 doi:10.20944/preprints202008.0172.v2

Article

Vegetation survival in green roofs without irrigation

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Abstract: The implementation of green roofs as sustainable urban drainage systems provides benefits for stormwater control and the environment and is more and more encouraged. A model for the estimation of the probability of vegetation survival without irrigation is proposed. The model, developed through a probabilistic analytical derivation procedure, can also consider the effects of chained rainfall events, without the need of continuous simulation of hydrological processes. The model equations can be useful in the design of green roofs, allowing to determine the growing medium thickness in terms of an assumed risk of vegetation withering in dry periods. The proposed model is also able to identify the optimal thickness of the growing medium, over which the survival performances can be increased only with irrigation. Model performances were tested by the application to two case studies in Italy. Comparison between the probabilities and the cumulative frequencies from a continuous simulation of water content in the growing medium shows a good agreement and provide a first confirm of reliability.

Keywords: Sustainable Urban Drainage Systems; green roofs; analytical probabilistic approach; pre-filling; vegetation survival

1. Introduction

The use of Sustainable Urban Drainage Systems (SUDS) delivers several benefits: the relief of loads in the sewer networks, the increase of efficiency of wastewater treatments plants, the reduction of polluted waters discharged into the environment and the growth of biodiversity in urban areas.

In highly urbanized cities, characterized by a large amount of impervious areas that strongly reduce soil infiltration, with consequent rise of the flooding risk, green roofs can be an effective countermeasure, since they are largely widespread and do not require additional space respect to the building footprint [1]. Their implementation also entails significant environmental and economic benefits, besides stormwater management and the improvement of quality of receiving water bodies, such as energy savings, the reduction of heat island effects, the support, and the enhancement of biodiversity. Focusing on stormwater management, green roofs allow: the reduction, through evapotranspiration, of runoff volumes; the time delay of runoff, that starts after soil saturation; the reduction of runoff peak rates, thanks to the temporary storage of infiltrated water in the substrate and in the drainage layer; the improvement of stormwater quality through percolation into the soil. The first green roofs were installed in Germany in the 1970s [2] and since then they spread in many Countries, in some cases also due to national or regional programs to encourage or even impose their realization. Green roofs have been deeply studied to analyze their performance under different climate and design conditions [3-7], often with reference to a specific place [8-10] on small spatial and time scale [11, 12] while on a large scale there are few studies that demonstrate their hydrological benefits [13]. The focus of most of these studies is mainly on the retention capacity of green roofs in relation to rainfall depth, antecedent dry period [14, 15] and evapotranspiration [16].

The aim of this paper is to develop a probabilistic model for the analysis of green roof water content evolution due to a series of rainfall events. Particularly, the green roof performance in term of vegetation survival without irrigation has been investigated, to achieve an operational procedure that may be useful for designers. The analytical semi-probabilistic approach, used in this study, was first proposed in the present form by [17] and applied by others also to SUDS and Rain Water Harvesting Systems [18, 19], infiltration trenches [20], permeable pavements [21], bioretention systems [22], green roofs [23, 24, 25, 26], stormwater

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detention facilities [27-32]. Generally, these studies consider a couple of rainfall events at a time, neglecting, or only partially considering the possibility of pre-filling from previous events.

Becciu and Raimondi observed that for low outflow rates, pre-filling is generally due to more than one previous rainfall and to fill this lack, neglected in previous studies in literature, they developed a procedure to consider a chain of three events [27]. For green roofs, where the outflow rate is characterized by evapotranspiration from soil and vegetation, this issue becomes particularly relevant. In this paper, a chain of N consecutive rainfall events has been considered in the modeling. This aspect represents a significant improvement of the analytical probabilistic approach, since allows to consider the possibility of having a reduction of water storage capacity, due to chain effect of successive rainfall events, especially with low outflow rates.

Considering this chain effect, probabilistic estimation of both runoff from the green roof and vegetation survival without irrigation during dry period is more accurate. The first issue, about runoff estimation, was discussed by the Authors in another paper [26]. Results presented in this paper are focused on the second issue and can be considered complementary. The proposed approach, based on the estimation of vegetation survival probability in dry periods without irrigation, allows to define the proper thickness of growing medium as a function of potential evapotranspiration and of parameters of the rainfall stochastic process. This depth can be used together with the minimum depth for runoff reduction in design procedures. Resulting equations have been validated by their application to two case studies of experimental green roofs located at Politecnico di Milano and University of Calabria, Italy.

1.1. Green roof hydrology

Green roofs are engineered multi-layered structures, with a vegetated upper surface, working in very shallow systems without connection to the natural ground. Typical layers in green roofs are: vegetation; growing medium, a blend of mineral material enriched with organic material where water is retained and in which vegetation is anchored; filter fabric; drainage layer, generally constituted of plastic profiled trays, in which water is stored, for plants sustainment during dry periods and for runoff and outflow peak attenuation; root resistant membrane. Water content in a green roof varies according to rainfall, evapotranspiration, runoff, and outflow. Figure 1 shows the conceptual reference scheme considered here for the green roof modelling.

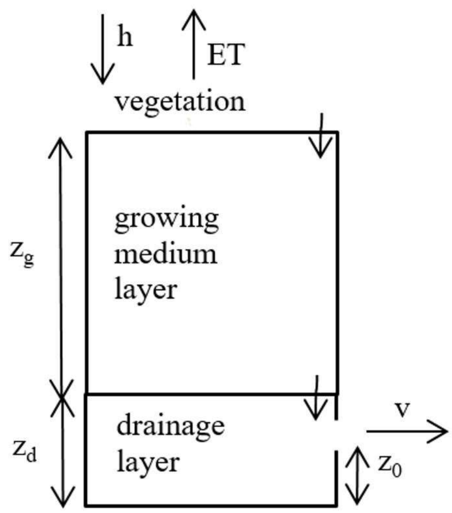

Figure 1. Conceptual scheme considered for the modelling of green roofs.

h: rainfall depth
ET: evapotranspiration volume
v: runoff volume

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z_g: growing medium thickness
z_d: drainage layer thickness
z_0: overflow height

Rainfall is first intercepted by vegetation and then infiltrated into the growing medium, where it is retained, used by roots, and released back into the atmosphere through evapotranspiration. The excess is stored in the underlying drainage layer, equipped with an overflow. Interception by vegetation generally is of few millimetres and is neglected in this study. Volumes in Figure 1 must be intended as specific for unit area.

Green roofs design includes the definition of the thickness of each layer and the choice of vegetation, according to rooting depth, drought resistance, time to reseed, aesthetics, ability to withstand temporary soil waterlogging and need for maintenance. Drainage layer is usually made with pre-cast standard elements, to achieve a storage capacity generally variable between 5 and 10 [cm]. The focus in this paper is on growing medium and on its retention capacity, with the aim of defining a proper thickness in terms of probability of vegetation survival without irrigation.

2. Material and Methods

To evaluate the probability of vegetation survival without irrigation, the water content at the end of dry period between consecutive events, representing the condition of minimum water content into growing medium, has been estimated. Extended rainless periods, especially occurring during the hot season, can result in the soil moisture falling to its 'wilting point', with the subsequent withering of vegetation. After this, transpiration is nullified, but the progressive soil desiccation, due to evaporation, on the other side, is initially positive in terms of increased capacity to buffer runoff.

Evapotranspiration, that is the amount of water released to the atmosphere from plants transpiration and soil evaporation, can be estimated by the following equation:

$$ET = \begin{cases} ET_P & h \geq ET_P \text{ or } h < ET_P \text{ and } h + h_{ge} \geq ET_P \\ h + h_{ge} & h < ET_P \text{ and } h + h_{ge} < ET_P \end{cases} \quad (1)$$

where ET_p is the potential evapotranspiration, that is the maximum value of ET, reached when the vegetation water demand is completely fulfilled. Water content into the growing medium at the beginning of a rainfall event h_{ge} can be expressed as a volume per unit surface area, that is as a "water" depth. It varies between zero (completely dry) and a maximum value (at saturation), that can be expressed by the product $\phi_f \cdot z_g$ of growing medium moisture content per unit of depth at saturation ϕ_f and the growing medium thickness z_g.

If a constant evapotranspiration rate Et is assumed during the rainfall, the water content at the end of a rainfall event of rainfall depth h and duration θ can be estimated as:

$$h_{gu} = \begin{cases} h_{ge} + h - Et \cdot \theta & 0 \leq h_{ge} + h - Et \cdot \theta < \phi_f \cdot z_g \\ \phi_f \cdot z_g & h_{ge} + h - Et \cdot \theta \geq \phi_f \cdot z_g \\ 0 & otherwise \end{cases} \quad (2)$$

Analogously, if the same constant evapotranspiration rate Et is assumed also after the rainfall, the water content at the end of the dry period of duration d, that is at the beginning of the successive rainfall event, can be estimated as :

$$h_{ge} = \begin{cases} h_{gu} - Et \cdot d & h_{gu} - Et \cdot d > 0 \\ 0 & otherwise \end{cases} \quad (3)$$

Equation (2) and (3) could be used for a simplified continuous simulation of a green roof, starting from an initial condition of water content, when a series of rainfall depth records is available.

2.1. Probabilistic model

The aim of the proposed probabilistic model is to give an estimate of the growing medium thickness to be considered in the green roofs design. This estimation is based on the assumed probability of having a minimum water content to allow vegetation survival during dry periods without irrigation. The random variables considered in the stochastic process of rainfall events, that is rainfall depth h, rainfall duration θ and

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interevent time d have been assumed to be independent and exponentially distributed. The model neglects the random nature of runoff coefficient [33]. To define the independent rainfall events in the stochastic process, a minimum interevent time *IETD* has been defined for their extraction from the series of rainfall records [34]. If the dry period between two consecutive rainfall events (interevent time) is smaller than *IETD*, they are joined into a single event. There are different methods to select *IETD*: estimating the autocorrelation coefficient of observations sample, choosing the values for which the coefficient of variation tends to one, evaluating the relationship between *IETD* and the average number of rainfall events.

In the developed model of probabilistic derivation, it was assumed that the rainfall variables have an exponential distribution. This hypothesis is usually considered in literature as a good compromise between compliance to rainfall records and the need of an easier mathematical tractability [35-37]. Some authors suggested other probability distribution functions (PDFs), such as the Weibull [38] or the double-exponential [27]. Although a better fitting of the observed frequencies of rainfall records can be achieved with these alternative PDFs, the improvement in terms of model accuracy seems negligible compared with the significant increase of the mathematical difficulty in the model development.

Exponential PDFs of rainfall depth, rainfall duration and interevent time are expressed as:

$$f_h = \xi \cdot e^{-\xi \cdot h} \tag{4}$$

$$f_\theta = \lambda \cdot e^{-\lambda \cdot \theta} \tag{5}$$

$$f_d = \psi \cdot e^{-\psi \cdot (d - IET\ \ )} \tag{6}$$

where: $\xi = 1/\mu_h$; $\lambda = 1/\mu_\theta$; $\psi = 1/(\mu_d - IETD)$ and μ_h, μ_θ and μ_d are respectively the mean values of rainfall depth, rainfall duration and interevent time. Water content can be different from zero at the end of a dry period, due to a pre-filling from previous events, when results $(z_g \cdot \phi_f - w)/Et > IETD$. To translate this condition in probabilistic terms, two different cases have been analyzed: a single rainfall and a series of chained rainfall events .When a single rainfall event is considered, the probability P to have, at the end of the dry period between two consecutive rainfalls, a minimum water content into the growing medium to ensure vegetation survival results to be:

$$P = \int_{h=w+E\ \cdot(d+\theta)}^{\infty} f_h \cdot dh \int_{d=IET}^{\frac{\emptyset_f \cdot z_g - w}{Et}} f_d \cdot dd \int_{\theta=0}^{\infty} f_\theta \cdot d\theta =$$

$$= \gamma \cdot \beta \cdot \left[e^{-\xi \cdot (Et \cdot IETD + \ \ )} - e^{\psi \cdot \left(IETD\ \ \frac{w}{Et} \right) - \phi_f \cdot z_g \cdot \left(\xi + \frac{\psi}{Et} \right)} \right] \tag{7}$$

When a series of N chained rainfall events is considered, the probability P results to be:

$$P = \int_{\theta=0}^{\infty} f_\theta \cdot d\theta \cdot \left\{ \int_{d=IETD}^{\frac{\emptyset_f \cdot z_g - w}{Et}} f_d \cdot dd \cdot \left[\int_{h=\emptyset_f \cdot z_g + Et \cdot \theta}^{\infty} f_h \cdot dh \cdot + \int_{h=\frac{w}{N-1} + Et \cdot (\theta + d)}^{\frac{\emptyset_f \cdot z_g + Et \cdot d \cdot (N-2)}{N-1} + Et \cdot \theta} f_h \cdot dh \right] \right.$$

$$\left. + \int_{\frac{\phi_f \cdot z_g + Et \cdot d \cdot (N-1)}{N} + Et \cdot \theta}^{\frac{\phi_f \cdot z_g + Et \cdot d \cdot (N-2)}{N-1} + Et \cdot \theta} f_h \cdot dh \int_{d=IET}^{d = \frac{\emptyset_f \cdot z_g \cdot (N-1) - N \cdot w}{Et \cdot (N-1)}} f_d \cdot dd \right\} =$$

$$= \gamma \cdot \left\{ e^{-\xi \cdot \emptyset_f \cdot z_g} \cdot \left[1 - e^{\psi \cdot \left(IETD + \frac{w}{Et} - \frac{\phi_f \cdot z_g}{Et} \right)} \right] + \frac{2 \cdot (1-\beta) \cdot \beta_N}{N-1} \cdot e^{-\left(\frac{\psi}{Et} + \xi \right) \cdot (\phi_f \cdot z_g - w) + \psi \cdot IETD - \frac{\xi \cdot w}{N-1}} - \beta_N \left[2 \cdot \right. \right.$$

$$e^{-\frac{\xi}{N-1} \cdot [\phi_f \cdot z_g + Et \cdot IETD \cdot (N-2)]} + e^{\frac{\xi \cdot w \cdot N \cdot (N-2)}{(N-1)^2} - \phi_f \cdot z_g \cdot \left(\frac{\psi}{Et} + \xi \right) + \psi \cdot IETD\ \ \frac{\psi \cdot N \cdot w}{Et \cdot (N-1)}} \Bigg] + \beta \cdot e^{-\frac{\xi \cdot w}{N-1} - \xi \cdot Et \cdot IETD} + \beta_N^* \cdot$$

$$\left. \left[e^{-\phi_f \cdot z_g \cdot \left(\frac{\psi}{Et} + \xi \right) + \psi \cdot IETD\ \ \frac{\psi \cdot N \cdot w}{Et \cdot (N-1)}} - e^{-\frac{\xi}{N} \cdot [\phi_f \cdot z_g + Et \cdot IETD \cdot (N-1)]} \right] \right\} \tag{8}$$

The quantities γ, β, β_N and β_N^* are equal to:

$$\gamma = \frac{\lambda}{\lambda + \xi \cdot Et}; \ \beta = \frac{\psi}{\psi + \xi \cdot Et}; \ \beta_N = \frac{(N-1) \cdot \psi}{(N-1) \cdot \psi + \xi \cdot Et \cdot (N-2)}; \ \beta_N^* = \frac{\psi \cdot N}{\xi \cdot Et - N \cdot (\xi \cdot Et + \psi)}$$

Equation (8) can be used to estimate the growing medium thickness z_g required in the green roofs design. Inputs to the model are: the mean values of rainfall variables, the *IETD*, the growing medium moisture content per unit depth at saturation ϕ_f, the evapotranspiration rate Et, the minimum water content for vegetation survival w, the number of chained events N. The evapotranspiration rate Et was assumed constant and equal to its potential value Et_p. Results are shown in term of the probability P to have a minimum water content in a green roof without irrigation for vegetation survival.

2.2. Case studies

To validate the proposed procedure, equations (7) and (8) have been applied to two experimental green roofs. One located on a building in Milano, at Politecnico di Milano [39] (called in the following GREEN ROOF 1); the other on a building in Cosenza, at University of Calabria [40] (called in the following GREEN ROOF 2). They are both extensive green roofs, vegetated with three native Mediterranean species and sedum. The thickness of growing medium is 170 [mm] in GREEN ROOFS 1 and 80 [mm] in GREEN ROOF 2.

They are representative respectively of continental-temperate and Mediterranean climate conditions: average annual precipitation in Milano is about 1013 [mm/year], with a mean annual temperature of 13.1 [°C]; average annual precipitation at University of Calabria is about 881 [mm/year], with a mean annual temperature of 15 [°C] [41]. The main difference lies in the distribution of precipitation over the year: in Milano there are not, on average, completely dry months; in Cosenza summer is much less rainy than winter, with dry periods that can last for more than one month. For the green roof simulation two rainfall series were used: for GREEN ROOF 1, the series recorded at Milano-Monviso raingauge station in the period 1971-2005; for GREEN ROOF 2 the series recorded at the raingauge station of the experimental site of University of Calabria in the period October 2015-September 2016 [40] . The length of the second series of rainfalls is quite limited, so results of application of the first case study are more reliable. The period considered for the analysis of GREEN ROOF 2 represents a wet year with an annual precipitation of 1256.3 [mm/year], respect to the average annual precipitation for the site equal to 881 [mm/year]. For both case studies, to identify independent events a minimum interevent time IETD=6 [hours] has been assumed. This is considered a good choice for green roofs, as supported by other studies [2, 5, 7, 15, 40]. Tables 1-2-3 report the average values, the coefficients of variation and the correlation indexes of rainfall variables estimated from the two series of records.

Table 1. Average values of rainfall variables.

μ	GREEN ROOF 1	GREEN ROOF 2
h [mm]	17.97	20.26
θ [hour]	11.67	11.59
d [hour]	150.70	127.72

Table 2. Coefficient of variation of rainfall variables.

V	GREEN ROOF 1	GREEN ROOF 2
h [-]	1.16	1.17
θ [-]	1.04	1.04
d [-]	1.42	1.31

Table **3.** Correlation indexes among rainfall variables.

	GREEN ROOF 1	GREEN ROOF 2
$\varrho_{h,d}$ [-]	0.10	-0.02
$\varrho_{\theta,h}$ [-]	0.69	0.88
$\varrho_{d,\theta}$ [-]	0.10	-0.10

With reference to the evapotranspiration rate, experimental results in literature show values ranging from 1 to 6 [mm/day] [42, 43] according to different climate scenarios and green roof characteristics. For the two case

 doi:10.20944/preprints202008.0172.v2

studies analyzed in this paper, constant evapotranspiration rates have been assumed. For annual analysis values of 0.075 [mm/hour] for GREEN ROOF 1 and 0.122 [mm/hour] for GREEN ROOF 2 were assumed, according to measurements reported in [39], [44] and [40]. For summer, the assumed values were Et=0.115 [mm/hour] for GREEN ROOF 1 [39], [44] and Et=0.700 [mm/hour] for GREEN ROOF 2 [40].

The growing medium moisture content at saturation per unit depth has been set equal to ϕ_f =0.40 [-] for GREEN ROOF 1 and ϕ_f =0.58 [-] for GREEN ROOF 2; these values were taken from past studies of the two green roofs [39, 40, 44, 45]. Eleven values of the growing medium thickness z_g ranging from 50 [mm] to 200 [mm] have been considered. The minimum water content w has been set to zero, to test the pre-filling conditions.

2.3. Assumptions

The hypothesis of exponential distribution of rainfall variables was tested. Results in Table 2 show a good fitting for rainfall duration, less for rainfall depth and interevent time. However, previous studies [26] revealed that this simplifying assumption does not strongly influence the accuracy of the proposed approach.

The hypothesis of independence of rainfall variables was also tested. Results in Table 3 show that it substantially holds in all cases except for rainfall depth and rainfall duration. Although probabilistic models based on copulas could be used to take into account this issue [46], to allow the mathematical derivation of equations (7) and (8), they have not been considered. Climate changes are not considered in the analysis as well as the building's type that can affect the roof temperature and result in the evapotranspiration by the green roof.

The hypothesis of constant evapotranspiration, although assumed in other studies before [25, 26], is usually too simplifying respect to green roof behaviour observed in real cases, especially during dry periods. A soil moisture retention/drying curve and hydraulic conductivity model should be used to simulate the evolution in time of soil moisture content. However, for the aim of this paper, that is to develop a probabilistic estimation model of water content evolution due to successive rainfall events, the simple scheme of equations (2) and (3) is at the same time essential and adequate. Moreover, we suggest the use of the potential evapotranspiration rate, to achieve conservative results and counterbalance the effects of this simplifying hypothesis.

3. Results and discussion

The proposed probabilistic model has been validated and tested by the comparison with continuous simulation. Probabilities *P*, from equations (7) and (8) with N=5, and cumulated frequencies *F* from continuous simulation are compared in Figures 2-3.

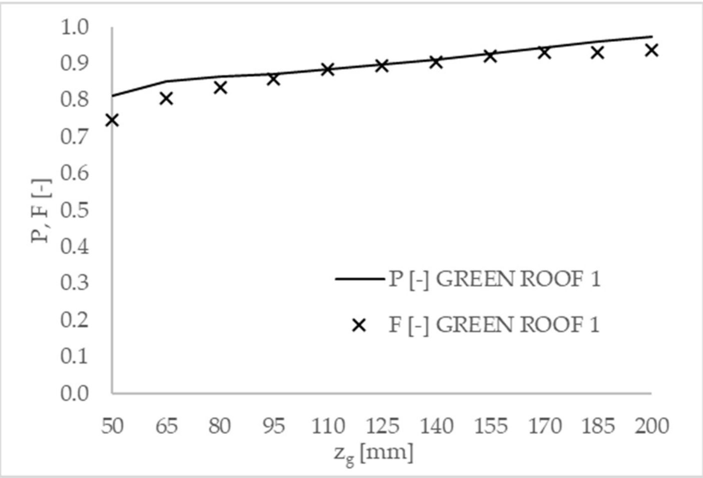

Figure 2. Comparison between probability (*P*) and frequency (*F*) distribution function of water content into growing medium varying its thickness (z_g), GREEN ROOF 1.

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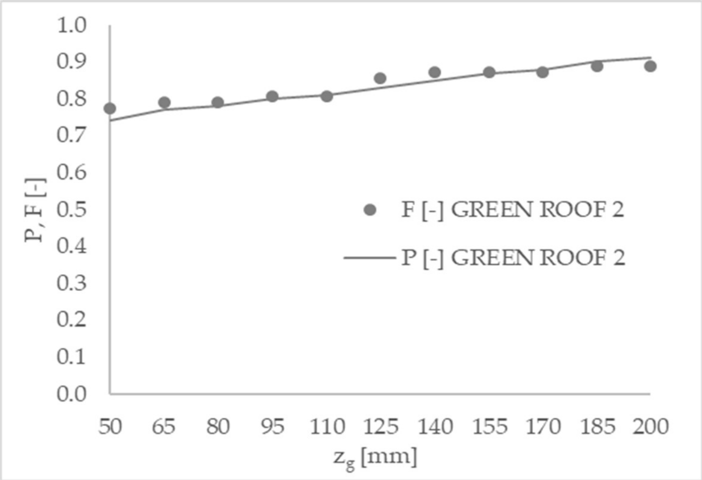

Figure 3. Comparison between probability (*P*) and frequency (*F*) distribution function of water content into growing medium varying its thickness (z_g), GREEN ROOF 2.

As can be seen, there is a good fitting between *P* and *F* for both sites. In both cases, as expected, the probability to have a minimum water content for vegetation survival without irrigation increases with the thickness of growing medium. Considering the whole period of analysis, *P* results slightly higher for GREEN ROOF 1 respect to GREEN ROOF 2. This is due to the higher value of constant evapotranspiration rate used for the roof at University of Calabria. In Tables 4 and 5, the probability of vegetation survival *P*, estimated by equations (7) and (8), and the related average return interval[1] (ARI = 1/(1-P)) are reported for growing medium thickness ranging from 50 [mm] to 200 [mm].

Table 4. Analysis results on the whole period of records, GREEN ROOF 1.

z_g [mm]	50	65	80	95	110	125	140	155	170	185	200
P [-]	0.81	0.85	0.86	0.87	0.88	0.90	0.91	0.93	0.94	0.96	0.97
ARI [years]	5	7	7	8	9	10	11	14	18	24	37

Table 5. Analysis results on the whole period of records, GREEN ROOF 2.

z_g [mm]	50	65	80	95	110	125	140	155	170	185	200
P [-]	0.74	0.77	0.78	0.80	0.81	0.83	0.85	0.87	0.88	0.90	0.91
ARI [years]	4	4	5	5	5	6	7	7	8	10	11

In the case of GREEN ROOF 1, *P* varies between 0.81 and 0.97. For the actual growing medium thickness z_g=170 [mm], *P* is equal to 0.94, corresponding to an ARI=18 [years]. In the case of GREEN ROOF 2, *P* varies between 0.74 and 0.91. For the actual growing medium thickness z_g=80 [mm], *P* is equal to 0.78, corresponding to an ARI=5 [years].

Previous results are related to the behavior of green roofs along the whole year. In the following, the focus is on summer, the most critical season for vegetation survival without irrigation. Table 6 shows the average values of rainfall variables measured at Milano-Monviso station (GREEN ROOF 1) and at the experimental site of University of Calabria (GREEN ROOF 2) in this season.

[1] The Average Return Interval, also called return period, of a specific value of a random variable is the average time interval between two event occurrences in which that value is exceeded. It is used as a measure of acceptable risk in design procedure [Chow, V.T. (1964) Statistical and Probability Analysis of Hydrological Data. In: Chow, V.T., Ed., Handbook of Applied Hydrology, McGraw Hill, New Yok, 81-97].

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Table 6. Average values of rainfall variables in summer.

μ	GREEN ROOF 1	GREEN ROOF 2
h [mm]	17.19	13.96
θ [hour]	5.42	7.66
d [hour]	175.02	206.18

For both sites, summer is characterized by higher rainfall intensities and longer dry periods; this climatic feature is more evident for GREEN ROOF 2, because it is characterized by a Mediterranean climate with summers much less rainy than winters.

Tables 7-8 show the coefficients of variation and the correlation indexes in summer.

Table 7. Coefficient of variation of rainfall variable in summer.

V	GREEN ROOF 1	GREEN ROOF 2
h [-]	1.13	0.90
θ [-]	1.32	0.95
d [-]	1.18	0.60

Table 8. Correlation indexes among rainfall variables in summer.

	GREEN ROOF 1	GREEN ROOF 2
$\varrho_{h,d}$ [-]	0.05	-0.49
$\varrho_{\theta,h}$ [-]	0.56	0.71
$\varrho_{d,\theta}$ [-]	0.02	-0.49

The same considerations previously done for the whole year are valid for summer. In the case of GREEN ROOF 2 at University of Calabria, however a stronger correlation among variables is observed. This result could be influenced also by the short length of the series of rainfall records. In Figures 4-5, probabilities *P*, from equations (7) and (8) with N=5, and cumulated frequencies *F* from continuous simulation are compared for summer.

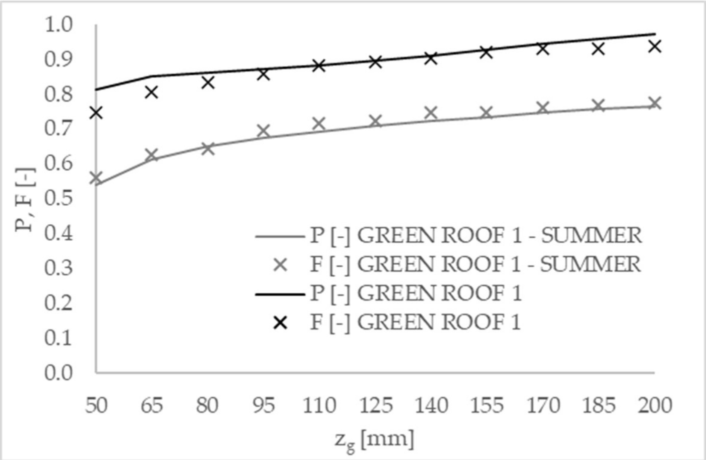

Figure 4. Probability (*P*) and frequency (*F*) distribution function of water content into growing medium varying its thickness (z_g) during the whole year and summer, GREEN ROOF 1.

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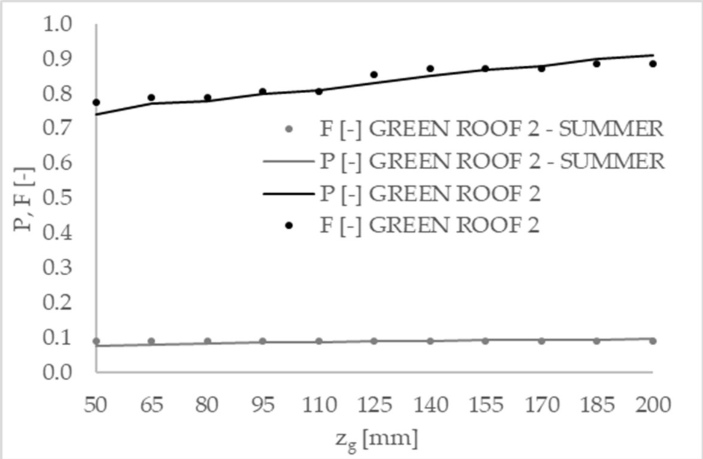

Figure 5. Probability (*P*) and frequency (*F*) distribution function of water content into growing medium varying its thickness (z_g) during the whole year and summer, GREEN ROOF 2.

Also, in the case of summer, results show a good accordance between *P* and *F*. Obviously, during summer the probabilities of vegetation survival without irrigation are lower, due to the higher evapotranspiration rates and longer dry periods.

In Tables 9 and 10, resulting *P* and *ARI* for summer are reported.

Table 9. Analysis results in summer, GREEN ROOF 1.

z_g [mm]	50	65	80	95	110	125	140	155	170	185	200
P [-]	0.54	0.61	0.65	0.68	0.69	0.71	0.72	0.73	0.75	0.76	0.77
ARI [years]	2	3	3	3	3	3	4	4	4	4	4

Table 10. Analysis results in summer, GREEN ROOF 2.

z_g [mm]	50	65	80	95	110	125	140	155	170	185	200
P [-]	0.08	0.08	0.08	0.09	0.09	0.09	0.09	0.09	0.09	0.10	0.10
ARI [years]	1	1	1	1	1	1	1	1	1	1	1

In the case of GREEN ROOF 1, *P* varies between 0.54 and 0.77. For the actual growing medium thickness z_g=170 [mm], *P* is equal to 0.75, corresponding to an ARI=4 [years]. For GREEN ROOF 2, P varies between 0.08 and 0.10. For the actual growing medium thickness z_g=80 [mm], P is equal to 0.08, corresponding to an ARI=1 [years].

It is important to observe that the increase of growing medium thickness does not correspond to a significant increase of the *ARI*, so a meaningful growth of the probability a of vegetation survival can be achieved only by irrigation.

4. Conclusions

A model for the estimation the probability of survival for vegetation of green roofs without irrigation is proposed. Developed equations relate this probability to the thickness of growing medium, average potential evapotranspiration rate, and climate features. The application to two cases study at Politecnico di Milano and at University of Calabria (Italy) have shown an excellent accordance to results from continuous simulation.

An important value of the model is the possibility of taking into account the effects of chained rainfall events, without the need of continuous simulation of hydrological processes. This makes results more reliable and application easier and cheaper in terms of computational time and data needs.

Equations (7) and (8) can be used in green roof design, together with others from previous studies [26], to achieve the identification of a thickness of growing medium that results proper for both runoff control and vegetation survival. An interesting achievement is the possibility to identify an optimal value of the growing medium thickness above which the probability of vegetation survival does not increase significantly without irrigation.

Further future improvements of this study will focus mainly on the identification of the optimal number chained rainfall events to be considered in the analysis. Another issue will be the extension of the model also to cases where limited information on the stochastic process for rainfall event is available. The model will be tested also on case studies in different climate conditions.

Author Contributions: Conceptualization, Gianfranco Becciu and Anita Raimondi; methodology, Anita Raimondi, Umberto Sanfilippo and Gianfranco Becciu; formal analysis, Anita Raimondi; validation: Anita Raimondi; data curation, Anita Raimondi; writing—original draft preparation, Anita Raimondi; writing—review and editing, Anita Raimondi, Gianfranco Becciu and Mariana Marchioni; supervision, Gianfranco Becciu. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Notation

The following symbols are used in this paper:

h: rainfall depth;
θ: rainfall duration;
d: interevent time;
v: runoff volume;
z_g: growing medium thickness;
z_d: drainage layer thickness;
z_0: overflow height;
ET: evapotranspiration volume;
ET_p: potential evapotranspiration volume;
Et: evapotranspiration rate;
Et_p: potential evapotranspiration rate;
ϕ_f: growing medium moisture content per unit depth at saturation;
h_{ge}: water content into growing medium at the end of the dry period (from previous rainfalls);
h_{gu}: water content into growing medium at the end of rainfall event;
N: number of consecutive events;
μ_h: average rainfall depth;
μ_θ: average rainfall duration;
μ_d: average interevent time;
w: minimum water content;
IETD: Inter Event Time Definition;
P: probability;
F: frequency;
ARI: Average Return Interval;
V: coefficient of variation;
ρ: correlation index;

References

1. Carter, T.L.; Rasmussen, T.C. Hydrologic behavior of vegetated roofs 1. JAWRA Journal of the American Water Resources Association, 2006. 42(5): p. 1261-1274.

2. Getter, K.L.; Rowe D.B.; Andresen, J.A., Quantifying the effect of slope on extensive green roof stormwater retention. Ecological engineering, 2007. 31(4): p. 225-231.
3. Li, Y.; Babcock, R.W., Jr. Green roof hydrologic performance and modeling: a review. Water science and technology, 2014. 69(4): p. 727-738.
4. Li, Y.; Babcock, R.W., Jr. Modeling hydrologic performance of a green roof system with HYDRUS-2D. Journal of Environmental Engineering, 2015. 141(11): p. 04015036.
5. Palla, A.; Gnecco, I.; Lanza L. Compared performance of a conceptual and a mechanistic hydrologic models of a green roof. Hydrological Processes, 2012. 26(1): p. 73-84.
6. Locatelli, L.; Mark, O.; Mikkelsen, P.S; Arnbjerg-Nielsen, K.; Bergen, J.M.; P.J. Binning. Modelling of green roof hydrological performance for urban drainage applications. Journal of hydrology, 2014. 519: p. 3237-3248.
7. Stovin, V.; Vesuviano, G.; De-Ville, S. Defining green roof detention performance. Urban Water Journal, 2017. 14(6): p. 574-588.
8. Hakimdavar, R.; Culligan, P.J.; Finazzi, M.; Barontini, S.; Ranzi R. Scale dynamics of extensive green roofs: Quantifying the effect of drainage area and rainfall characteristics on observed and modeled green roof hydrologic performance. Ecological Engineering, 2014. 73: p. 494-508.
9. Peng, L.L.; Jim, C.Y. Seasonal and diurnal thermal performance of a subtropical extensive green roof: The impacts of background weather parameters. Sustainability, 2015. 7(8): p. 11098-11113.
10. Herrera, J.; Flamant, G.; Gironás, J.; Vera, S.; Bonilla, C.A.; Bustamante, W.; Suárez F. Using a hydrological model to simulate the performance and estimate the runoff coefficient of green roofs in semiarid climates. Water, 2018. 10(2): p. 198.
11. Carbone, M.; Turco, M.; Nigro, G.; Piro, P. Modeling of hydraulic behaviour of green roof in catchment scale. Proceedings of International Multidisciplinary Scientific GeoConferences SGEM 2014, Albena, Bulgaria, 2014. p. 471-478.
12. Palermo, S.A.; Talarico, V.C.; M., Turco. On the LID systems effectiveness for urban stormwater management: case study in Southern Italy. IOP Conference Series: Earth and Environmental Science, 2020. 410(1): p. 012012.
13. Nawaz, R.; McDonald, A.; Postoyko S. Hydrological performance of a full-scale extensive green roof located in a temperate climate. Ecological Engineering, 2015. 82: p. 66-80.
14. Berndtsson, J.C. Green roof performance towards management of runoff water quantity and quality: A review. Ecological engineering, 2010. 36(4): p. 351-360.
15. Voyde, E.; Fassman, E.; R. Simcock. Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. Journal of hydrology, 2010. 394(3-4): p. 384-395.
16. Bengtsson, L. Peak flows from thin sedum-moss roof. Hydrology Research, 2005. 36(3): p. 269-280.
17. Adams, B.; Papa F. Analytical Probabilistic Models for Stormwater Management Planning. 2000, John Wiley and Sons, New York.
18. Becciu, G.; Raimondi, A.; Dresti, C. Semi-probabilistic design of rainwater tanks: a case study in Northern Italy. Urban Water Journal, 2018. 15(3): p. 192-199.
19. Raimondi, A.; Becciu, G. Probabilistic modeling of rainwater tanks. Procedia Engineering, 2014. 89: p.1493-1499.
20. Raimondi, A.; Becciu G. Probabilistic design of multi-use rainwater tanks. Procedia Engineering, 2014. 70: 1391-1400.
21. Zhang, S.; Guo, Y. An analytical equation for evaluating the stormwater volume control performance of permeable pavement systems. J Irrig Drain Eng, 2015. 141(4): p. 06014004.
22. Zhang, S.; Guo, Y. Stormwater capture efficiency of bioretention systems. Water resources management, 2014. 28(1): p. 149-168.
23. Guo, Y. Stochastic analysis of hydrologic operation of green roofs. Journal of Hydrologic Engineering, 2016. 21(7): p. 04016016.
24. Zhang, S.; Guo, Y. Analytical probabilistic model for evaluating the hydrologic performance of green roofs. Journal of Hydrologic Engineering, 2013. 18(1): p. 19-28.
25. Guo, Y.; Zhang, S.; Liu, S. Runoff Reduction Capabilities and Irrigation Requirements of Green Roofs. Water Resour Manage. 2014, 28: p.1363–1378.
26. Raimondi, A.; Becciu, G. Performance of Green Roofs for Rainwater Control. Water Resour. Manage., 2020. 34(15): p. 1-13.
27. Becciu, G.; Raimondi, A. Factors affecting the pre-filling probability of water storage tanks. WIT Transactions on Ecology and the Environment, 2012. 164: p. 473-484.
28. Becciu, G. and A. Raimondi, Probabilistic analysis of spills from stormwater detention facilities, WIT Transactions on the Built Environment, 2014. 139: p. 159-170.
29. Becciu, G.; Raimondi, A. Probabilistic analysis of the retention time in stormwater detention facilities. Procedia Engineering, 2015. 119: p. 1299-1307.

 doi:10.20944/preprints202008.0172.v2

30. Becciu, G.; Raimondi, A. Probabilistic modeling of the efficiency of a stormwater detention facility. Int. Journal of Sustainable Development and Planning, 2015. 10(6): p. 795-805.
31. Raimondi, A. and G. Becciu, On pre-filling probability of flood control detention facilities. Urban Water Journal, 2017. 12: p. 344-351.
32. Raimondi, A.; Becciu, G. On the efficiency of stormwater detention tanks in pollutant removal. International Journal of Sustainable Development and planning, 2017. 12(1): p. 144-154. Lamera, C.; Becciu, G.; Rulli, M.C.; Rosso, R.Green roofs effects on the urban water cycle components. Procedia Engineering, 2014. 70: p. 988-997.
33. Becciu, G.; Paoletti, A. Random characteristics of runoff coefficient in urban catchments. Water Science and Technology, 1197. 36(8-9), p. 39-44.
34. United States Environmental Protection Agency (US-EPA). Methodology for analysis of detention basins for control of urban runoff quality, U.S. Environmental Protection Agency Office of Water, Nonpoint Source Branch, 1986, pp. 51, United States.
35. Adams, B.J.; Fraser, H. G.; Howard, C. D.; Sami Hanafy, M. Meteorological data analysis for drainage system design. Journal of Environmental Engineering, 1986. 112(5): p. 827-848.
36. Eagleson, P.S. Climate, soil, and vegetation: 2. The distribution of annual precipitation derived from observed storm sequences. Water Resources Research, 1978. 14(5): p. 713-721.
37. Bedient, P.B.; Huber, W.C.; Vieux, B.E. Hydrology and floodplain analysis. 2008.
38. Bacchi, B., Balistrocchi, M.; Grossi, G. Proposal of a semi-probabilistic approach for storage facility design. Urban Water Journal, 2008. 5(3): p. 195-208.
39. Fiori, M.P.G.; Paolini, R.; Poli, T. Monitoring of eight green roofs in Milano. Hygrothermal performance and microclimate mitigation potential.39th World Congress on Housing Science. Changing Needs, Adaptive Buildings, Smart Cities, 2013, p. 1365-1372.
40. Palermo, S.A.; Turco, M.; Principato S.; Piro, P. Hydrological effectiveness of an extensive green roof in Mediterranean climate. Water, 2019. 11(7): p. 1378.
41. Brunetti, G.; Šim° unek, J.; Piro, P. A Comprehensive Analysis of the Variably Saturated 461 Hydraulic Behavior of a Green Roof in a Mediterranean Climate. Vadose Zone J. 2016, 15.
42. Wolf, D.; Lundholm, J.T. Water uptake in green roof microcosms: effects of plant species and water availability. Ecological Engineering, 2008. 33(2): p. 179-186.
43. Kaiser, D., Kohler, M.; Schmidt, M.; F. Wolff, Increasing Evapotranspiration on Extensive Green Roofs by Changing Substrate Depths, Construction, and Additional Irrigation. Buildings, 2019. 9(7): p. 173.
44. Lamera, C.; Becciu, G.; Rulli, M.C.; Rosso, R.Green roofs effects on the urban water cycle components. Procedia Engineering, 2014. 70: p. 988-997.
45. Van Genuchten, M.T. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils 1. Soil Sci. Soc. Am. J. 1980, 44: p. 892–898.
46. Abdollahi S.; Akhoond-Ali, A.M.; Mirabbasi, R. Adamowski JF (2019) Probabilistic Event Based Rainfall-Runoff Modeling Using Copula Functions. Water Resour Manage 33:3799–3814