Impact of green roofs on stormwater runoff coefficients in a Mediterranean urban environment

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Abstract: -In this paper an analysis of green roof impact, a typical stormwater management facility constructed with the aim to reduce the volume of stormwater produced by traditional concrete roofs, is performed. As an example an application to the urban drainage network system of the University of Salerno Campus is illustrated. The main results show that the soil thickness and the water storage capacity are the most important factor affecting the soil water budget of the green roof, especially for event scale analysis. Depending on their values, a minimum and maximum reduction of stormwater production respectively of about 40% and 98% is provided by the green roof construction.

Key-Words: -Green roofs, Best management practices, urban drainage system

1 Introduction

The increasing urbanization of the territory has caused an increase in soil sealing with a consequent reduction of natural infiltration of rainwater into the ground.Rainfall events are then more and more severe because of the climate change.The combination of such factors causes an excess of discharge that has to be routed into existing urban drainage system. But the discharge that is used to plan the urban system is smaller, so a big part of this volume overflows on the soil surfaces causing flooding and damaging. To mitigate the effects induced by an excess of stormwater production, the green roof technology has been investigated to understand the relevant impact on stormwater production.The green roof (Fig. 1) is alayered retention system that creates a storage volume for stormwater, bringing several hydraulic benefits compared to a traditional roof: reduction of runoff volume because a part of rainwater stored inthe layers can return to the natural cycle by evaporation and transpiration, delay time increase because green roofallows the lamination offlow, controls and regulates evacuation of the water so as to avoid tooverload the hydraulic system and finally reduction of the peak flowas combined effect of the previous effects.With particular reference to the runoff volume reduction, various scientific contributions proposed in the recent past, comment on an extremely variable level of reduction, ranging from 40 to 90% of total rainfall volume ([1], [4], [5], [6], [8], [12], [13]). The stormwater response of a green roof is indeed highly impacted by the climate conditions and by the green roof structure itself, and this conditions make generalization a very difficult task.

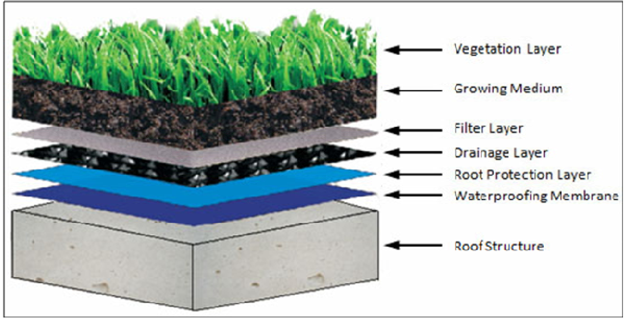


Fig1.: Green roofs structure.

In this paper an empirical formulation is compared to a conceptual framework to investigate the stormwater runoff coefficients dynamic, through an assessment of the stormwater runoff reduction caused by the implementation of the green roof technology. Emphasis is given to the importance of the conceptual simulations and particular relevance has been given to the impact of climate factor, green roof setting and storage capacity on the green roof soil water dynamic.

2 Case study and methodology

To investigate the effect induced on stormwater production by the green roof technology, the Campus of the University of Salerno has been selected as the case study. The University Campus is located in a typical Mediterranean region ([9], [10]). According to the Thornthwaite classification the climate is humid, with mean annual rainfall equal to 1170 mm and mean annual potential evapotranspiration (PET) equal to 780 mm. Figure 2 shows the entity of rainfall deficit and rainfall excess respectively during the dry and wet season.

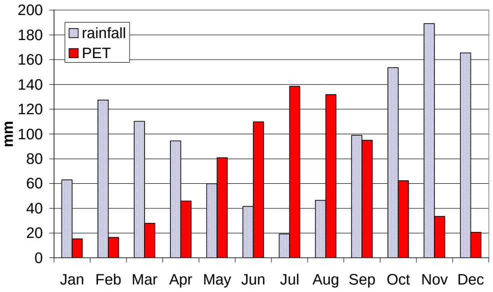


Fig.2: Mean monthly rainfall and mean monthly PET.

The relevant urban drainage network is represented in Fig. 3. Three different urban sub-catchment can be identified, with the sub-catchment B being the most urbanized area, where then the green roof technology is supposed to be implemented for assessment purposes.

At first, an empirical formulation, the classic "Rational Method" is applied to quantify the runoff coefficient reduction associated to the green roof realization. Such an empirical framework is based on the existence of rational runoff coefficients, variable as a function of the surface permeability.

In a second step, a conceptual model is applied to simulate the runoff coefficient reduction. The conceptual framework, allow the possibility to account for the different climate and setting factors that would impact the soil water dynamic of a green roof and, consequently, the runoff coefficient reduction. An analysis of the rainfall characteristic of the studied area, with particular reference to the rain depth-intensity-duration relationships, is preliminary provided, as it represent the basis for successive simulations.

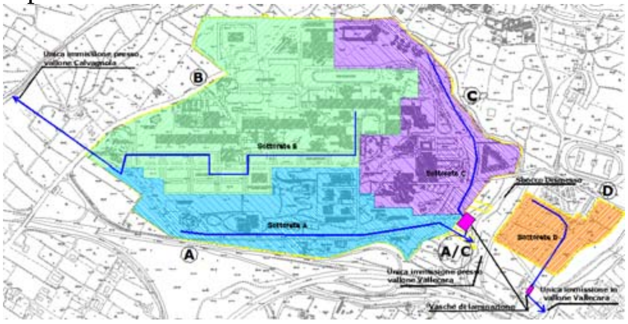


Fig.3: University of Salerno drainage network.

2.1 Analysis of the rainfall characteristics of the study area

To start the analysis of the hydraulic benefits induced by a green roof it is necessary to perform a rainfall characterization of the study area. Three raingauge stations have been installed over the campus area. Observed rainfall data observed at the "Faculty of Engineering Building" station have been here used, as they are representative of the sub-catchment area B. Rainfall data have been recorded with a five minutes time step, during the time period 2004-2008. Rainfall data aggregated at 5 min, 10 min,15min, 20min, 25min, 30min, 1h, 2h, 3h, 6h, 12h and 24hhave been considered, as their representation and statistics would be important for successive simulations. A statistical analysishas been performed, assuming that, for each duration, rainfall data are distributed according to the Gumbel probability function. The rainfall intensity-duration curves for different return period are illustrated in the following Fig. 4.

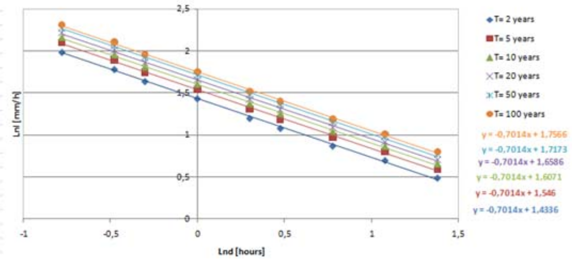


Fig.4: Rainfall intensity-duration curves

2.2 Green roof technologies reference settings

In Italy, the construction of a green roof is regulated by the rule UNI 11235: 2007"Guidelines for the design, implementation, testing and maintenance of green roofs" that definesa green roof a superstructure on top of a traditional roof which includes several layers.

The top layer is the vegetation one. The type of vegetation here selected is grass and herbaceous plants because they are typical of the studied area.

The second layer is the vegetation support layer where the rain water is stored and where the roots of plants of the upper layer grow, the chosen material is common agricultural ground. Entering with the chosen kind of vegetation, in the table given by the law, we try a depth of this layer of 15 cm.

Italian guidelines suggests to adopt a coefficient of discharge of0.35 for a layer with a depth of 15 cm and roof slope lower than 15 degrees.

The range of water storage capacity is borrowed from the German law DIN 4095 "Drainagefor the protection of the plant construction, planning, determination, and execution of requirement" that suggest values from 35% to 65%. The other layers that are less important in evaluation of hydraulic advantages are:filter course, the drainage layer, root protection layer, waterproofing membrane [2], [3].

3 The rational method

The rational method is a simple technique for estimating a design discharge from asmall watershed. It was developed by Kuichling ([7]) for small drainage basins inurban areas. The formula is

$$Q = c*i*A \tag{1}$$

where:

Q = design discharge

c = runoff coefficient

i = design rainfall intensity

A = watershed drainage area

The runoff coefficient, c, is a dimensionless ratio intended to indicate the amount ofrunoff generated by a watershed given an average intensity of precipitation for a storm. The Rational method runoff coefficient is a function of the soil type and drainage basin slope.

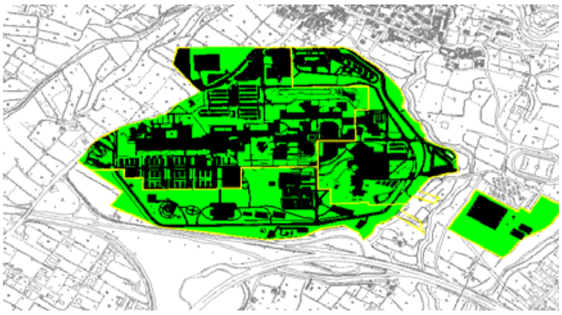


Fig. 5: Impervious areas (in black) and permeable areas (in green) for the campus of Fisciano.

For the investigated urban environment, three main surface cover can be identified which are, according to the classification given for the application of the rational method, concrete streets, concrete roofs and lawns dominated surfaces (Fig. 5).

The rational method considers a runoff coefficient of about 0.7-0.95 for both concrete streets and roofs (the most impervious), and a runoff coefficient of about 0.05-0.35 for lawns areas (the most pervious). It is possible to calculate the average runoff coefficient $\varphi$for non-homogeneous areas considering:

$$\varphi = c_{imp}\frac{A_{imp}}{A_{tot}} + c_{per}\frac{A_{per}}{A_{tot}} \tag{2}$$

where:

c_{imp} is the runoff coefficient for impervious areas (concrete streets and roofs), set equal to 0.8

c_{per} is the runoff coefficient for pervious areas (lawns grass), set equal to 0.1

A_{imp} is the impervious areas, equal to 19.60 ha

A_{per} is the pervious areas, equal to 9.62 ha

The average runoff coefficient is equal to 0.56. If the green roof technology is widespread implemented for each of the roof buildings included in the sub-catchment B under investigation, the impervious area decreases as the roof surfaces has to be included into the pervious area class (Fig. 6).

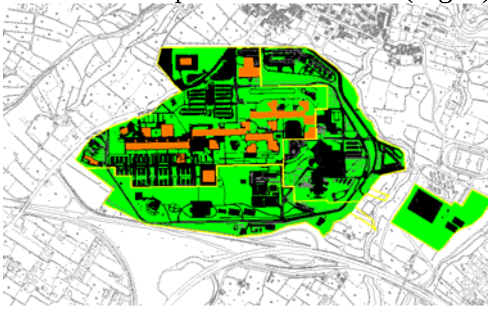


Fig. 6: Impervious areas (in black),permeable areas (in green), green roofs (in orange) for the campus of Fisciano

In this case, the average runoff coefficient is:

$$\varphi = c_{imp}\frac{A_{imp}}{A_{tot}} + c_{per}\frac{A_{per}}{A_{tot}} + c_{green}\frac{A_{green}}{A_{tot}} \tag{3}$$

where:

c_{imp} is the runoff coefficient for impervious areas (concrete streets), set equal to 0.8

c_{per} is the runoff coefficient forlawns grass pervious areas, set equal to 0.1

c_{green} is the runoff coefficient forgreen roofs pervious areas, set equal to 0.1

A_{imp} isconcrete streets the impervious areas, equal to 14.80 ha

A_{per} is thelawns grass pervious areas, equal to 9.62 ha
A_{green} is the pervious areas, equal to 4.80 ha

The average runoff coefficient is in this case equal to 0.45. According to the rational method, the widespread implementation of the green roofs facilities causes a reduction of the runoff coefficient of about 20%, essentially originated by the increase of the permeable surfaces, accordingly to the sustainable stormwater management principles.

4 The conceptual framework

To quantify the benefit that agreen roof cover can provide, compared to a traditional concrete roof, a conceptual water balance framework “LANGZEIT” has been applied. LANGZEITis a conceptual model provided by the faculty of engineering of the University of Applied Sciences of Trier (Germany). This program is used to simulate the physical processes for anhydrological system,which, in the case of a green roof cover, is the vegetation support layer. The term given as input are:

- Precipitation-P

We use the rainfall data(rainfalldepth) provided by the recording raingauge on the building of the facultyof engineering. The provided data are the rainfall heights for every 10 minutesduring the 5 years of observation from 2004 to 2008.

- Maximum Water Storage volume-W

It is sum of two terms, the first one is valid only for the green roof and is the volume of water which is stored in the vegetation support layer, given multiplying the volume of layer by the water storage capacity.The second term is the storage volume due to the initial loss, generally it can be calculated by multiplying the area of the surface inanalysis (6940 m^2 for building engineering) by the initial loss value of the rain "I_a".To estimate "I_a" we use CN model that asserts:

$$I_a=0.2\cdot S \tag{4}$$

Where S is the maximum specific volume (expressed in mm) of water that thesoil can hold in saturated conditions. The value of S is normally given, usingan intermediate parameter, that is Curve Number (CN), according to the relation:

$$S=(25400-254CN)/CN \tag{5}$$

The CN parameter is a dimensionless number that is linked to the kind of the soil that is common agricultural ground (kind D) and to the use of ground that is farmland for green roofs and impervious car parks for traditional roofs. CN is 81 for green roof and 98 for traditional roof. Finally the values of Ia are 12mm for green roofs and 1 mm for traditional roofs.

- Evapotranspiration- ET

The evapotranspiration is considered in the program through the yearly average hydrograph (Fig. 7). Observed data of actual evapotranspirationare available for the studied area where for the period 2008-2011 a micrometeorological weather station has been installed ([11]).

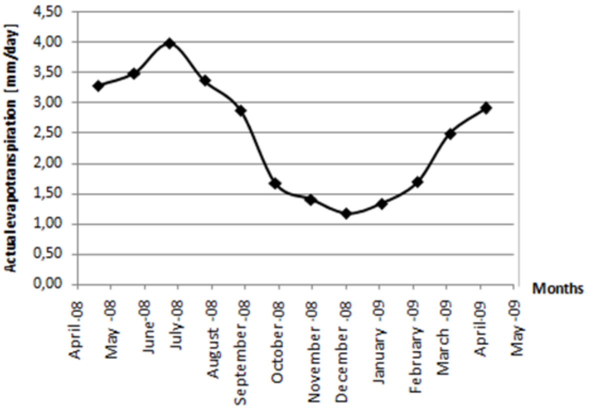


Fig. 7: The yearly average hydrograph of actual evapotranspiration

- Overflow

This term is important because it provides the load that goes to insist on the drainage network. It is provided by the following balance equations on which the program is set:

- When $V_{t+1} = V_t + P\text{-}ET \leq W$ then: $OV = 0$ (6)
- When $V_{t+1} = V_t + P\text{-}ET > W$ then: $OV = V_{t+1}\text{-}W$ (7)

where:

V_t is the volume of storage in the layer at time "t". At t = 0 there is $V_o = 0$

More input data are needed for simulation purposes are the depth of the vegetation support layer, the climatic factor, the initial loss.As the results of the simulations are sensitive to such variables, the values used are described and commented in the following paragraphs.

4.1 Simulation results

The “LANGZEIT” is applied to characterize both the long term average and the event scale benefit associated to the use of the green roofs facilities. Increases in evapotranspiration losses as well as reduction of overflow production, along with the variability of the model parameters are in the following discussed.

4.1.1 Long term simulations

In long termsimulation, the whole period of observation, from 2004 to 2008, has been considered. The findings of a longterm balance are used for an average characterization of the site and to quantify the reduction of runoff during a medium to long time window, so for this simulation it is not important to see how the hydrological response of the green roof changes by varying the values of the several design parameters. Thus a single set of model parameters are used. For the water storage capacity a value of 50% is considered, as it represent an average of the values recommended by the regulations, ranging from 35-65%. The depth of the support layer is fixed in 15 cm, as it represent an average depth measure.

Long term simulations show the differences in evapotranspiration losses and overflow production, comparing traditional concrete and green roof structures. Results are illustrated in Table 1. In the case of green roof facilities, the evapotranspiration losses increase of about 32%, as the existence of the support vegetation layer enhances soil water content evapotranspiration. The evapotranspiration increase is balanced by a consequent reduction in runoff production. As for traditional concrete roofs and green roofs, respectively the 58% and the 90% of total rainfall became overflow, it is possible to say that long term simulation provide a reduction of the runoff coefficient of about 30%. Such a decrease is larger than the one considered by the rational method application but, compared to the rational method itself, has a more oriented physical base.

Table 1: long term simulation results

50 % water storage capacity				
%	green roof	traditional roof	OV reduction	ET increase
ET	42	9,7		32,3
OV	58	90,3	32,3	

4.1.1 Event scale simulations

Much more relevant is the assessment of the dynamicsthat occur during a single event because to design the pipe of the urban drainagesystem, the maximum instantaneous flow of the critical event has to be designed.So simulations about single events were furthermore performed, referring to short (duration of 10 minutes) and high-intensity (142 mm/h) events, long (3 days) and low-intensity (2 mm/h) ones and finally events with medium duration (6 hours) and intensity(18 mm/h).considered event type have been selected according to the rainfall characterization provided in the previous paragraph for the studied area.

Because of the importance of this type of simulations, it would be appropriate to evaluate the influence of several design factors on the reduction of runoff production, with a specific interest in understanding the impact of the water storage capacity and the depth of the support layer, as their combination provide an estimation of the available volume of soil available for water storage.

The impact of the vegetation support layer, using the value of water storage capacity of 50%, is represented in the following Fig. 8 and Table 2.

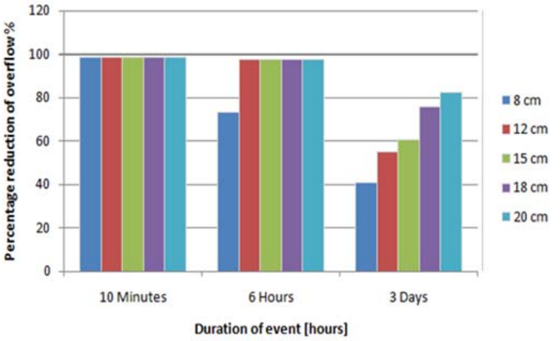
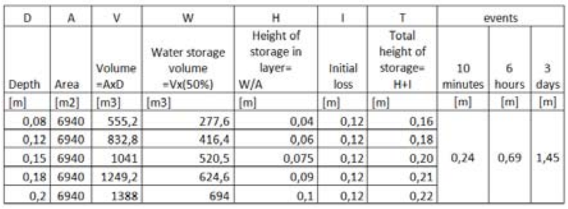


Fig.8:Vegetation support layer depth impact on overflow production

The percentage reduction of the overflow becomes greater when the depth ofvegetation support layer increases because as the depth increases, the watervolume that can be stored increases too.If this condition occur, then a reduction of overflow production would occur, essentially caused by two different coupled mechanism. If a soil layer is available for rainwater storage than a fraction of rain is subtracted to the runoff but this is also reduced because the soil water availability would increase the evapotranspiration process.

Table 2: Total height of storage for varying vegetation support layer depth



D	A	V	W	H	I	T	events		
Depth	Area	Volume =AxD	Water storage volume =Vx(50%)	Height of storage in layer= W/A	Initial loss	Total height of storage= H+I	10 minutes	6 hours	3 days
[m]	[m2]	[m3]	[m3]	[m]	[m]	[m]	[m]	[m]	[m]
0,08	6940	555,2	277,6	0,04	0,12	0,16	0,24	0,69	1,45
0,12	6940	832,8	416,4	0,06	0,12	0,18			
0,15	6940	1041	520,5	0,075	0,12	0,20			
0,18	6940	1249,2	624,6	0,09	0,12	0,21			
0,2	6940	1388	694	0,1	0,12	0,22			

Overall it appear that when the duration ofrainfall event increases, the percentage reduction of overflow decreases and consequently there will be a larger quantity of water flowing into the urban drainage system network. Specifically for events with durations of 10 minutes, the reduction is of about 100% for each value of the depth because events have a small entity so the rain volume can be totally contained in the total height of storage, while the remaining part of the rain volume will does evapotranspirate. For events with duration of 6 hours, the overflow reduction ranges from 97.9% to 73.3%, while when the time interval is of 3 days, the reduction is in the range between 82.6% and 41.1%. for intermediate and low intensity events, the impact of soil depth is larger. The design rain heights related to these events are such that they cannot be completely stored in total height of storage, the evapotranspiration loss is not able to balance the rain volume thus a residual volumeof overflow will flow towards the drainage system. This volume of overflow become greater when value of height of rain and duration of the event increase and so on the contrary the percentage of reduction of overflow is less when the rain event duration is longer.

The impact of water storage capacity, using the value of depth of 15 cm, is instead represented in the following Fig. 9 and Table 3.

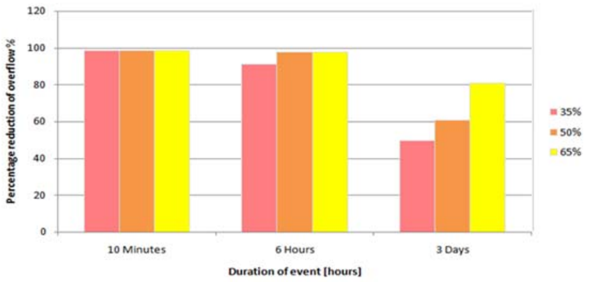
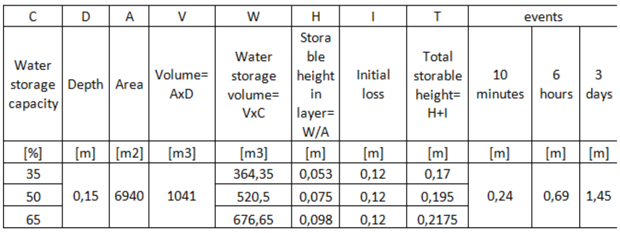


Fig. 9: Influence of depth of water storage capacity in overflow production

Table 3: Total height of storage for varying water storage capacity



C	D	A	V	W	H	I	T	events		
Water storage capacity	Depth	Area	Volume= AxD	Water storage volume= VxC	Storable height in layer= W/A	Initial loss	Total storable height= H+I	10 minutes	6 hours	3 days
[%]	[m]	[m2]	[m3]	[m3]	[m]	[m]	[m]	[m]	[m]	[m]
35	0,15	6940	1041	364,35	0,053	0,12	0,17	0,24	0,69	1,45
50				520,5	0,075	0,12	0,195			
65				676,65	0,098	0,12	0,2175			

When water storage capacity of the roof increases, the percentage reduction ofoverflowincreases too, because the total height of storage where the height of rainmust be contained becomes bigger and a smaller quantity of water will flow into thedrainage network system.

The percentage reductionappear to decrease for low intensity events. Specifically, for events with a duration of 10 minutes, thereduction is of about 98.5%, regardless to the storage capacity. For events with a duration of 6 hours, the percentage variesfrom 91.4% to 97.9% whilst for long duration events the reductionranges from 49.8 to 80.9%.

After observing the impact of the single variable on the green roof water balance,to evaluate the range of effectiveness of this structure, we simulate what happenswhen we vary in combined way all the parameters so we can see what is theworst simulation condition. The results are illustrated in the following Fig. 10.

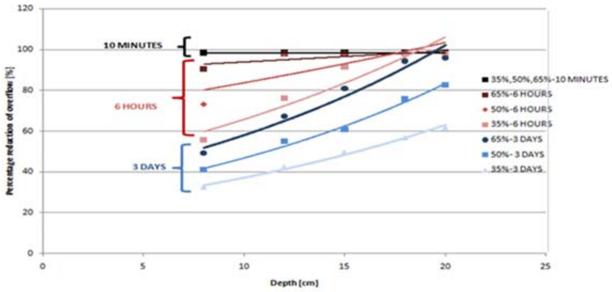


Fig. 10: Overview of percentage reduction of overflow

Short duration events appear not to be affected neither by the soil depth nor by the storage capacity. For such conditions, almost all of the rainfall volume is stored into the soil layer, with a reduction of about 98%. Progressively increasing the duration of the rainfall events, the storage volume represent an increasingly important parameter. Long duration events appear to be the events type with the largest fraction of runoff reduction, thus represent the simplest events to be managed by the green roof facilities. For these events type the largest percentage of runoff reduction of about 95.8% is obtained combining the largest soil depth and storage capacity.

4 Conclusion

The construction of a green roof involves beneficial effects of ecological and energetic type but above hydraulic advantages compared to a traditional concrete roof in terms of urban stormwater management. Green roof facilities act as a reduction of impervious surfaces where the largest, or almost integrally, the rainfall volumes produces runoff flowing into the urban drainage system. The current paper has focused on the analysis of the impact of green roof construction on stormwater production. A particular case study has been selected to this purpose, the campus of the University of Salerno, located in Southern Italy, characterized by a typical Mediterranean climate. Two different approaches have been applied and for each approach the impact has been measured by the runoff coefficient reduction. The traditional rational method quantify the reduction of the runoff coefficient in 20%. This reduction, is basically and only provided by an reduction of the computed impervious areas, featured by the largest runoff coefficient. The runoff production decrease has been further determined, on a more physical base, considering the soil water balance of the vegetation support soil layer. Long term simulations provide a reduction in the runoff coefficient up to 30%. A large variability in the hydrological response of a green roof has instead appeared in the case of event scale simulations. The corresponding runoff coefficient reduction is extremely uncertain. Short duration events appear to be completely managed by the green roof structure, regardless to the technical setting, whilst, for increasing event duration, large soil depth and storage capacity are needed to efficiently manage stormwater production. The large uncertainty and the strong dependence on climate feature and technical settings require a more detailed investigation.

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Acknowledgment:

The author would like to thank Mr. A. Vitale of the Technical office of University of Salerno, who provided all the necessary data to perform the presented analysis.