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Article

Vegetation survival in green roofs without irrigation

Anita Raimondi [1], Mariana Marchioni [1], Umberto Sanfilippo [1] * and Gianfranco Becciu [1]

[1] Dipartimento di Ingegneria Civile e Ambientale, Politecnico di Milano
* Correspondence: anita.raimondi@polimi.it

Abstract: The Sustainable Urban Drainage Systems on stormwater management provide benefits for sewer networks, treatment plants and environment and should be encouraged. Green roofs are part of these systems and can contribute both to delay and cut peak runoff and reduce discharged volumes. In this paper the probability of vegetation survival without irrigation has been proposed as a guide to operators on selecting vegetation and irrigation system as well as design parameters. An analytical probabilistic approach has been proposed; a chain of consecutive rainfall events has been considered to take into account the possibility that storage capacity is not completely available at the beginning of the considered event but pre-filled from previous rainfalls, as typical of green roofs. Finally, an application to a case study has been proposed to validate proposed equations.

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

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1. Introduction

The use of Sustainable Urban Drainage Systems delivers several benefits: relief on the sewer networks, increase the efficiency of treatments plants, reduce water contaminates load and increase biodiversity. The growth of impervious areas, especially in highly density populated cities strongly reduces soil infiltration with consequent rise of flood events; in such context green roofs can be effective since rooftops constitute from 30 to 50% of impermeable surfaces and don't require additional space beyond a building's footprint [1]. Their implementation also entails significant environmental and economic benefits besides stormwater management and the improvement of water quality, as like energy conservation, reduction of heat island and protection of biodiversity. Focusing on stormwater management, green roofs allow especially if widespread: the local disposal of runoffs; the reduction of runoff volumes, through evapotranspiration from vegetation and exposed surfaces; the delay of runoff, that only starts after soil saturation; the reduction and delay of runoff peak rates, for the infiltration of rainwaters into the soil and their temporary storage in the substrate and in the drainage layer; the improvement of stormwater quality for effect of its percolation into the soil. First green roofs were installed in Germany in the 1970s [2] and since then they have spread in all major modern countries where in some cases have been developed incentive programs to encourage or even impose their installation.

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 or climate [8-10] on small spatial and time scale [11, 12]; especially for full-scale installations, there is not enough scientific evidence yet to demonstrate hydrological benefits of green roofs [13, 14]. Often the focus of studies on green roof is on their retention capacity in relation to rainfall depth [1, 2]), antecedent dry period [15, 16] and evapotranspiration [17].

Raimondi and Becciu have evaluated green roofs performances for stormwater control estimating the runoff probability distribution function by mean of an analytical probabilistic approach. This kind of methodology, first proposed by [18] has been applied by different authors also to SUDS: Rain Water Harvesting Systems [19] infiltration trenches [20], permeable pavements [21] bioretention systems [13], green roofs [13, 20, 22], stormwater detention facilities [23]. Generally, these studies consider a couple of rainfall events at time and neglect or only partially consider the possibility that storage volume is not completely empty at the beginning of considered rainfall. Becciu and Raimondi [24] observed that for low outflow rate structures as SUDSs, pre-filling is generally due to more than one previous rainfall and developed a procedure to consider a chain of N rainfall events [25].

In this paper the analytical probabilistic approach has been proposed to estimate the probability of vegetation to survive without irrigation, that is the probability to have a minimum water content into growing medium during dry periods between rainfall events; to consider the possibility of pre-filling of storage capacity from a chain of previous rainfall events is fundamental for green roofs, since outflows are limited to evapotranspiration from vegetation and soil. Resulting equations can guide operators in the choice of suitable vegetation and irrigation for the analyzed context as well as of design parameters. An application to a case study in Milano, Italy has been proposed to validate proposed formulas by a comparison of results obtained from them with those obtained from the continuous simulation of recorded data.

2. Green roofs hydrology

Green roofs are engineered multi-layered structures, with a vegetated upper surface, working in very shallow systems without connection to natural ground. Layers, involved in stormwater control 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 elements, that stores water for plants sustainment during dry periods evacuating excess water in roof drains; root resistant membrane, mechanic protection geotextile. Figure 1 shows the scheme of reference for the modeling of green roofs, used in this paper.

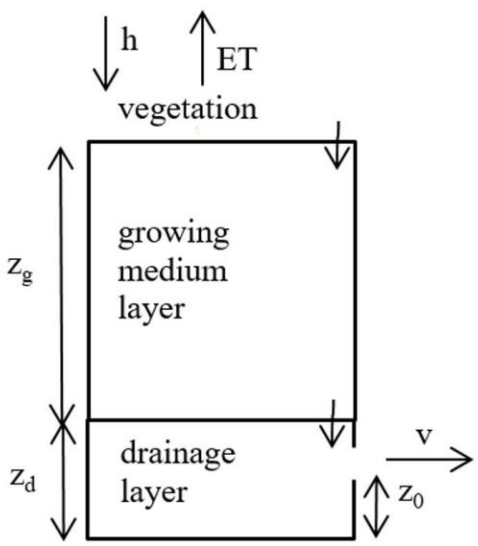

Figure 1. Green roof scheme considered for the modeling.

h: rainfall depth
ET: evapotranspiration
v: runoff
z_g: growing medium thickness
z_d: drainage layer thickness
z_0: overflow height

Input variables are rainfall depth, rainfall duration and interevent time, while output variables are evapotranspiration and runoff; three layers have been considered: vegetation, growing medium

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and drainage layer; volumes must be intended as specific for unit of area. Rainfall is first intercepted by vegetation and then infiltrated into growing medium where is retained, used by roots and released back into atmosphere through evapotranspiration; the excess is infiltrated into drainage layer equipped with an overflow to discharge excess rainwater into the sewer when retention capacity is full. Interception by vegetation, generally of a few millimetres and drainage layer capacity, generally variable between 5-10 [cm], have been neglected in the following: the focus is on growing medium layer and on its thickness.

To evaluate the probability of vegetation to survive without irrigation, water content at the end of dry period between events has been be calculated: this is the condition of minimum water content into growing medium.

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

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

Evapotranspiration ET equals potential evapotranspiration ET_P, in case rainfall depth is higher than potential evapotranspiration or when rainfall depth is lower than potential evapotranspiration but rainfall depth added to water content into growing medium from previous rainfalls h_{ge} exceeds potential evapotranspiration. Water content into growing medium can vary between zero if it is completely dry and the maximum value $\phi_f{\cdot}z_g$, (where ϕ_f represents the growing medium moisture content at saturation), if storage volume is full, as in the case of two very close heavy rainfall events. For the aim of the paper, evapotranspiration has been assumed equal to potential evapotranspiration, that is equal to its maximum, the worst condition for vegetation.

Water content into growing medium has been estimated both at the end of the dry period (subscript e) and at the end of rainfall event (subscript u).

Considering i=1, …, N water depth into growing medium at the end of considered event results:

$$h_{gu,i-1} = \begin{cases} h_{ge,i-1} + h_{i-1} - Et \cdot \theta_{i-1} & 0 \leq h_{ge,i-1} + h_{i-1} - Et \cdot \theta_{i-1} < \phi_f \cdot z_g \\ \phi_f \cdot z_g & h_{ge,i-1} + h_{i-1} - Et \cdot \theta_{i-1} \geq \phi_f \cdot z_g \\ 0 & otherwise \end{cases} \tag{2}$$

For i=1, growing medium has been considered empty ($h_{e,0}$=0).

Et is the evapotranspiration rate, assumed equal to its maximum, the potential one, as discussed above.

Water depth into growing medium at the beginning of a generic rainfall (always considering i=1, …, N) results:

$$h_{ge,i} = \begin{cases} h_{gu,i-1} - Et \cdot d_{i-1} & h_{gu,i-1} - Et \cdot d_{i-1} > 0 \\ 0 & otherwise \end{cases} \tag{3}$$

During dry period between rainfall events, in absence of irrigation, water depth into growing medium can only decrease.

3. Probabilistic model

In the analytical probabilistic model proposed to evaluate the capacity of vegetation to survive without irrigation, input variables are rainfall depth h, rainfall duration θ and interevent time d: they have been considered independent and exponentially distributed. To isolate independent rainfalls from a continuous record of events, a minimum interevent time, the so called Inter Event Time Definition (IETD) (USEPA 1986) has been defined. If the interevent time between two consecutive rainfall events is smaller than IETD, the two rainfall have been joined into a single event, otherwise they have been assumed independent.

With reference to the assumption of exponential distribution of considered rainfall parameters, lot of studies on many basins, concluded that it can considered acceptable in order to reduce the complexity of analytical derivation [26-28]. [29] tested that for most Italian basins the Weibull probability distribution function, ensures a better fitting to the frequency distribution function of input variables; however, its use involves a considerable numerical complication. [30] verified that the double-exponential probability distribution function well fits the frequency distribution function of observed data for main rainfall characteristic parameters; such distribution may be easily integrated but derived expressions are more complex. Moreover, its application to a case study highlighted that the use of a double-exponential probability distribution function little improves the accuracy of results and that the bias due to the use of the exponential probability distribution function is negligible when compared to the simplicity of equations integration. Exponential probability density function of rainfall depth, rainfall duration and interevent time, is:

$$f_h = \xi \cdot e^{-\xi \cdot h} \qquad (4)$$

$$f_\theta = \lambda \cdot e^{-\lambda \cdot \theta} \qquad (5)$$

$$f_d = \psi \cdot e^{-\psi \cdot (d - IETD)} \qquad (6)$$

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.

These models neglect the random nature of runoff coefficient, despite its random nature (Becciu and Paoletti [31]). For green roofs, the input is rainfall directly fallen on the green roof.

To estimate the probability of green roofs vegetation to survive without irrigation, a minimum water content w has been considered. The condition for which water content can be different of zero at the end of the considered dry period is $(z_g \cdot \phi_f - w)/Et > IETD$: this means the possibility to have pre-filling from previous events.

Two different conditions have been discussed: a single rainfall i=1 and a chain of rainfall events i>1.

For i=1, that is when a single rainfall is considered, the probability to have a minimum water volume into the growing medium at the end of dry period between rainfalls to ensure vegetation survival results:

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

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

For i >1, that is if a chain of rainfall events is considered, the probability to have a minimum water volume into growing medium at the end of the considered dry period to ensure vegetation survival results:

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

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

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

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

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

(8)

Symbols γ, β, β_i and β_i^* are equal to:

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

4. Case study

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Equations (7) and (8) have been applied to a case study in Milano (Italy). As input for the analysis, rainfall records of Milano-Moviso gauge station in the period 1971-2005 have been used; to identify independent events a minimum interevent time IETD=1 [hour] has been assumed. Table 1 reports mean and coefficient of variation of rainfall depth h, rainfall duration θ and interevent time d.

Table 1. Mean and coefficient of variation of rainfall variables.

	μ [mm]	V [-]
h	7,62	1,63
θ	4,32	1,34
d	66,5	1,94

The assumption of exponential distribution of rainfall variables is not completely satisfy but the bias due to its use can be considered negligible as discussed and tested by [24]. Table 2 contains correlation index among rainfall variables.

Table 2. Correlation index among rainfall variables

$\varrho_{h,d}$ [-]	0,01
$\varrho_{\theta,h}$ [-]	0,7
$\varrho_{d,\theta}$ [-]	0,01

With reference to correlation index, it's evident that correlation between rainfall depth and interevent time and correlation between interevent time and rainfall duration is negligible while correlation between rainfall depth and rainfall duration is high; effects on this assumption on results have been discussed in previous works [32]. Potential evapotranspiration and water content at saturation have been assumed respectively equal to Et=0,131 [mm/hour] and ϕ_f =0,58 [-] [8]; growing medium thickness z_g has been varied between 50 [mm] and 500 [mm]. A minimum water content w=0 [mm] has been considered, that corresponds to the probability of prefilling from previous events, that is the minimum condition for vegetation survival without irrigation.

Results from application of equations (7) and (8) have been compared with those obtained by the frequency analysis of continuous simulation of recorded data. Figure 2 shows a good fit to cumulated frequency, for i=5. The probability to have a minimum water content for vegetation survival without irrigation increases with growing medium thickness, varying from a return period T≈4 [years] with z_g=50 [mm] to T≈7 [years] with z_g=500 [mm]; to get higher return period values is not sufficient the increase of growing medium thickness but water supply from irrigation is required.

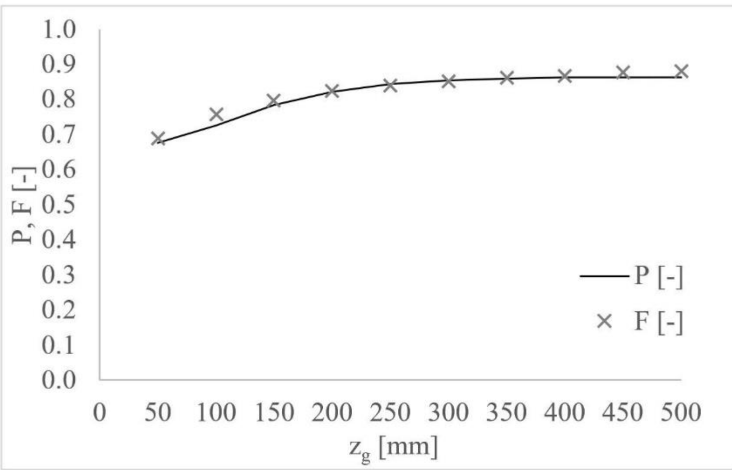

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Figure 2. Comparison between probability and frequency distribution function of water content into growing medium layer varying its thickness in the period of analysis.

In the following the same analysis discussed above have been made with reference to each season; the behavior of green roofs, especially water need of vegetation, is different for each season mainly due to different rainfall conditions and different evapotranspiration rates. Different studies in literature collected results of field measurements trying to define a range of reasonable values of green roofs evapotranspiration: [31] experimental estimated this rates range from 0,69 to 6-9 [mm/day] with typical values of 1-6 [mm/day] using a Penman-Monteith model; [33] found evapotranspiration rates variable between 0 to 5 [mm/day] analyzing wet, intermediate and dry conditions; [16] averaged evapotranspiration rates of about 2 [mm/day] for the seven days following saturation. For the case, discussed in Figure 2 an evapotranspiration rate equal to Et=0,131 [mm/hour] has been used; to diversify evapotranspiration rate during different seasons, this value has been maintained for Spring and Autumn, while for Winter a minimum value equal to Et_{winter}=0,09 [mm/hour] has been considered and for Sumer a maximum value equal to Et_{summer}=0,21 [mm/hour] has been considered. Table 3 shows average values of each rainfall variable for each season.

Table 3. Mean values of rainfall variables.

	Spring	Summer	Autumn	Winter
μh [mm]	6,32	8,9	7,89	8,06
μθ [hour]	3,17	2,55	5,39	6,75
μd [hour]	48,98	78,23	61,34	84,62

Maximum average rainfall depth occurs in Summer with, however, the minimum rainfall duration resulting in high rainfall intensity; maximum average rainfall duration occurs in Winter, typically characterized in temperate climate by long but low intensity rainfalls; again in Winter maximum average rainfall interevent time occur: this is due to the low number of rainfall events especially if compared with Spring (Table 4).

Table 4. Number of rainfall events for season in the considered period.

	Spring	Summer	Autumn	Winter
N [-]	1430	928	1113	862

Table 5 presents coefficients of variation for each variable in different seasons: according to Table 1 minimum values are always for rainfall duration for which the assumption of exponential distribution is more suitable; as previously highlighted in Table 1 interevent time probability distribution function differs more from the exponential one, especially in Autumn and Winter.

Table 5. Coefficients of variation of considered rainfall variables.

	Spring	Summer	Autumn	Winter
V_h [-]	1,62	1,59	1,65	1,56
V_θ [-]	1,3	1,39	1,17	1,17
V_d [-]	1,97	1,61	2,04	2,05

According to Table 2, both correlation index between rainfall depth and interevent time and between rainfall duration and interevent time are negligible, while correlation index between rainfall depth and duration is quite high with its maximum in Winter.

Table 6. Correlation index among rainfall variables.

	Spring	Summer	Autumn	Winter

$\varrho_{h,d}$ [-]	-0,02	0,03	0,02	-0,02
$\varrho_{\theta,h}$ [-]	0,72	0,63	0,76	0,87
$\varrho_{d,\theta}$ [-]	-0,05	-0,02	0,05	0,02

Figure 3 reports the probability distribution function of water content into growing medium varying layer thickness, computed applying equation (8), compared with the frequency distribution function of observed data. There is a good fitting between the two curves (mean square deviation is equal to 0,6%); in this case the number of considered chained events is equal to i=6, one more than for the whole period discussed in Figure 2: this because as average interevent time is lower the probability of pre-filling from previous rainfall events increases.

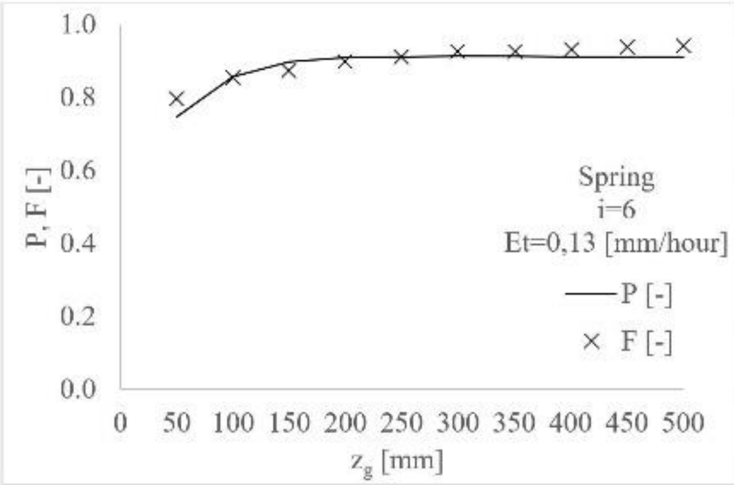

Figure 3. Comparison between probability and frequency distribution function of water content into growing medium layer varying its thickness during Spring.

Figure 4 shows results for Summer: the fitting of results from the application of proposed method to the frequency distribution function of observed data is good (mean square deviation equal to 0,4%) except for a small underestimation for the smallest and greatest values of growing medium layer thickness. The increased value of evapotranspiration rate involves a lower probability of pre-filling from previous rainfalls; this effect is balanced by a high value of rainfall depth compared with other seasons (i=5 has been used).

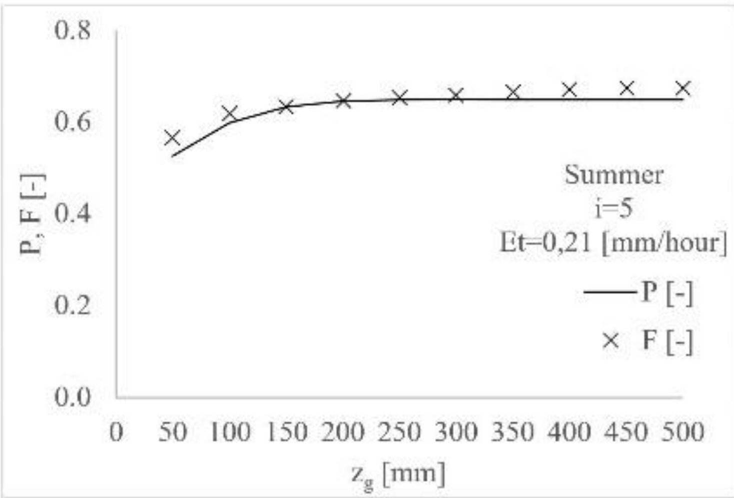

Figure 4. Comparison between probability and frequency distribution function of water content into growing medium layer varying its thickness in Summer.

Figure 5 shows results for Autumn: in this case the comparison with the frequency distribution of observed data, reveals a good fitting for low thickness of growing medium layer while if it increases proposed method underestimates the probability distribution function of water content. The agreement to frequency distribution function of probability distribution function is greater considering i=5 than for i=6 (mean square deviation equal to 1,3% for i=6 and equal to 1,1% for i=5). Comparing Autumn with Summer, the lower evapotranspiration rate with consequent increase of chained rainfall events is balanced by a lower average interevent time.

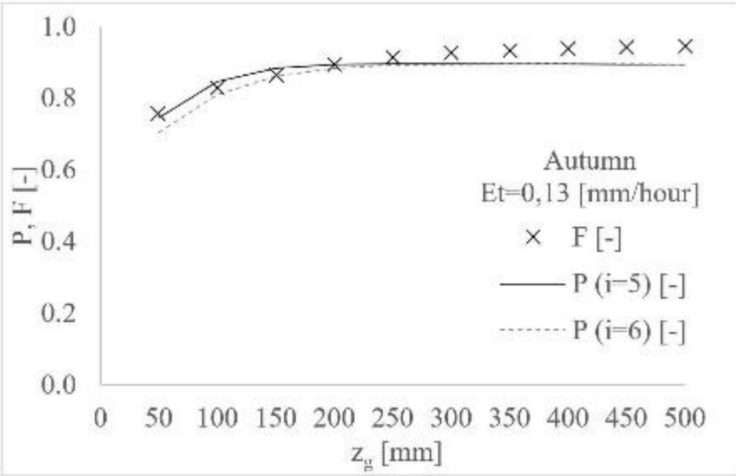

Figure 5. Comparison between probability and frequency distribution function of water content into growing medium layer varying its thickness in Autumn.

Figure 6 reports the comparison between water content probability distribution function and frequency distribution function of observed data varying growing medium thickness in Winter: the fitting is good (mean square deviation equal to 0,5%). In this case low evapotranspiration rate with consequent increase of probability of pre-filling from previous events is balanced by a high average interevent time (Table 2).

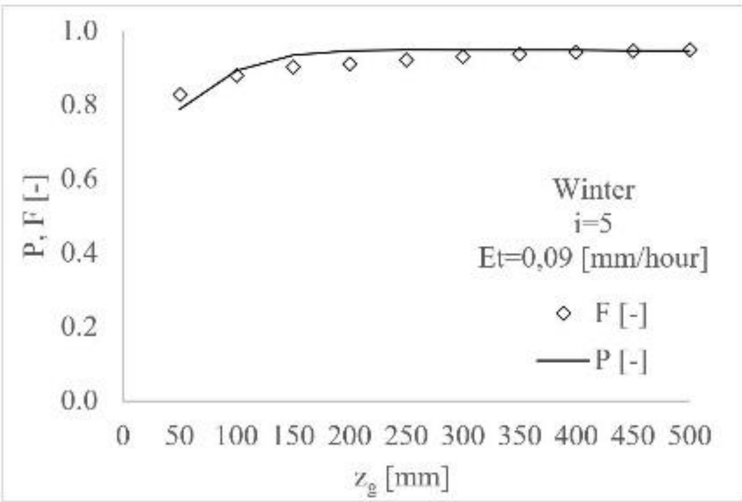

Figure 6. Comparison between probability and frequency distribution function of water content into growing medium layer varying its thickness in Winter.

Figure 7 compares results of the application of equation (8) for different seasons: as expected, in Summer the probability to have a minimum water content during dry period between rainfall events is not high, so irrigation is needed. On the contrary, in Winter the probability to have a minimum water content for vegetation survival is maximum, especially due to low evapotranspiration rate during this period; irrigation is not requested also for vegetation rest. It's important to highlight that for all seasons an increase of layer thickness corresponds to an increase of the probability only for low values of z_g: in this case values of growing medium thickness higher than 20 cm don't increase the probability to have a minimum water content at the end of dry periods for vegetation survival.

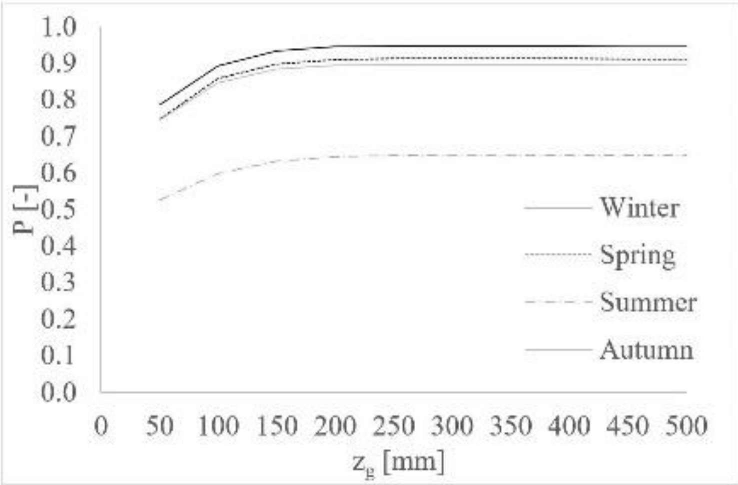

Figure 7. Probability distribution function of water content into growing medium varying growing medium thickness for different seasons.

5. Conclusion

The proposed method allows to analyse the probability to have enough water content for vegetation survival in conditions of lack of irrigation; enables to study the influence on results of variation of growing medium thickness, evapotranspiration, kind of vegetation, climate conditions. The possibility of considering that water storage capacity can be not completely available at the beginning of each rainfall because partially pre-filled from previous events makes the method more realistic especially for structures such as green roofs characterized from a low release flow. Resulting equations can be a valid aid for green roofs design since they allow to define the thickness of growing medium layer, for different condition of vegetation and soil water content at saturation and for a fixed level of probability (return period); they can be applied to different climate conditions since input rainfall variables are simply the average values of rainfall depth, rainfall duration and interevent time. The application to a case study shows an excellent fit of proposed formulas to the frequency analysis of continuous simulation of observed data, highlighting the great potentiality of the suggested method.

Supplementary Materials: The following are available online at www.mdpi.com/xxx/s1, Figure S1: title, Table S1: title, Video S1: title.

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