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PROBABILISTIC ESTIMATION OF RUNOFF FROM GREEN ROOFS

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ABSTRACT

In recent decades, green roofs are encouraged as effective tools of sustainable urban drainage system for stormwater management. They contribute to the reduction of runoff peak flows and volume discharges to sewer systems. Green roof reliability in stormwater control is mainly a function of storage capacity, given by the growing medium and the drainage layers. While the thickness of this last layer is usually defined by standards, the growing medium thickness strictly depends on vegetation type and rainfall regime. This paper presents an analytical probabilistic approach to evaluate this thickness as a function of the reliability of green roofs in term of runoff reduction. The possibility of pre-filling from previous events was also considered, by mean of chained rainfall events. The proposed model has the advantage to combine the simplicity of design methods with the accuracy of continuous simulation.

The proposed equations were validated by an application to a case study in Milano, Italy. Monthly analyses were carried out to highlight monthly differences in roof operation due to rainfall distribution and evapotranspiration rate all along the year. Results showed a good agreement with those obtained by the continuous simulation.

Keywords: green roof, probabilistic model, stormwater management, SuDS.

1 INTRODUCTION

With an estimation of 68% of the population living in urban areas by 2050, efforts to apply strategies for improving the sustainable development of territories and communities have strongly intensified. With reference to stormwater control and management, strategies are generally named as sustainable urban drainage systems (SuDS), low-impact developments (LIDs), best management practices (BMPs), nature-based solutions (NBS), blue-green infrastructures and water-sensitive cities (WSCs) [1, 2]. The concepts behind these measures go beyond hydrological risk and water resources management, also considering the goals of improving water and life quality in urban areas. In this framework, rainwater has a central role as a precious resource, since its control and use can provide multiple benefits. Implementing areas of living vegetation on the top of buildings, commonly referred as green roofs, is one of the SuDS strategies, giving benefits as ecological value, increased building thermal efficiency, heat island mitigation, air pollution reduction and source control of stormwaters [3–13].

The origin of green roofs dates back to old civilisations, while modern applications on flat top of concrete reinforced buildings were first developed since the 1960s, initially in Germany [14]. Nowadays, green roofs are diffused in many countries and their construction is often supported by incentive policies [15, 16]. The multi-layers engineered system consists typically, moving bottom-up, in a water-proof membrane, a mechanic protection

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geotextile, a drainage layer with an overflow, a filter fabric and a growing medium layer where the vegetation grows [4]. Hydrological response of green roofs to rainfall includes stormwater retention, detention and peak attenuation, as documented both in laboratory and full-scale experiments. Rainfall is first intercepted by vegetation, soaked up by the substrate, until it reaches saturation, and then percolated to the drainage layer, where excess water overflows as runoff when storage capacity is reached [7]. Runoff can leach organic and inorganic components from the green roof system, although ageing can reduce leaching [9, 17, 18]. The retained water volume returns to the atmosphere as evapotranspiration, that is, a combination of transpiration from vegetation and evaporation from the soil substrate. Extensive researches were conducted on green roofs hydrological behaviour, looking into runoff reduction, evapotranspiration, vegetation choices, irrigation and long-term performances [4, 9, 10, 17, 19–25]. The response on runoff peak flow and volume reduction is considerable when comparing green roofs with impervious roofs at building level but can be neglectable at an urban watershed level for larger storms; however, the multiple benefits of green roofs are relevant and should be considered [4, 22, 26–28]. Several authors studied the green roofs retention capacity, with attention on the storage volume and rainfall depth relation, antecedent dry periods, evapotranspiration, presence of vegetation and slope [3, 22, 25, 29–32]. Results are, however, often limited to a specific site or seasonal rainfall regime [21, 33, 34].

The reliability of green roofs on runoff reduction depends on the storage capacity of the growing medium and drainage layers. The drainage layer thickness is normally defined by standards, while the growing medium layer is usually designed considering, empirically, rainfall regime and vegetation type. Event-based design methods, based on intensity–duration–frequency (IDF) relationships, are easily developed and applied, but they lack on providing long-term performance analysis. On the other side, adopting continuous simulation models provides more reliable results, but it requires more climatic data, that is, long-term rainfall records, and some computational effort. Therefore, a balance between the two approaches is needed, combining accuracy and simplicity. Such a balance can be achieved with the semi-probabilistic analytical approach. This approach is based on the rules of probabilistic analysis and is aimed to derive analytically the probability distribution functions (PDFs) of random variables that are function of other random variables. In the case of hydrological processes involved in stormwater generation, storage and flow, some simplifying hypotheses are usually needed [35, 36]. Various models and applications were presented in literature for flood frequency analysis [35], detention storage [37–44], rainwater harvesting [45, 46, 47, 48], permeable pavements [49, 50], infiltration trenches [51, 52]. The method was also applied to estimate runoff and irrigation requirements of green roofs [7, 8, 40, 52, 53]. In most of these studies, however, only a couple of storm events were considered, neglecting the possibility of effects due to chained previous events. In the study here presented, this issue is addressed, following a methodology previously developed by the authors [7, 8, 41]. The robustness of the proposed approach is increased by considering the possibility of pre-filling from previous events. The method was validated by the application to a case study in Milan, Italy. Monthly analyses were carried out to highlight monthly differences in roof operation due to rainfall distribution and evapotranspiration rate all along the year. Results of the model showed a good agreement with those obtained by the continuous simulation of recorded data.

2 METHODOLOGY

2.1 Hydrological modelling

The design of a green roof consists in selecting plant covers, definition of layer structure, calculation of thickness of each layer and design of the overflow system. The main elements for the stormwater control are the growing medium layer, composed by a blend of mineral and organic materials, where the vegetation in anchored and some water is retained, and the drainage layer, normally made of stones or plastic boards and providing water storage for the vegetation survival during dry periods. Since the design of the drainage layer is generally performed by application of standards, the focus is often on the definition of the thickness of the growing medium layer (z_g). A simple tank model can be developed to simulate the hydrological behaviour of a green roof, in which the inflow is the rainfall depth (h) and the outflows are the evapotranspiration (ET) and the runoff (v). The retention capacity w, composed of the sum of the retention capacity of vegetation, growing medium and drainage layers, can then be estimated by the following set of relationships. All water volumes are expressed, for convenience, as values for unit area.

$$\begin{cases} w_v & 0 < h \le w_{v,max} \\ w_{v,max} + w_g & w_{v,max} < h \le w_{v,max} + w_{g,max} \\ w_{v,max} + w_{g,max} + w_d & w_{v,max} + w_{g,max} < h \le w_{v,max} + w_{g,max} + w_{d,max} \\ w_{v,max} + w_{g,max} + w_{d,max} & h > w_{v,max} + w_{g,max} + w_{d,max} \end{cases} \tag{1}$$

Symbols w_v, w_g and w_d represent, respectively, volumes of water stored in the vegetation, growing medium and drainage layers; $w_{v,max}$, $w_{g,max}$ and $w_{d,max}$ are their maximum values. Rainfall storage in a green roof can vary from zero (completely dry) to w_{max}, when storage capacity is completely used up (eqn 2).

$$w_{max} = w_{v,max} + w_{g,max} + w_{d,max} \tag{2}$$

Rainfall depth intercepted by vegetation is usually below 2 mm and can be neglected. The drainage layer capacity generally ranges between 5 and 10 cm. The water content of the growing medium layer can be estimated as a percentage of its maximum storage capacity $w_{g,max}$, expressed by a reduction coefficient c_g ranging from zero to one ($0 \le c_g \le 1$). The maximum storage capacity $w_{g,max}$ can be estimated as the product between the saturated moisture content Φ_f and the layer thickness z_g (eqn 3).

$$w_g = c_g \bullet w_{g,max} = c_g \bullet \phi_f \bullet z_g \tag{3}$$

The evapotranspiration ET can be estimated from eqn (4), and it is equal to the potential evapotranspiration ET_p when the sum of the rainfall depth (h) and the residual water content in the layer (ΔW) from previous events is higher than ET_p. Δw varies from zero (layer completely dry) to w_{max} (saturated layer).

$$ET = \begin{cases} ET_P & h \ge ET_P \; or \; h < ET_P \; and \; h + \Delta w \ge ET_P \\ h - \Delta w & h < ET_P \; and \; h - \Delta w < ET_P \end{cases} \tag{4}$$

To have cautionary estimates, however, in this study, ET was assumed always equals to ET_p, as happens with two heavy storm events in a row with a small interevent time.

2.2 The probabilistic model

The development of a probabilistic analytical model requires assumptions on the form of the probability distribution functions (PDFs) of rainfall variables, which is of rainfall depth h, rainfall duration Θ and interevent time d and on their interrelationships. Various distribution functions, such as the gamma, the GEV or the double-exponential, should be appropriate for the purpose (see, e.g. [44]). However, both derivation procedure and resulting equations are more complex, and accuracy improvement is not so significant. In this study, the three rainfall random variables were assumed as independent and exponentially distributed, to reduce the mathematical complexity of the analytical derivation procedure. As observed in several studies in literature, the hypothesis of exponential distribution for interevent time is usually not well supported by rainfall records, as well as the assumption of negligible correlation between rainfall depth and duration [7, 8, 36–53]. However, the effects of these hypotheses were tested and resulted acceptable in some cases (see, e.g. [54]). For the statistical analysis of the three rainfall random variables, it is necessary to isolate independent storm events from the series of continuous records by an inter-event time definition (IETD). If the dry time interval between two consecutive storms is smaller than IETD, they are combined in a single event; otherwise, they are considered as independent events. Once all the independent events are identified in the series of records, it is possible to calculate the main sample moments of the variables and then also to estimate the parameters of their exponential PDFs (eqns 5–7).

$$f_h = \xi \bullet e^{-\xi \bullet h} \tag{5}$$

$$f_\theta = \lambda \bullet e^{-\lambda \bullet \theta} \tag{6}$$

$$f_d = \psi \bullet e^{-\psi \bullet (d - IETD)} \tag{7}$$

where $\xi = 1/\mu_h$; $\lambda = 1/\mu_\theta$; $\psi = 1/(\mu_d - IETD)$ and μ_h, μ_θ and μ_d are the mean values of rainfall depth, rainfall duration and interevent time. The water content w_i at the end of each storm event can be calculated by the set of relationships in (8). Runoff occurs when the water content in the green roof reaches the maximum storage capacity. Several possible cases, with different combinations of runoff and water content, are analysed, and the possibility of storage capacity partially used by the previous storm event (pre-filling) is considered.

$$w_i = \begin{cases} w_{i-1} - Et \bullet d_{i-1} + h_i - Et \bullet \theta_i & Case_1 \\ h_i - Et \bullet \theta_i & Case_2 \\ w_{max} & Case_3; Case_4 \\ 0 & Otherwise \end{cases} \tag{8}$$

The subscript $i = 1 \ldots N$ refers to the position of the event in the sequence of chained events, with N = number of chained storm events. Four cases of water balance were considered for the green roof water content:

$$\begin{aligned}
&Case_1: w_{i-1} - Et \bullet d_{i-1} > 0;\ 0 < w_{i-1} - Et \bullet d_{i-1} + h_i - Et \bullet \theta_i < w_{max}\\
&Case_2: w_{i-1} - Et \bullet d_{i-1} \le 0;\ 0 < h_i - Et \bullet \theta_i < w_{max}\\
&Case_3: w_{i-1} - Et \bullet d_{i-1} \le 0;\ h_i - Et \bullet \theta_i \ge w_{max}\\
&Case_4: w_{i-1} - Et \bullet d_{i-1} > 0;\ w_{i-1} - Et \bullet d_{i-1} + h_i - Et \bullet \theta_i \ge w_{max}
\end{aligned}$$

Conditions in the four cases are as follows: Case$_1$, event with pre-filling from the previous event, but no runoff; Case$_2$, event with no pre-filling and no runoff; Case$_3$, no pre-filling, but with runoff; Case$_4$, with both pre-filling and runoff. Both the initial water content w$_0$ and interevent time d_0 are set equal to zero. The runoff v_i after the end of each event can be estimated according to the set of relationships (9).

$$v_i = \begin{cases} w_{i-1} - Et \bullet d_{i-1} + h_i - Et \bullet \theta_i - w_{max} & Case_5\\ h_i - Et \bullet \theta_i - w_{max} & Case_6; Case_7\\ w_{max} - Et \bullet d_{i-1} + h_i - Et \bullet \theta_i - w_{max} & Case_8\\ 0 & Otherwise \end{cases} \tag{9}$$

As previously discussed for eqn (8), the subscript $i = 1 \ldots N$ refers to the position of the event in the sequence of chained events, with N = number of chained storm events. Other four cases of water balance were considered for runoff:

$$\begin{aligned}
&Case_5: w_{i-1} \le w_{max};\ w_{i-1} > Et \bullet d_{i-1};\ w_{i-1} - Et \bullet d_{i-1} + h_i - Et \bullet \theta_i > w_{max}\\
&Case_6: w_{i-1} \le w_{max};\ w_{i-1} \le Et \bullet d_{i-1};\ h_i - Et \bullet \theta_i > w_{max}\\
&Case_7: w_{i-1} > w_{max};\ w_{max} \le Et \bullet d_{i-1};\ h_i - Et \bullet \theta_i > w_{max}\\
&Case_8: w_{i-1} > w_{max};\ w_{max} > Et \bullet d_{i-1};\ w_{max} - Et \bullet d_{i-1} + h_i - Et \bullet \theta_i > w_{max}
\end{aligned}$$

Case$_5$ represents the case where the previous event doesn't produce runoff, there is pre-filling and runoff is not generated at the end of the given event; Case$_6$ represents the case where the previous event doesn't produce runoff, there is no pre-filling, and runoff is generated by the given event; Case$_7$ represents the case the previous event produces runoff, there is no pre-filling, and runoff is generated by the given event; Case$_8$ represents the case the previous event produces runoff, there is pre-filling, and runoff is generated by the given event. Both initial water content w$_0$ and interevent time d_0 are set equal to zero.

The exceedance probability distribution of runoff can be derived from the above equation, applying the rules of probabilistic analysis. It must be observed that when the time to completely empty the storage when it is full is lower than the inter-event time definition, there is no possibility of pre-filling from the previous event. So, when IETD is greater than the ratio w_{max}/Et, a single event should be considered at a time, with the maximum storage capacity w_{max} always available at the beginning of each storm event (Case A: $N = 1$). Otherwise, a number N of chained events should be considered (Case B: $N > 1$). Previous research assessed that, when the outflow rates are low, as it is for green roofs, at least three chain rainfall events should be considered ($N = 3$) [44].

$$Case\ A: w_{max} / Et \le IETD$$

$$P_v = P\left(v > \bar{v}\right) = \int_{h=w_{max}+\bar{v}+Et\bullet\theta}^{\infty} f_h \bullet dh \int_{\theta=0}^{\infty} f_\theta \bullet d\theta = \gamma \bullet e^{-\xi\bullet\left(w_{max}+\bar{v}\right)} \tag{10}$$

$$\text{where } \gamma = \frac{\lambda}{\lambda + Et \bullet \xi}$$

$$P_v = P\left(v > \overline{v}\right) = \int_{\theta=0}^{\infty} f_\theta \bullet d\theta \int_{d=IETD}^{\infty} f_d \bullet dd \int_{h=w_{max}+\overline{v}+Et\bullet\theta}^{\infty} f_h \bullet dh$$

$$+\sum_{i=2}^{N}\left[\int_{\theta=0}^{\infty} f_\theta \bullet d\theta \int_{d=IETD}^{\frac{w_{max}+\overline{v}}{Et}} f_d \bullet dd \int_{h=\frac{w_{max}+\overline{v}+(i-1)\bullet Et\bullet d}{i}+Et\bullet\theta}^{\frac{w_{max}+\overline{v}+(i-2)\bullet Et\bullet d}{i-1}+Et\bullet\theta} f_h \bullet dh\right] =$$

$$= \gamma \bullet \left\{ e^{-\xi\bullet\left(w_{max}+\overline{v}\right)} + \psi \bullet \sum_{i=2}^{N}\left[-\left(i-1\right)\bullet \beta_i \bullet e^{-\xi\bullet Et\bullet IETD\bullet\left(\frac{i-2}{i-1}\right)-\frac{\xi}{i-1}\bullet\left(\overline{v}+w_{max}\right)} - i \bullet \beta_i^* \bullet \right.\right.$$

$$\left.\left. e^{-\frac{\xi}{i}\bullet\left[Et\bullet IETD\bullet(i-1)+\left(\overline{v}+w_{max}\right)\right]} - \xi \bullet Et \bullet \beta_i \bullet \beta_i^* \bullet e^{\psi\bullet IETD-\left(\overline{v}+w_{max}\right)\bullet\left(\frac{\psi}{Et}+\xi\right)} \right]\right\} \tag{11}$$

$$\text{where } \beta_i = \frac{1}{\xi \bullet Et \bullet \left(i-2\right) + \psi \bullet \left(i-1\right)};\ \beta_i^* = -\frac{1}{i \bullet \psi + \left(i-1\right) \bullet \xi \bullet Et}.$$

3 CASE STUDY

The proposed methodology for the probabilistic estimation of runoff from green roofs was applied to a case study in Milan, Italy (45°27′40.68N; 9°09′34.20E). Climate pattern in Milan is of alpine/continental type, with the wet season occurring in fall and the dry one at the end of spring. Average interevent time is higher on summer and lowest in fall or spring. The highest number of storms are recorded, on average, in May or in November. Average evapotranspiration is between 0.07 mm/hour (March and May) and 0.09 mm/hour (December). An interevent time of IETD = 6 hours and an initial abstraction of IA = 2 mm were assumed in calculation. Statistics of *h*, *θ*, *d* (μ = mean, σ = standard deviation, V = coefficient of variation) and cross-correlation coefficients parameters were obtained from rainfall data recorded at the Milano-Monviso rain gauge in the period 1971–2020. Results at annual scale are presented in Table 1 and Table 2. In Table 3, the monthly statistics, together with the average evapotranspiration rate, are also presented.

Table 1: Annual main statistics of *h*, *θ*, *d*.

	h [mm]	*θ* [hour]	d [hour]
μ [mm]	18.49	14.37	172.81
θ [mm]	21.33	14.81	223.89
V [–]	1.15	1.03	1.30

Table 2: Annual cross-correlation coefficients among rainfall variables.

$\rho_{h,d}$ [–]	$\rho_{\theta,d}$ [–]	$\rho_{\theta,h}$ [–]
0.11	0.11	0.62

Table 3: Monthly hydrologic parameters and evapotranspiration.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
μ_h [mm]	18	18	18	17	16	17	13	17	18	21	22	21
μ_θ [hour]	11	17	17	13	12	10	5	4	5	9	13	16
μ_d [hour]	169	192	175	198	131	119	147	206	184	246	172	133
Et [mm/hour]	0.08	0.08	0.07	0.07	0.08	0.07	0.07	0.07	0.07	0.08	0.09	0.09

4 RESULTS

Continuous simulation of water content and runoff was performed for the case study, using the series of rainfall data recorded in Milano-Monviso, for green roofs with variable growing medium thickness. A range of thickness from 0 to 200 mm was considered. Sample cumulated frequencies of runoff were calculated at both annual and monthly scale. Results were compared with the exceedance probability to have runoff, that is, $P(v > 0)$, calculated by eqns 10 and 11 (Figs. 1–5). A variable number N of chained storm events was considered, according to the best fit to the frequency distribution.

In all cases, as expected, the probability to have runoff decreases as the growing medium thickness increases. On annual basis (Fig. 1), increasing z_g reduces the probability of runoff from 0.45 for $z_g = 100$ mm to 0.35 for $z_g = 200$ mm. In monthly scale, results are obviously affected by seasonality (Figs. 2–5), with wetter months showing higher probability of runoff. For the months with the highest rainfall depths (October and November), the probability of runoff for $z_g = 100$ mm is equal to 0.48 in October and 0.50 in November; for $z_g = 200$ mm equals 0.38 in October and 0.48 in November. In July, the month with the lowest average rain depth, the runoff probability is equal to 0.38 for $z_g = 100$ mm and to 0.30 for $z_g = 200$ mm. In

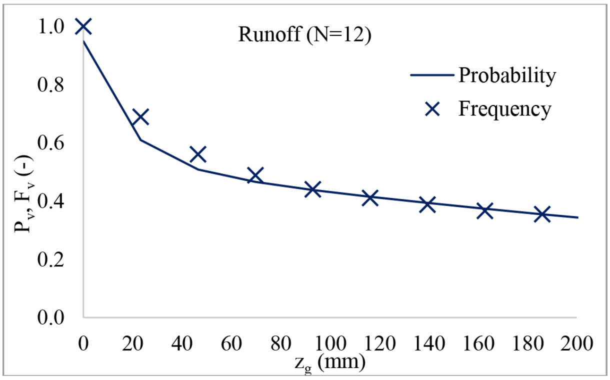

Figure 1: Exceedance probability and sample frequency of runoff at annual scale.

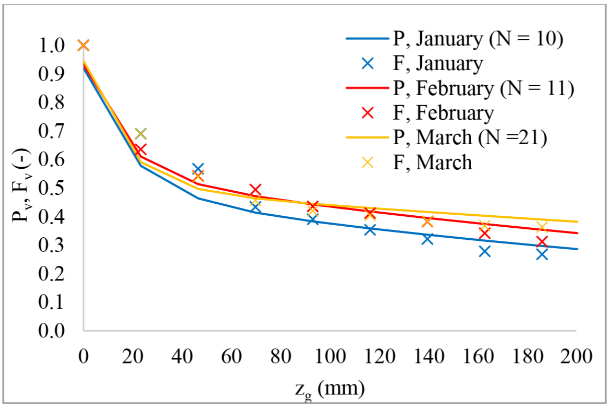

Figure 2: Exceedance probability and sample frequency of runoff, January–March.

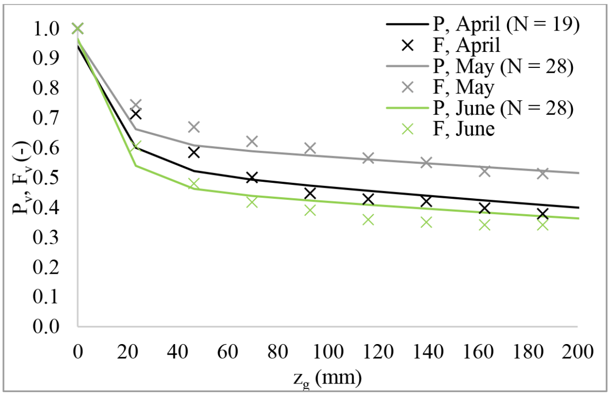

Figure 3: Exceedance probability and sample frequency of runoff, April–June.

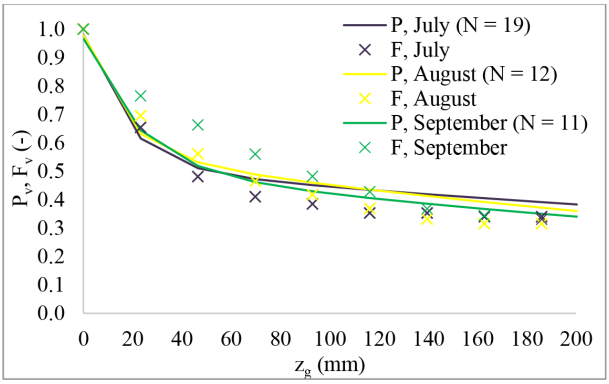

Figure 4: Exceedance probability and sample frequency of runoff, July–September.

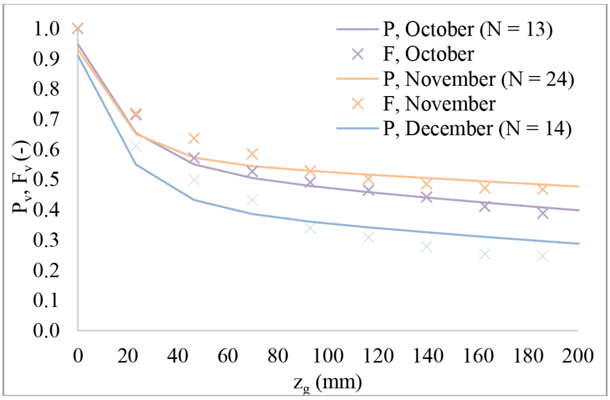

Figure 5: Exceedance probability and sample frequency of runoff, October–December.

May, the month with a combination of an average rainfall depth of 16 mm, lower than the wet season, but with also a lower *Et* rate (0.07 mm/hour, while in November it is of 0.09 mm/hour), the probability of runoff is equal to 0.55 with z_g = 100 mm and equal to 0.50 for z_g = 200 mm.

These results highlight the importance of making the analysis of runoff from green roof at a monthly scale, to identify the critical combination of rainfall depth and evapotranspiration rate on which green roof design should be performed. For example, the growing medium thickness needed to have a 50% probability of runoff is z_g = 70 mm from analysis at annual scale, while it is z_g = 200 mm for the most critical month (May) identified by the analysis at monthly scale. The number *N* of concatenated rainfall events is also quite variable for different months: it is maximum in May, the most critical month in term of runoff probability, and it is minimum in January.

5 CONCLUSION

The proposed probabilistic approach, based on the estimation of the exceedance probability of runoff, is useful for the optimal design of green roofs. The main advantage is to allow, for different climatic scenarios, the same accuracy of continuous simulations, but without the need of having long series of rainfall records. Moreover, the proposed equations also consider the chained effects due to successive storm events with reference to the possibility of pre-filling of the storage capacity. This is particularly important with systems that are characterised by slow hydrological dynamics, as green roofs are. Application of the proposed equations to a case study in Milan (Italy) gave satisfactory results, in accordance with those achieved by continuous simulation. Monthly analyses showed differences of runoff from green roofs due to rainfall distribution and evapotranspiration rate along the year. They allow to identify the critical combination of rainfall depth and evapotranspiration rate on which green roof design should be performed. The number of chained storm events is quite variable, greater in wetter months with short dry time between consecutive rainfalls. The definition of a procedure for their definition will be object of future developments of the method.

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