory measures, such us rain barrels, permeable pavements, drainage wells, drainage trenches in order to comply with runoff limitation (Kang et al. 2013). It follows that accurate estimations of design floods are essential for designing these NWRMs (Masi et al. 2018). Hundreds of different methods have been proposed for estimating floods in small urban drainage watersheds, most of which involve the use of arbitrary formulas (Campana & Carlos 2001). The choice of method depends on the applicable design criteria and the availability of data (Boni et al. 2007). Moreover, the basis for many of the elements used in these methods, such as the choice of the design storm duration, are not yet well documented and clarified (Michailidi et al. 2018). Therefore, an effective but handy flood estimation procedure for designing HHI measures appears to be a strong request coming from the practitioners' community to which the scientific community should give an answer.

This paper is an attempt to provide a procedure, through the adoption of a semi-distributed, CN-SCS based runoff production model accounting for NWRMs effect, combined with a simple routing model and complemented by a set of tools to determine the critical runoff duration and to compare different hyetograph types. The application of the procedure to case study shows the potential of this procedure, as well as the limitations of some practices traditionally used in the estimation of the critical storm duration.

MODELLING APPROACH

In order to obtain a reliable rainfall-runoff description that is also easily applicable, to meet the needs of practitioners, a semi-distributed approach based on the combination of (i) the Soil Conservation Service CN method (SCS-CN, Mishra & Singh 2003) for determining rainfall excess and (ii) lag-time approach (Maidment 1993) for simulating runoff propagation on watershed was implemented for GI design purposes, and its framework is shown in Figure 1. The model was originally implemented in Excel® and is currently being developed into a web-app named '*W-Invariance*', that will be freely available on the web site of SMART-GREEN project (https://sites.unimi.it/smartgreen/ Ercolani *et al.* 2018).

The SCS method is widely accepted and it has been used in numerous hydrologic studies (Mishra & Singh 2013). Although it was originally developed for estimating rainfall excess at daily time resolutions in small-medium sized agricultural watersheds (Ponce & Hawkins 1996; Garen & Moore
Q2 2005; Grimaldi *et al.* 2013), it has been extensively used throughout the world (including urban areas), far beyond what its original developers would have imagined (Kuichling 1889; Maidment 1993; Sample *et al.* 2001; Kadam *et al.* 2012). When applied for computing incremental rainfall excess at sub-daily time resolutions the method was shown to overestimate infiltration compared to the Green-Ampt model
Q3 (Brenova 2001; Grimaldi *et al.* 2013). This, however, is particularly true when impulse-like rainfall events, of the Chicago type, are considered (Eli & Lamont 2010), while the difference between the two models is much smaller with 'smoother' hyetographs, like those analyzed in our study (see below under 'Total rainfall hyetographs') (Hawkins *et al.* 2009).

The pillar of the SCS method is the curve number (CN). It is a conceptual parameter which depends on soil, cover, and hydrology condition of the land surface. It varies from 0 to 100 for totally pervious and impervious soils respectively. The rainfall excess (P_e) is obtained from total rainfall (P_{tot}) through Equation (1):

$$P_e = \begin{cases} 0 \; se \; P_{tot} \leq I_a \\ \dfrac{(P_{tot} - I_a)^2}{(P_{tot} - I_a + S)} \; se \; P_{tot} > I_a \end{cases} \tag{1}$$

where S is the potential retention (Equation (2)), while I_a is the initial abstraction (Equation (3)).

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2}$$

$$I_a = 0.2 \cdot S \tag{3}$$

Two important abstractions for any single storm event are lumped in I_a, i.e. rainfall interception (meteorological rainfall minus throughfall, stem flow and water drip) and depression storage (topographic undulations). The runoff is triggered when the total rainfall exceeds I_a.

Once the runoff is triggered its propagation is simulated through a simple translation of water flow over the drainage basin, excluding natural storages already considered in the SCS method (Maidment 1993). The runoffs originating from different types of surfaces are translated without modifications and then summed together, ignoring any kind of interaction between them. The runoff travel time distribution is instead described by a time-area curve. The overall procedure to estimate design floods proposed in this study can be summarized into the conceptual diagram shown in Figure 2, whereas the implementing steps are described below under 'Model implementation'.

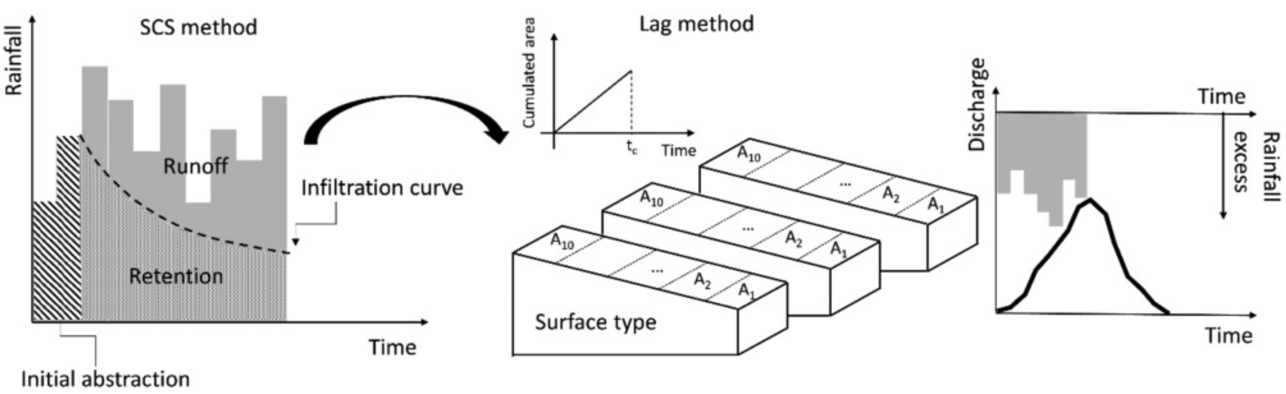

Figure 1 | Schematic hydrological response of the proposed system.

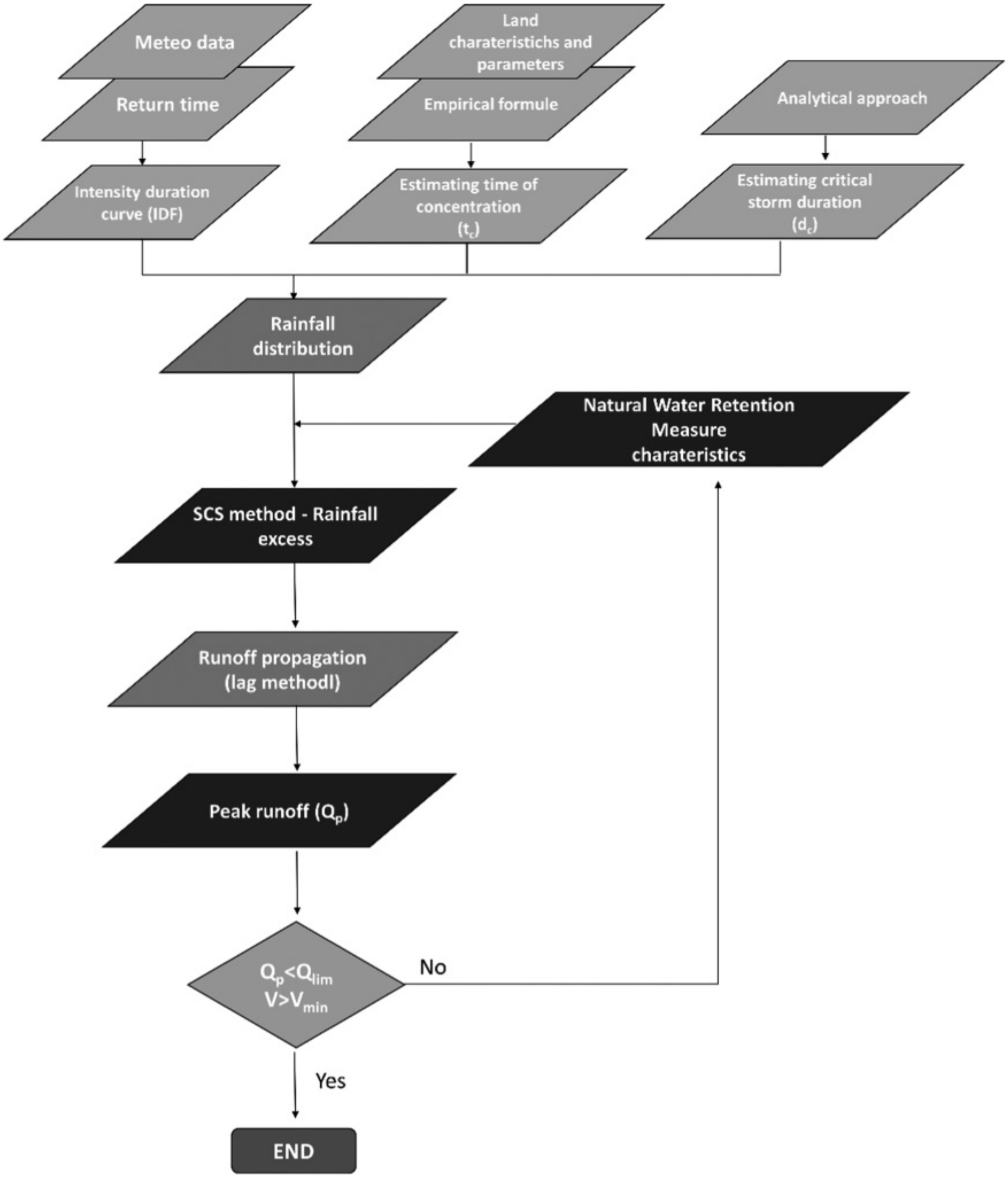

Figure 2 | Conceptual diagram of the proposed approach.

Natural water retention measures

Including NWRMs behavior in the SCS method is not straightforward. However, there are consolidated experiences on (i) the determination of CN value for permeable surfaces (Bean *et al.* 2007), (ii) the influence of Rainwater Harvesting Systems (RHSs) on initial abstraction (Damodaram *et al.* 2010) and (iii) the relationship between CN and infiltration rate (Gabellani *et al.* 2008). In the *W-Invariance* app, in addition to permeable surfaces, the behavior of three types of NWRMs (i.e. rain barrels, drainage wells and drainage trenches) can be implemented to mitigate the **Q4** runoff from impervious surfaces, also when the new development includes pre-existing constructions. The schematization employed to represent the functioning of these three types of NWRMs is shown in Figure 3. In particular, in terms of geometrical characteristics, rain barrels and drainage wells have a cylindrical shape that can be described by diameter and height, while drainage trenches cross-sections are assumed trapezoidal and can be described by short base, height and legs slope. Both drainage wells and drainage trenches disperse water in the soil and are not connected with the sewerage system.

In the proposed approach, the CN of permeable surface is defined by the *S-Storage CN method* described in Bean *et al.* (2007). In this method the maximum potential retention (S) is set equal to the effective storage, which is the depth of rain stored by the permeable pavement, as determined by the product of depth and porosity of the pavement. CN and I_a are then calculated using Equations (2) and (3) respectively, while Equation (1) is used to calculate runoff for any precipitation event.

The SCS modeling approach can also be adopted to predict the watershed-level impact of placing RHSs (in this case the rain barrels). In the proposed model, RHS captures the initial abstraction from impervious surfaces, and once the RHS is full, it is bypassed and the runoff continues unaltered downstream. To represent this behavior, the *I_a-Storage CN*
Q4 *method*, already described in Damodaram *et al.* (2010), is proposed here. The initial abstraction, I_a, is set equal to the effective depth of the RHS, which is the depth of rain stored by the RHS, as determined by the ratio between the storage volume of the rain barrel and the drained impervious area, while S is neglected. A combination of the two methods is implemented here for describing the behaviors of drainage wells and drainage trenches. I_a for both infrastructures is calculated with *I_a-Storage CN method* (where the volume of the drainage well is the volume of the well, whereas in the case of the drainage trench it is determined by the product between the furrow volume and the porosity of the backfill material), while S depends on CN (Equation (3)), the latter derived by infiltration rate at saturated conditions (f_1) of the drain, as reported by Gabellani *et al.* (2008) and shown in Figure 4.

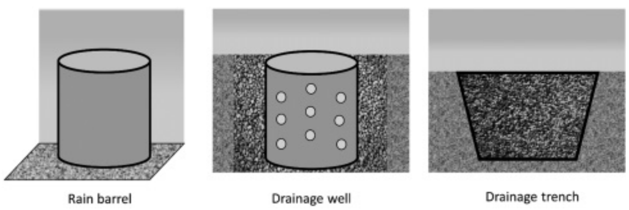

Figure 3 | Natural water retention measure (NWRM) features and layouts.

NWRMs geometries, soil porosities and drain hydraulic characteristics are selected in order to limiting the peak of runoff under a regulatory threshold (Q_{lim}).

Total rainfall hyetographs

Rainfall events of various intensities and durations are used in the hydrologic design of structures that control stormwater runoff and floods (Kang *et al.* 2013). Rainfall Depth-Duration-Frequency (DDF) curves allow the calculation of the rainfall depth of the design event for any given exceedance probability (or return period – T) over a range of storm durations. Once the rainfall depth and duration have been determined, different hyetographs are then usually compared for designing the NWRMs (Marsalek & Watt 1984). In the *W-Inavariance* procedure six of the most widely used types of design hyetographs can be applied and compared, namely: uniform (Water Pollution Control Federation 1970); Chicago (Keifer & Chu 1957); Sifalda Q5
(Sifalda 1973); triangular (Yen & Chow 1980) in the three variants: with peak intensity at the beginning, at the middle and at the end of storm duration.

In the following, a brief summary of the hyetograph characteristics is presented, but for more details the reader is invited to refer to the aforementioned literature works.

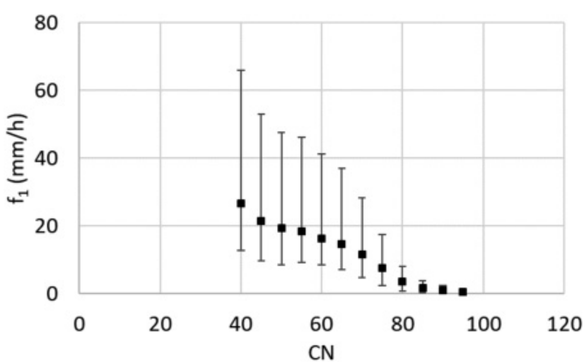

Figure 4 | Relation between infiltration rate at saturated conditions and CN values in antecedent moisture condition AMC II (rearranged from Gabellani *et al.* 2008).

Uniform hyetograph

It is the most widely used for hydraulic structure design. Its intensity is directly developed by DDF curve and is constant for the entire rainfall duration.

Chicago hyetograph

The Chicago hyetograph is usually adopted for designing sewers and drainage management systems. The general equations of the rising and falling limbs are described by Equations (4) and (5).

$$i(t) = n \cdot a \cdot \left(\frac{t_r - t}{k}\right)^{n-1} for \;\; t \leq t_r \tag{4}$$

$$i(t) = n \cdot a \cdot \left(\frac{t - t_r}{1 - k}\right)^{n-1} for \;\; t \geq t_r \tag{5}$$

where $i(t)$ is the rainfall intensity, t is the time, t_r is the time where the peak of hyetograph occur, k is a dimensionless parameter ranging between 0 and 1 and defines the position of the peak. It is traditionally assumed equal to 0.4. The peak is cut at the maximum rainfall intensity resulting from DDF as suggested by Becciu & Paoletti (2010).

Sifalda hyetograph

This hyetograph is composed of three intervals: in the first time interval the intensity of precipitation increases linearly; in the second interval it is constant, whereas in the third interval the intensity decreases, again linearly. The first and the second intervals last a quarter of rainfall duration while the third is equal to half of rainfall duration. The hyetograph is subdivided in such a way that 14 and 30% of precipitation volumes are included in the first and third parts, whereas the remaining 56% is included in the second part.

Triangular hyetograph

The average intensity of the hyetograph is equal to uniform one, but with a peak two times the average intensity. The position of the peak can be located at the beginning of the rainfall duration (Tri-r = 0 in the following), at the middle (Triangular in the following) or at the end (Tri-r = 1 in the following).

Critical storm duration

Determining the duration of the critical storm event is key to the assessment of the suitability of NWRMs to guarantee the satisfaction of HHI requirements. *W-Invariance* explores three different approaches to the problem: (i) based on the estimation of the time of concentration, (ii) an iterative model based approach and (iii) an analytical model based approach. The latter method is proposed by the authors in order to overcome limitations inherent in assuming the time of concentration as the critical storm duration, while maintaining the computational effort negligible (i.e. without requiring several numerical simulations as the iterative model based approach).

Time of concentration approach

The time of concentration (t_c) represents the time it takes for runoff to travel to the outlet of the watershed from the hydraulically most distant point (Maidment 1992). The t_c of an urban watershed is usually obtained using empirical equations or equations originally established for rural watersheds (Kang *et al.* 2013). These equations are useful as a first approximation, but they do not satisfactorily describe all local conditions (Campana & Carlos 2001). For rural watersheds, t_c is normally calculated as the watershed length divided by the water velocity, which is determined using either hydraulic formulas or tabulated values (Chen & Wong 1993). This approach was described for the first time by Kirpich (1940) and appears suitable, albeit rudimentary, in urban situations where the watershed slopes and the framework of drainage channel network are often unclear (Becciu & Paoletti 2010). A plethora of other empirical formulas are quoted in literature (Grimaldi *et al.* 2012; Michailidi *et al.* 2018), however, their application depends largely on the knowledge of physiographic characteristics of the watersheds, often unavailable in urban situations.

Once t_c is determined, whatever formula is used to obtain its estimate, practitioners usually assume that the critical storm duration is equal to t_c itself. The rationale for this choice is that at that duration all upstream areas start contributing together to the discharge at the control section (Kang *et al.* 2013); shorter durations would not satisfy this condition, while longer rainfall would, but rainfall intensity would be smaller. By doing so, however, the delay between start of the rainfall and inception of runoff production is disregarded and, particularly in watersheds with high storage capacities (high values of I_a and S), this may cause significant deviations from the condition that all the area contributes to the peak discharge.

Iterative model-based approach

An alternative way of determining the critical duration is to derive it through an iterative procedure, based on repeated simulations model with changing rainfall durations, until the peak flow reaches a maximum (Kang *et al.* 2013). This allows the watershed storage effects to be found, such as surface retention, forest cover, and land use, which may delay surface runoff production substantially. To allow an accurate determination of d_c it is therefore necessary to use models that simulate the watershed dynamics (Botticelli *et al.* 2018). Although simplified, the one presented at the beginning of 'Modelling approach' above, is one of such models and *W-Invariance* automatically derives d_c by the iterative approach, for any given watershed configuration.

The main goal of the procedure proposed here is to estimate NWRM geometries which satisfy specific constraints on stormwater runoff. Hence, being a design-oriented problem, we aim at identifying rainfall duration that is critical for the urban watershed already including the NWRM systems, although the design of the systems depends on the critical duration itself. The iterative procedure allows the management of the two unknowns jointly. Namely, while iterating on rainfall duration, we add a second iteration on NWRM geometries, so that we obtain the critical storm for a design that satisfy the constraints on runoff. In practice, when the constraint is on runoff peak, for each rainfall duration, NWRM geometries are iteratively modified (and the mean value of CN for the development area adjusted accordingly) until the peak runoff value is equal to the regulatory limit (Q_{lim}).

Analytical model-based approach

Finally, a novel procedure to estimate d_c is proposed. The aim is to maintain the main advantages of the iterative model-based approach in respect of the time of concentration approach while reducing the computational effort. In particular, the method estimates d_c analytically, and hence it does not require any numerical simulation, abating completely the computational cost. It assumes that the new development area behaves like a reservoir whose volume W – which represents both storage and infiltration capacities – has to be maximized under the constraint that the discharge must not exceed Q_{lim}. The inflow to the reservoir is represented by the total rainfall (P_{tot}), obtained by the DDF curve.

If the outflow is supposed constant and equal to Q_{lim}, then the value of W for any given rainfall duration (θ) is:

$$W = P_{tot} - \frac{Q_{lim}}{A} \cdot \theta = a \cdot \theta^n - \frac{Q_{lim}}{A} \cdot \theta \tag{6}$$

where A is the watershed area (i.e. the total area where the new development takes place) and a and n are the DDF parameters. By computing the first order derivative of Equation (6) one can easily obtain the rainfall duration that maximizes W, i.e.:

$$d_c = \left(\frac{Q_{lim}}{A \cdot n \cdot a}\right)^{\frac{1}{n-1}} \tag{7}$$

The analytical solution for the critical duration d_c can also be obtained under the assumption that the outflow hydrograph has a triangular shape. In this case Equation (6) modifies as follows:

$$W \quad = P_{tot} - \frac{Q_{lim}}{A} \cdot \theta = a \cdot \theta^n - \frac{Q_{lim}}{2 \cdot A} \cdot \theta \tag{8}$$

and the critical duration is given by:

$$d_c = \left(\frac{Q_{lim}}{2 \cdot A \cdot n \cdot a}\right)^{\frac{1}{n-1}} \tag{9}$$

It can be noticed that, in both cases, d_c depends only on watershed size and DDF parameters, therefore it can be computed in *ante-operam* conditions, providing a rapid scanning of critical storm durations, that can be useful in the preliminary design phases.

Model implementation

All the various model components described in the previous sections are combined to build an effective flood estimation procedure for designing NWRMs, whose implementation goes through the following steps:

(1) Computing DDF curve from a, n parameters and return period T;
(2) Estimating t_c of the development area using Kirpich (1940) empirical approach;
(3) Calculating d_c analytically from DDF and Q_{lim};
(4) Computing synthetic hyetographs;
(5) Setting NWRM configurations (geometries, soil porosities etc.);
(6) Applying SCS method for obtaining rainfall excess for each surface type;
(7) Applying lag-time module for simulating runoff propagation for each surface type;
(8) Evaluating the peak of runoff summing runoff contributes of each surface type; if it is larger than Q_{lim}, NWRM configuration should be rearranged and the procedure restart from point 5; if the peak is lower than Q_{lim} it is possible to continue at point 9;
(9) Evaluating the sum of storage and infiltration volumes provided by NWRM configuration. If they are larger than V_{min}, the procedure is finished otherwise the configuration of NWRMs need to be changed and the procedure restarted from point 5.

From a computational point of view, in the proposed procedure the evolution of rainfall-runoff process is discretized as a function of time of concentration (t_c), i.e. the time-step of simulation is obtained as the ratio between t_c and the number of subareas on which the user decides to subdivide each surface type of the new development area.

CASE STUDY

In order to assess the potentialities of the procedure described in the previous section, the method was applied to a case study in Northern Italy. The objective was to evaluate different potential NWRM configurations able to satisfy local regulation requirements regarding urban stormwater management. The case study consists of a new development area (about 1.4 hectares) located in the municipality of Inveruno (Lombardy region, northern Italy). The area can be subdivided into three different construction areas: two main buildings (a primary and a secondary school) and an urban square in the middle. In Figure 5 the preliminary project of the new development area is shown together with the layout of the surrounding buildings. The surface types for each construction area are classified in three main categories, i.e. impervious, pervious and semi-pervious surfaces, respectively 46, 44 and 10% of the total area (as reported in Table 1).

According to the Lombardy regional directive n°7 of 23 November 2017, the municipality of Inveruno is included in the HHI criticality level B, corresponding to an *ante-operam* peak of the permitted runoff (Q_{lim}) of 18.79 L/s and a minimum storage volume (V_{min}) for the entire development area of 564 m^3. As anticipated, the main objective is to study, through the proposed methodology, various NWRM solutions which can maintain the peak runoff under the prescribed threshold of 18.79 L/s and simultaneously generate water storage and dispersion capacity with an overall volume at least equal to 564 m^3.

Model setup

In order to compare the effects of different NWRM configurations on runoff of the new development area, the six different synthetic hyetograph described above under 'Modelling approach' (i.e. uniform, Chicago, Sifalda and triangulars) were compared. All hyetographs were determined by DDF curves with a return period of 50 years (as prescribed by the aforementioned regional directive). The values of the DDF parameters (a and n) obtained from the Regional Authority for Environmental Protection (ARPA 2019) were 62.02 mm/h^{-n} and 0.32, respectively.

The time of concentration for the new development area was calculated applying the Kirpich (1940) formula. In the specific case, the watershed length was approximated to the square root of the total area, while the water velocity was supposed to be 1 m/s, as suggested by Becciu & Paoletti (2010). To this time was added a standard delay of 3 minutes to account for the time needed by the runoff to reach the preferential drainage channels (Becciu & Paoletti 2010).

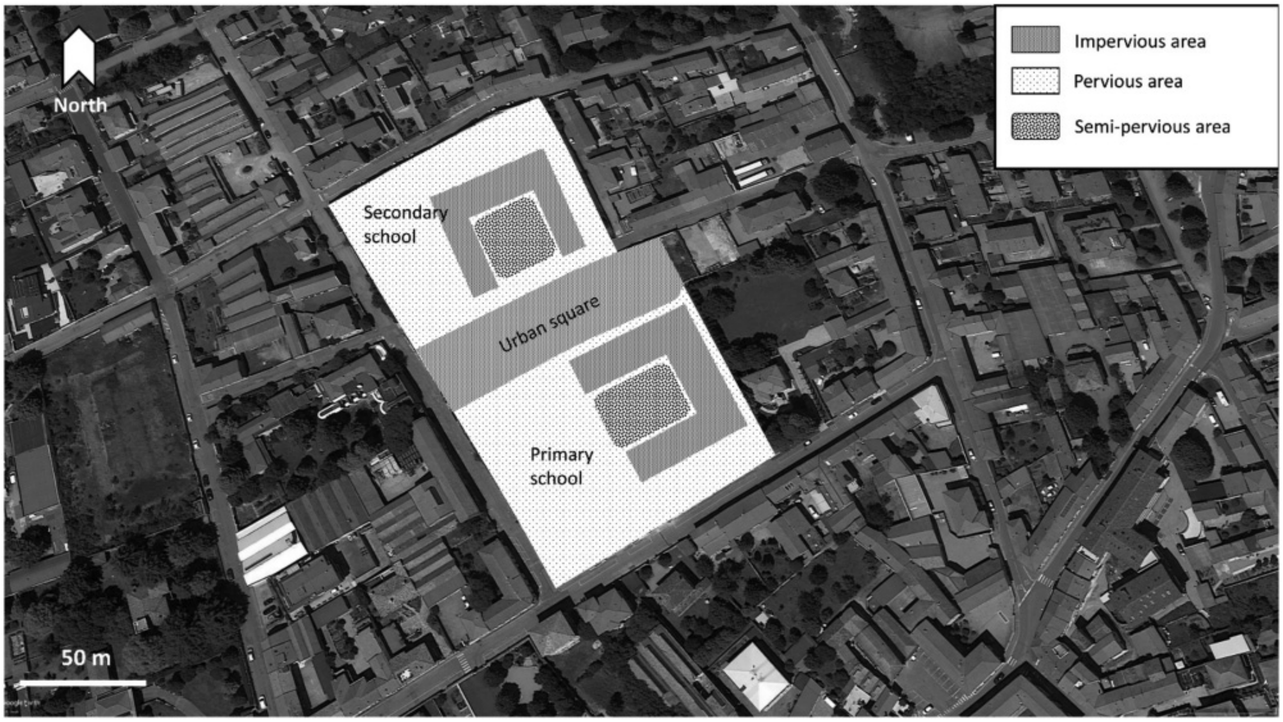

Figure 5 | Study site and preliminary project of surface subdivision.

Table 1 | Subdivision of surface types in each construction area

	Surface types (m^2)			
	Impervious	**Semi-pervious**	**Pervious**	**Total**
Primary school campus	1,392.4	472.5	2,337.9	4,202.8
Secondary school campus	1,272.0	950.5	3,947.7	6,170.2
Urban square	3,847.0	0	0	3,847.0
Total	6,511.4	1,423.0	6,285.6	14,220.0

The time of concentration for the case study was about 5 minutes.

The study area is characterized by three types of surfaces (as explained above under ‘Case study’). The maximum potential retention (S) for pervious and semi-pervious surfaces is obtained through the *S-Storage CN method* (as described above under ‘Natural water retention measures’), considering depth and porosity of the soils (which can be modified through a mix of blended materials to ameliorate infiltration capacity), while I_a is assumed equal to 20% of the S value. The rainwater drained from the impervious surface can be diverted in the three NWRM systems as described above under ‘Natural water retention measures’ (i.e. rain barrels, drainage wells and drainage trenches). In order to represent their functioning through the proposed SCS-lag modelling approach, these systems must be opportunely parametrized. Concerning the rain barrel, I_a depends on the number of rain barrels located in the area and their maximum storage volume, whereas S is neglected. In the case of drainage wells and drainage trenches, S depends on the infiltration capacity of the drains. I_a for a drainage well depends on the storage volume, while for a drainage trench it depends on the length and on depth and porosity of backfilling material. S and I_a for the impervious surface are zero.

The new value of S for the impervious area (if connected to NWRMs) is obtained as a surface-weighted average of the S values of drainage wells, drainage trenches and the remaining impervious surface. The surfaces, in the case of the drainage wells and the drainage trenches, are represented by the area of the interface between the drain and the surrounding soil. Finally, the new I_a value for the impervious area (if connected with NWRMs) is provided by the sum of the I_a values calculated for rain barrels, drainage wells and drainage trenches.

As described above under 'Modelling approach', runoff propagation is simulated through a lag-time approach, considering each surface type as a contributing sub-watershed. In the default setting each sub-watershed is subdivided into ten bands according to the travel time to the outlet and the simulation time-step is hence set to one tenth of t_c. In the Inveruno development area the impervious, pervious and semi-pervious surfaces were subdivided into ten bands of 651.14, 628.56 and 142.30 m^2 each, respectively, while the simulation time step was 0.5 minutes.

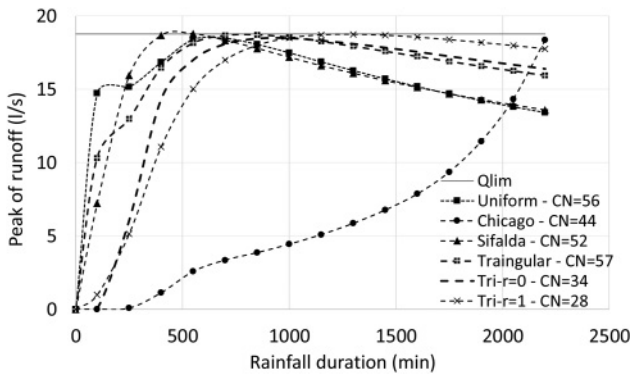

Figure 6 | Peaks of runoff for different storm durations and distributions (i.e. uniform, Chicago, Sifalda, triangular with the peak at the beginning (Tri-r = 0), at the middle (Triangular) and at the end (Tri-r = 1) of storm duration). Limit of the permitted runoff is shown (Q_{lim}). The CN value shown in the figure can be considered as a proxy of NWRM configuration that able to limit peaks of runoff lower than Q_{lim}.

RESULTS AND DISCUSSION

Rainfall duration

Following the proposed methodology, three different approaches were used for determining the critical storm duration, i.e. the time of concentration approach, the iterative and analytical model-based methods (see above under 'Critical storm duration'). Then, the three different d_c, in turn, were combined with the six types of synthetic hyetograph discussed above under 'Total rainfall hyetographs' (i.e. uniform, Chicago, Sifalda and triangular, the latter configured with three different layouts).

In Figure 6, the results of the iterative approach for each design storm are compared, showing that the peak flow increased until reaching a maximum at a given rainfall duration and decreased afterwards for longer durations. The critical storm duration is the one where the maximum of the peak flow occurs and is obviously different for the different hyetographs, ranging from about 9 hours for the Sifalda hyetograph to about 22 hours for the triangular with peak at the end of storm duration. Note that CN value varies among the various hyetographs, as the iterative procedure for determining critical rainfall duration needs to change NWRMs configurations (see above under 'Iterative model based approach'). Results obtained for the Chicago hyetograph are quite different from the others. In this case, no maximum is reached and the peak flow progressively grows with rainfall durations. This result is related to the invariance of rainfall intensity maximum, which does not decrease with increasing rainfall duration, unlike other hyetograph types. In literature, for this specific hyetograph, 1–6 hours are suggested as critical storm duration to avoid heavy overestimations of storage volumes (Gnecco et al. 2018).

Excluding the Chicago hyetograph from the following considerations, the results indicate that all critical storm durations are much longer than the time of concentration of the watershed (5 minutes). This is a crucial factor for correctly designing NWRM devices without underestimating storage volumes. In Table 2, comparison between volumes of the best NWRM configurations designed for limiting peak of runoff under Q_{lim}, both with the critical rainfall durations derived through the iterative procedure and that obtained by the time of concentration approach (i.e. assuming that $d_c = t_c$), are shown. The rational driving the subdivision of NWRMs volume between the three types considered in the analysis is that typologies which promote infiltration are preferred as far as possible, according to potential hierarchy classification already described above under 'Introduction' (i.e. drainage wells, drainage trenches and then rain barrels). The results show that the volumes obtained when the d_c value is determined through the iterative model-based approach are 4–6 times larger than those obtained through the time of concentration.

Examining the CN values reported in Figure 6, it is clear that the Lombardy HHI regulation prescribes extremely low values of Q_{lim} with respect to the standards provided in the past and by other regional regulations (Becciu & Paoletti 2010). In fact, in order to obtain Q_p lower then Q_{lim} for

Table 2 | Comparison between volumes of natural water retention measures (NWRM) configurations with iterative model-based approach and time of concentration approach

	NWRM volumes (m^3) with iterative model-based approach				NWRM volumes (m^3) with time of concentration approach			
Hyetograph	**Rain barrels**	**Drainage wells**	**Drainage trenches**	**Total**	**Rain barrels**	**Drainage wells**	**Drainage trenches**	**Total**
Uniform	–	529	162	691	–	83	59	142
Sifalda	–	883	162	1,045	–	110	59	169
Triangular	–	419	162	581	–	83	59	142
Triangular $r = 1$	588	1,987	189	2,764	–	353	162	515
Triangular $r = 0$	–	1,103	162	1,265	–	211	65	276

each rainfall duration, the mean value of CN of the new development area after the transformation should be equivalent to an agricultural or grazing land belonging to hydrologic group A or B. This is very difficult to achieve at the operational level if not through a combination of large storage volumes and infiltration facilities.

For facilitating the determination of the actual critical storm duration already in *ante-operam* condition and without applying an iterative procedure, the analytical model-based approach (with the two different outflow conditions as reported above under 'Analytical model-based approach') may be applied. In order to assess the actual robustness of this parsimonious approach, the results obtained for the case study under examination are compared with those from the iterative model-based approach. Figure 7 shows the outcome of this comparison, analyzing the differences of d_c calculated with both approaches at varying of DDF parameters a and n (which are the only two parameters referred to d_c calculation in Equations (7) and (9)). Specifically, uniform and triangular synthetic hyetographs were applied, whereas the ranges of a and n were assumed typical of the Lombardy region, i.e. where the case study is located. The results show that the analytical approach with uniform (Equation (7)) and linear outflow (Equation (9)) respectively underestimate and overestimate the actual critical storm duration determined by iterative approach. $d_{c,}$ in the latter case (i.e. dots or stars in Figure 7), is located at approximately the middle of each path described by Equations (7) and (9) (gray band in Figure 7).

Hydrological effects of different NWRM configurations

In order to understand differences derived by the adoption of NWRM typologies in terms of peak runoff reduction, performances of the three implemented NWRM devices have been compared. In Figure 8 the performances of each of these devices for reducing the peak of runoff from the development area were individually compared. In particular, the new development area was stressed by a triangular storm with d_c of 850 min (i.e. the duration where the peak of runoff occur in case of triangular hyetograph, as reported in Figure 6). During the simulation, pervious and semi-pervious surfaces did not change their configurations, while rainfall from the impervious surface was diverted only into rain barrels, or only into drainage wells or only into drainage trenches, whose dimensions are represented by their storage volumes. In the case of the drainage trench the simulation was stopped when the ratio between its overall surface area (i.e. the product of the width of the long base of the trapezoid cross-section and the drainage trench length) was less than 10% of the sum of pervious and semi-pervious surfaces, in order to avoid the need to consider explicitly the precipitation amount directly falling on the drainage trench in the computations. The results clearly show that NWRMs having infiltration capacities provide a gradually increasing reduction of the peak of runoff as their capacity increases, while rainwater harvesting systems (i.e. rain barrels) are not effective in reducing the peak unless they are large enough to store the whole runoff volume until the peak is reached. As far as peak of runoff reduction capacity is concerned, therefore, drainage trenches appear to be the best option, due to their wide dissipation interface with surrounding soil in comparison to drainage wells.

The best NWRM configurations to comply with HHI constrains are summarized in Table 3, for each storm characteristic, whereas in Figure 9 rainfall-runoff processes for each surface and hyetograph type are shown. Standard dimensions of rain barrel, drainage well and drainage

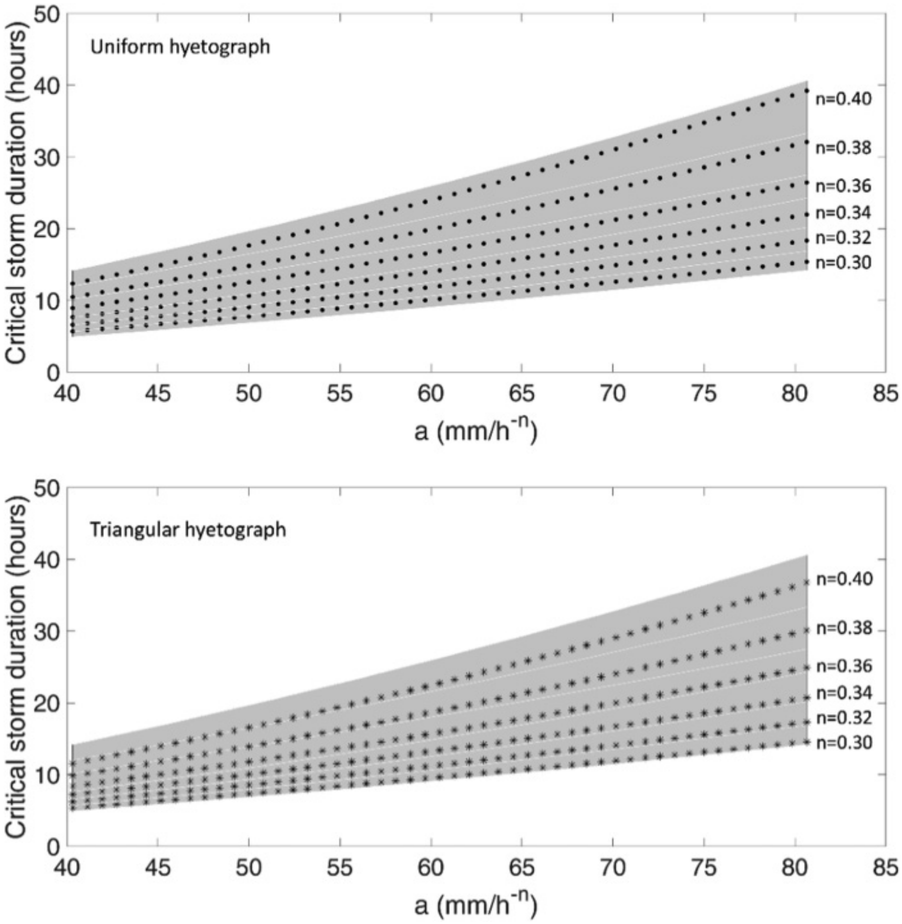

Figure 7 | Sensitivity of critical storm duration (d_c) with respect to DDF parameters *a* and *n* in the case of the iterative model-based and analytical approach applied at uniform and triangular hyetographs. The gray band represent the space of critical storm durations considering constant (bottom of the band) and linear (top of the band) outflow, while dotted lines represent the actual critical durations for different *n* parameters.

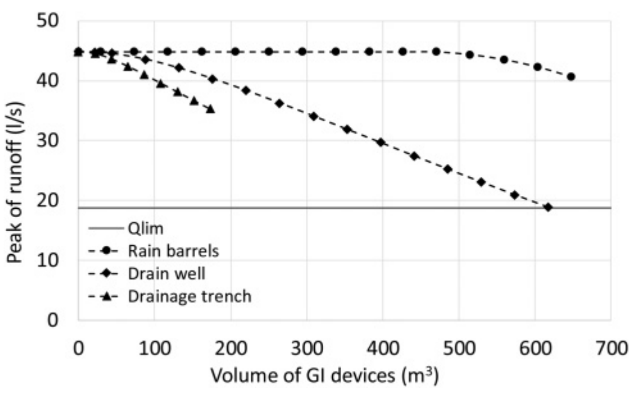

Figure 8 | Evolution of the peak of runoff in output of the development area draining rainfall from impervious surface through only rain barrels, drainage wells or drainage trenches.

trench cross-section are used. In particular, the diameter and height of the rain barrels are 0.5 and 1 m respectively, whereas for the drainage wells the diameter and height are 1.5 and 2.5 m respectively. The drainage trench has a trapezoid cross-section with short base, height and legs slope of 0.5 m, 0.7 m and 30° respectively. As shown in Figure 9, only in the case of Sifalda and triangular ($r = 1$) hyetographs does the rainfall from impervious surfaces have to be wholly drained in order to maintain the peak of runoff less than Q_{lim}. In both cases the number of rain barrels and drainage wells increased considerably, as well as the depth and porosity of soils in semi-pervious and pervious surfaces (Table 3).

In Table 4 details on rainfall, runoff, storage and infiltration volumes are reported. Analyzing the volumes stored by NWRMs, in all hyetograph cases the volumes are larger than the minimum volume prescribed by the regional directive (i.e. 564 m^3). On average an overall NWRM volume of about 900 m^3 is needed to reduce the peak of runoff under

Table 3 | Comparison between different natural water retention measure (NWRM) configurations that aim to comply with regulation limits subdivided for each design storm typology

Hyetograph	Element	Soil depth (m)	Porosity (–)	Diameter (m)	Height (m)	Short base (m)	Base angle (°)	Length (m)	f_1 (mm/h)	n°
Uniform	Semi-pervious surface	0.75	0.25							
	Pervious surface	0.75	0.35							
	Rain barrel			0.5	1					
	Drainage well			1.5	2.5				26.6	120
	Drainage trench				0.7	0.5	30	300	26.6	–
Sifalda	Semi-pervious surface	0.8	0.25							
	Pervious surface	0.82	0.35							
	Rain barrel			0.5	1					
	Drainage well			1.5	2.5				26.6	200
	Drainage trench				0.7	0.5	30	300	26.6	
Triangular	Semi-pervious surface	0.75	0.25							
	Pervious surface	0.75	0.35							
	Rain barrel			0.5	1					
	Drainage well			1.5	2.5				26.6	95
	Drainage trench				0.7	0.5	30	300	26.6	
Triangular (r = 1)	Semi-pervious surface	1.8	0.4							
	Pervious surface	2.1	0.45							
	Rain barrel			0.5	1					2,000
	Drainage well			1.5	2.5				26.6	450
	Drainage trench				0.7	0.5	30	350	26.6	
Triangular (r = 0)	Semi-pervious surface	1.7	0.35							
	Pervious surface	1.7	0.45							
	Rain barrel			0.5	1					
	Drainage well			1.5	2.5				26.6	250
	Drainage trench				0.7	0.5	30	350	26.6	

Soil depth and porosity are characteristics of semi-pervious and pervious surfaces, diameter, height and number (n°) are specific to rain barrels and drainage wells. Short base, base angle, height and length are specific to the drainage trench. The infiltration rate at saturated conditions (f_1) depends on drain characteristics both for drainage wells and drainage trenches.

the prescribed limit (18.79 L/s). Likewise, semi-pervious and pervious surfaces should be able to store about the same volume.

Limitations of the proposed procedure

The proposed approach presents some limitations that, in specific cases, could lead to inappropriate NWRM configurations. Special attention needs to be addressed to the selection of CN value of drains in drainage wells and drainage trenches. In fact, f_1 of Figure 4 refers to AMC II, while AMC III is sometimes preferred in water storage design procedures (Colombo 2012). Moreover, the determination of CN of permeable surfaces (i.e. semi-pervious and pervious surfaces) with the *S-Storage CN method* is based on only the storage capacity of the soils through the porosity characteristics, neglecting their infiltration capacity. Nevertheless, this simplification can be considered as a safety factor which leads to an overestimation of the soil depth. A further simplification is considering the runoff propagation without interactions between surface types. This assumption, which is typical of simplified rainfall-runoff methods, is again in favor of security (Doglioni *et al.* 2009). Finally, the time of hydrograph recession is considered equal to the time of concentration, according to the hypothesis of the lag method. This assumption could influence the correct estimation of the emptying time of NWRMs storage devices, which is a very important feature in case of multiple storm events.

CONCLUSIONS

In recent years, strategies addressed to stormwater control based on Hydraulic-Hydrologic Invariance (HHI) principles are increasingly promoted in urbanized areas of the world. In Italy, many water management agencies and regional

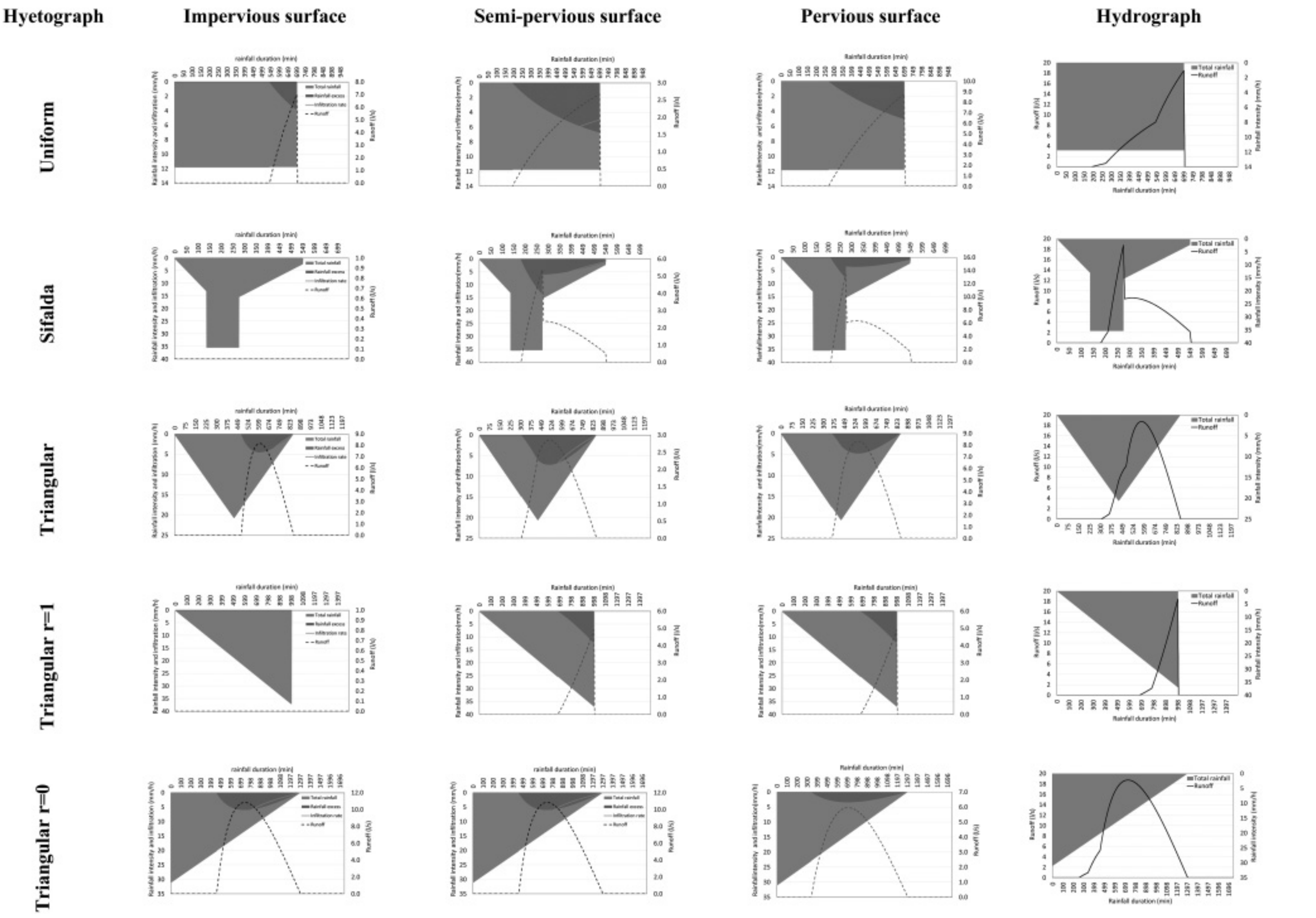

Figure 9 | Effects of different design storms and green infrastructure configurations on rainfall-runoff process.

Table 4 | Water balance of the new development area. Rainfall, runoff, storages and infiltration volumes are compared for each design hyetograph

	Uniform	**Sifalda**	**Triangular**	**Triangular (r = 1)**	**Triangular (r = 0)**
Storm volume (m^3)	1,955	1,945	2,083	4,393	4,779
Runoff (m^3)	217	153	331	129	657
Volume stored and infiltrated through GIs (m^3)	858	891	835	2,012	1,836
Volume stored and infiltrated through semi-pervious and pervious surfaces (m^3)	880	901	916	2,253	2,286

authorities have introduced directives and guidelines aimed at implementing strategies and practices to increase resilience to stormwater urban areas and in particular new development areas. However, the lack of standard and clear methodologies for designing Natural Water Retention Measures (NWRMs) may jeopardize the efforts of these mitigation actions.

In this work, a methodology based on the adoption of a SCS-lag method is proposed to support the design of NWRMs in new development areas. In particular, rain barrels, drainage wells and drainage trenches were modelled and the effects of different design storms on overall runoff were compared. The approach was tested on a new development area of about 1.4 hectares located in the municipality of Inveruno (northern Italy). The results showed that critical storm duration, ranging from 9 to 22 hours, was significantly longer than the time of concentration of the watershed (about 5 minutes). Accordingly, designing NWRM geometries assuming a rainfall duration equal to the time of concentration led to a wide underestimation of volumes (see Table 2). Hence, the first main conclusion of the present work is that a proper design of NWRMs requires that critical rainfall duration is estimated through methods accounting for the overall physical functioning of the system. Two model-based solutions are proposed: an iterative one and an analytical one. The results show that the analytical approach provides estimates of the critical rainfall durations that are close to those obtained with the iterative approach, although a correction coefficient is needed to refine the results. In particular, in the case study presented in this work, Q_{lim} must be multiplied by an empirical coefficient of about 0.75. However, further research should investigate the dependence of this coefficient from the different characteristics of the development area.

Finally, the results indicated that the combination of NWRMs endowed with both harvesting and infiltration capacities provide good mitigations of peak of runoff, but it appears that drainage trenches are more effective with respect to harvesting systems in reducing the peak runoff value. Additional researches for further testing and improving the proposed approach will be conducted in the future, especially in view of modelling more accurately the hydrograph recession for improving the estimation of the emptying time of NWRMs devices.

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