Green roofs hydrological performance under different climate conditions

MIRKA MOBILIA, ANTONIA LONGOBARDI
Department of Civil Engineering
University of Salerno
Via Giovanni Paolo II, 132, 84084 Fisciano (SA)
ITALY
mmobila@unisa.it
JOACHIM FRIEDRICH SARTOR
Department of Civil Engineering
Hochschule Trier
Schneidershof, D-54293 Trier
GERMANY

Abstract: - Green roof can provide a significant reduction of stormwater runoff in urban areas where stormwater management is increasing because urbanized areas are quickly replacing natural places with a consequent huge increase in impervious surfaces. In this study, runoff reduction assessment for a virtual green roof is provided under different weather conditions, with special reference to the characteristics of precipitation and evaporating power of the atmosphere.
In particular, the Mediterranean and Oceanic climate settings have been considered, with the use of local weather data to run long term, seasonal and single events simulations. On short time scales simulations, the virtual green roof performs similarly as the runoff reduction approaches a total mitigation. On the long term time scales, the green roof provides good performances in both climatic conditions, even though it seems to outperform in northern latitude climates, as in some seasons there can be a total mitigation of runoff. To improve the performances, in terms of runoff reduction, of Mediterranean areas, which amount to 60%, the depth of the greening rooftops and therefore its weight has to considerably increase, entailing an increase green infrastructure and underlying traditional concrete roof costs.

Key-Words: - Green roofs, stormwater management, climate impact, sustainable urban drainage.

1 Introduction

Green roof is a particular constructive technique and an important part of the Sustainable Urban Drainage Systems (SUDS) concept [1]. They consist of a range of techniques and management practices used to drain surface water in a more sustainable manner than traditional solutions. Their role is reducing the amount of surface water run-off and so restoring as possible the natural, pre-development drainage and flow regimes of the considered area. SUDS also have a role in improving the quality of the run-off from impermeable surfaces and the nature conservation/biodiversity, particularly in urbanized areas. Green roof system is well-known across the world as a low impact tool aiming at different purposes. It is used to manage urban heat island effects and to reduce energy use in buildings too([2], [3]) with consequent economic savings but this infrastructure also induces important hydraulic advantages: runoff reduction, delay time increase [4] and peak flow attenuation [5] as a superposition of the previous effects.

The first benefit is due to the layers of a green roof that can storage a part of precipitations during a rainfall event in fact they create an accumulation area for the meteorologic water and then a part of stored rainwater can also return to the natural cycle by evaporation and transpiration. The second benefit of the eco roof is due to its retention capacity because water is stored and takes some time to move from the drainage layer where it is contained, to the channel and then into the drainage network. It is laminated and distributed in time so that the volumes going into the delivery body or facilities are regularized and the roof delays the peak outlet discharge. In traditional roofs instead, rain water goes almost instantly to the channels and the runoff production is not delayed in time respect to the event. Many studies have shown that green roofs can reduce peak flow rate by 22 to 93% and delay the peak flow by 0 to 30 min [6]

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 ([7], [8], [9], [10], [11]).

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.

A lot of studies during the last years have analyzed the performance of green roofs under different climate conditions ([12], [13], [14]). But none of these has simultaneously investigated how green roof hydrological performance changes in different climate conditions.

To predict hydraulic and hydrological green roof performances, a large number of methods and approaches are reported in the scientific relevant literature. Several authors proposed water balance models ([15], [16]), others proposed approaches based on the rational method [17] and Curve Number method ([18], [19]). In literature there are also various studies about computational and mechanistic methods used for assessing efficiency of the vegetated covers, e.g. HYDRUS-1D ([20], [21]), Long-Term Hydrologic Impact Assessment-Low Impact Development 2.1 or simply L-THIA-LID 2.1 [22], Analytical Probabilistic Stormwater Models for Green Roofs or APSWM [23]. Other methods address the solution of the Green-Ampt infiltration equation or are based on regression analysis [24], analysis of variance (ANOVA) [25], hydrograph approach [26], cascades of linear [27] and nonlinear reservoirs [28] and Intensity–Duration–Frequency curves for rainfall–runoff prediction [29]. More sophisticated approaches have been also used to study the hydrologic benefits of green roofs, for example the commercial software Mike urban which includes a model referred to NAM (Nedbør-Afstrømnings-Model/rainfall–runoff model), developed to compute the runoff from pervious areas [30] or the Storm Water Management Model (SWMM) ([31], [32]) which is a dynamic rainfall-runoff-subsurface runoff simulation model used for single-event to long-term (continuous) simulation of the surface/subsurface hydrology quantity and quality from primarily urban/suburban areas.

The reported study aims to underline the variable response in runoff reduction of a green roof in particular under two different climatic regimes: the Mediterranean and the Oceanic climate. For this purpose, a number of simulations have been performed, on both the event and the long term scale, using the software code "LANGZEIT" [33, 34]. The model is based on a conceptual water balance approach and simulations refer to a virtual green roof infrastructure.

2 Simulation model

To evaluate the different performances in runoff reduction for the virtual green roof under the two different climatic conditions, a conceptual German model, "LANGZEIT", based on a water balance approach, is used. The virtual roof is supposed to have an area of about 100 m^2 and a depth of the layers of 15 cm. The conceptual model can simulate the physical processes for an hydrological system, which, in the present study is the virtual green cover. More details of model applications, for event scale and long term scale, are also provided in Mobilia et al. [35]. It is substantially based on a simple water storage balance where the inputs are precipitation, actual evapotranspiration and initial water storage volume, while the outputs are the percentage of runoff or overflow into the drainage channels. The software output is provided by the following balance equations on which the program is set:

- when $V_{t+1} = V_t + P - ET < W$ then: $R = 0$ (1)
- when $V_{t+1} = V_t + P - ET > W$ then: $R = V_{t+1} - W$ (2)

where:

-W is the water Storage volume
- ET is the evapotranspiration
- P is the precipitation
- V_t is the water storage volume in the layer at the time "t". For t=0, $V_0=0$
- R is the runoff

Results have been summarized in the following paragraphs.

Long-term water balances have been simulated to quantify the reduction of runoff during a medium-long temporal period, whereas seasonal balances have been simulated to evaluate the performances of the green roof during different periods of the year and so under different conditions of temperature and thus of evapotranspiration. Related findings are of particular interest in terms of sustainability of stormwater management. However, much more relevant for drainage system design is the assessment of the dynamics that occur during a single event because in this case, the maximum instantaneous flow of the critical event with an assigned return period has to be considered.

3 Analyzed climatic settings

The climate input data required for the investigations are the precipitation and thermometric regimes.
The simulations are performed under two substantially different weather conditions that are the Mediterranean and the Oceanic ones, so that the different responses in runoff reduction of the virtual green roof can be compared. The Mediterranean climate is characterized by warm to hot, dry summers and mild to cool, wet winters while the Oceanic climate generally features warm (but not hot) summers and cool (but not cold) winters. Two different meteorological stations have then been considered to mimic the climate conditions under study. One of the rainfall monitoring station is located in the campus of University of Salerno in Fisciano, located in Southern Italy with a typical Mediterranean climate. The other one is in Trier, located in Western Germany with a typical oceanic climate.

Fig.1:Meteorological stations location.

For the long term simulation, observed rainfall time series are available at 10 minutes time resolution, during a period of 3 years from 2004 to 2007 ([36], [37], [38]). For each individual year of observation, the hydrologic year is considered, from the month of October of the current year to the month of October of the following year, to consider that after the dry season the ground of the roof has a reduced content of water and the green cover can be considered to have an high water storage capacity (65% considered in the simulations). For each year the rainfall depth in Salerno station is about the double of the depth in Trier station, with an exception in the period 2006/2007, where rainfall occurrences in Salerno have been scarce (Fig.2).

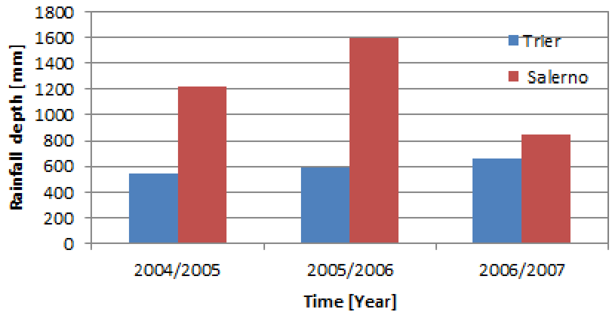

Fig.2:Annual rainfall amount

Seasonal simulations use rainfall data series from 23rd of December to 20th of March for simulations related to winter season, from 21st March to 21th of June for Spring, from 22nd June to 22nd of September for Summer and from 23rd of September to 22nd of December for Autumn.
Also the analysis performed using a seasonal scale show that rainfall during each season is more consistent in Mediterranean climates than in Oceanic ones (Fig.3).

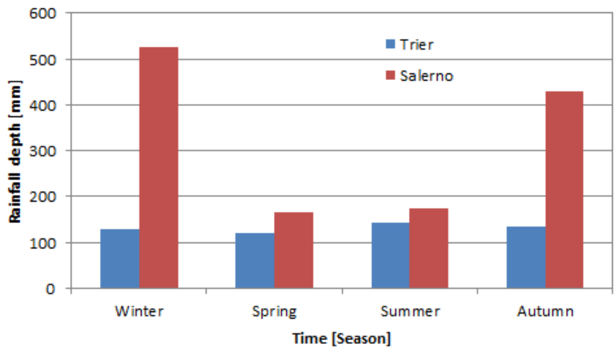

Fig.3:Averge seasonal rainfall pattern

Event scale simulations are performed, referring to short and intensive events (duration of 10 minutes), long and low-intensity (duration of 1 day) ones and finally events with medium duration (6 hours) and intensity. For a given duration, the depth of rain (Table 1) is provided by the depth-duration curves (Fig.4) for Trier and Fisciano gauging stations. Maximum annual depths with an assigned duration, have been considered for the current simulations.

Table 1: Depths of rain during considered events.

		Depth [mm]	
		Trier	Fisciano
Duration	10 minutes	7,9	16,9
	6 hours	19,0	42,9
	1 day	34,7	67,9

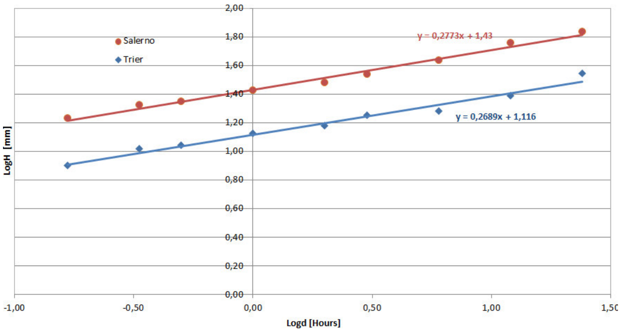

Fig.4:Rainfall depth-duration curves of Salerno and Trier.

Also for what concerns the short daily and sub-daily time scale, investigated locations are quite different. For each duration of the events, the rainfall depth in Trier is about halved compared to the depth in Salerno (Fig.5).

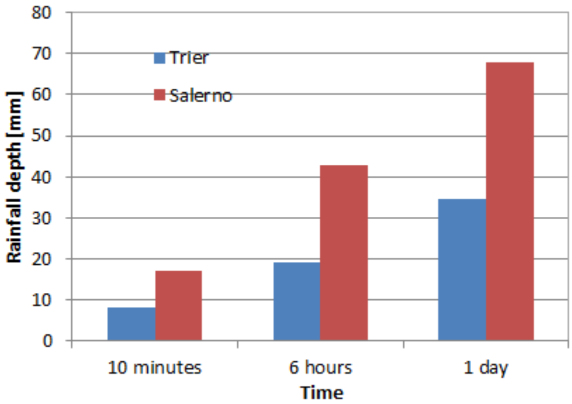

Fig.5: Single events rainfall amount.

To account for evapotranspiration losses, an yearly average local hydrograph has been used. The hydrograph relative to Salerno meteorological station (Fig. 6) has been built using the observed data of actual evapotranspiration recorded during the period 2008-2009 by a micrometeorological weather station located in the area [39]. For the German site the actual evapotranspiration monthly pattern (Fig.4) has been derived by the German Advisory Leaflet DWA-M 165 "storm runoff simulation in urban areas". The maximum value of actual daily evapotranspiration in Salerno is 3,98 mm/day and the maximum value in Trier is 3,2 mm/day. They both occur during the month of July. The minimum value in Salerno is 1,18 mm/day during December, while the minimum value in Trier is 0,5 mm/day during December and January.
The evapotranspiration process is confirmed to be more effective during the whole year in Mediterranean area than in high latitude areas.

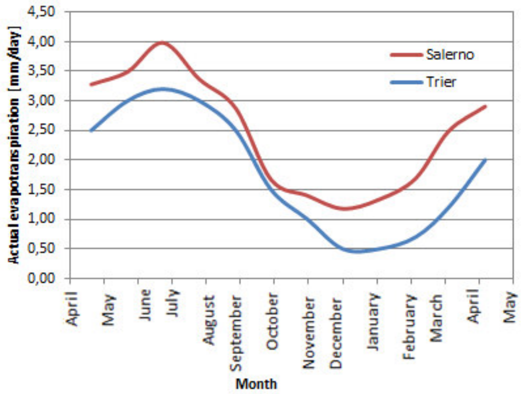

Fig.6:Meteorological stations yearly average actual evapotranspiration hydrograph.

Other terms of the water balance to be set in the simulations are the soil depth and the (initial) water storage volume. As a first step, soil depth of the virtual green roof has been set to 15 cm for both climate conditions. About the (initial) water storage volume it is assessed as the sum of the volume of water stored in the ground of the roof product of multiplying the volume of the layer of the cover by the water storage capacity, and the storage volume due to the initial loss product of multiplying the area of the hypothetic roof by the initial loss value of the rain. The latter term has been calculated using the curve number method linked to the type of the soil and to the use of roof used to set up the green infrastructure, that are respectively common agricultural ground and farmland. Finally the water storage volume is 11 m^3 (Table 2) and it is valid both for the Mediterranean climate and The Oceanic one.

Table 2: Virtual green roof water storage volume

	Water storage	Initial loss
Green roof surface [m^2]	100	
Water storage capacity [%]	65	-
depth of the roof [m]	0,15	-
Initial loss depth [m]	-	0,0125
Volume [m^3]	9,75	1,25
Total volume [m^3]	11	

4 Simulation results
The simulations performed for a long-term time scale from 2004 to 2007 show that annual runoff from a green roof, compared to a traditional concrete roof from which we assumed to have 100% of runoff into the drainage system, is quite large in Mediterranean sites, where also precipitation amounts are larger (Fig. 7). On a long term base, runoff can be reduced by up to 57% in Mediterranean climate whereas in Oceanic climate there can be a reduction of about 90 % (Table 3).

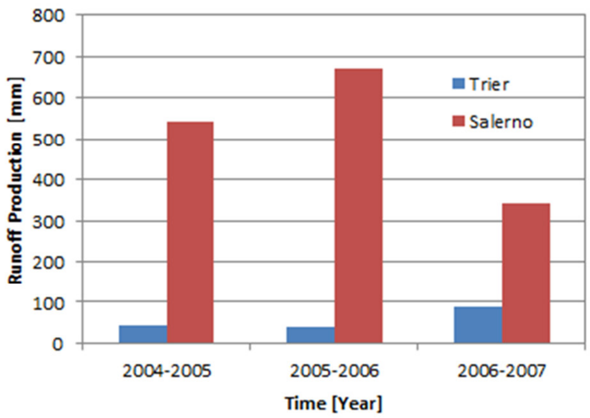

Fig.7:Green roof runoff production under Mediterranean (Salerno) and Oceanic (Trier) climate conditions

By comparing overflow reduction values, it appears that the green infrastructure performance in Mediterranean climate is halved compared to the northern latitude conditions.

Table 3: long term simulation results

	Trier	Salerno
Water storage volume [m^3]	9,765	
depth of the roof [cm]	15	
Area of the roof [m^2]	100	
Initial loss [mm]	12,5	
time series	2004-2007	
Run-off reduction [%]	90	57

Seasonal simulations results provide more insight about the capability in runoff reduction (Table 4). The best performances of the green roof occur during spring and summer in both climates when the complete mitigation of the run-off occurs. There is instead a lower performance in winter when, however, the roof is more effective in Oceanic climate than in Mediterranean one, and the reduction of performance, moving from high to mid latitude areas, ranges from 95.9% to 50% on average. Performances are particularly poor in Autumn, with extremely variable efficiencies from a climate to another one. A better mitigation capacity of the green roof in northern climates is evident, where the run-off reduction is on average 64.4%, compared to 42.7% for southern climate.

Table 4: Seasonal simulations results

		Salerno	Trier	Salerno	Trier
		Runoff reduction [%]		Average runoff reduction [%]	
Winter	2004-2005	45,9	100	50	95,9
	2005-2006	47,2	100		
	2006-2007	57	87,9		
Spring	2004-2005	100	100	100	100
	2005-2006	100	100		
	2006-2007	100	100		
summer	2004-2005	100	100	100	100
	2005-2006	100	100		
	2006-2007	100	100		
Autumn	2004-2005	40	67,6	42,7	64,4
	2005-2006	33,3	66,8		
	2006-2007	54,7	58,7		

These percentages of runoff reduction, obtained considering a small thickness of the layer of the roof, can be further raised, with consequent better hydraulic performances, increasing the thickness of the green cover compatibly with the load bearing capacity of the traditional underlying roof.
Overflow volume becomes smaller when the depth of the eco-roof increases because of an increase in water storage capacity. To achieve the green roof performances obtained with a minimum soil depth of 15 cm in northern latitude climates during a long period of time, the thickness of the soil layer should be considerably increased in Mediterranean climate, reaching a total depth of about 80 cm (Table 5).

Table 5: Changes in run-off reduction, for different depths of the green roof

Climatic area	Depth [cm]	Run-off reduction [%]
Trier	15	90,6
Salerno	15	57,5
	30	59,1
	50	76,3
	70	86
	80	89,5

The event scale simulations show that the green roofs technology is very effective in runoff reduction during single rainfall events for a very large range of duration. Green roofs allow, in this case, to reduce this term of the water balance of 100% (Tab.5) both during short events with duration of 10 minutes and long ones with duration of 1 day ones and medium events with duration 6 hours. Assessment are practically coincident for both Mediterranean and Oceanic climate conditions.

Table 6: Single events simulation results

		Trier	Salerno
		Runoff reduction [%]	
Duration	10 minutes	100	100
	6 hours	100	100
	1 day	100	100

5 Conclusion

The current paper has investigated the impact of climate conditions in the hydrological performance of green urban infrastructures, with particular reference to a virtual green roof.

The results reported demonstrate that green roofs perform differently in different climates. Both seasonal and long-term simulation indicate that hydrological performances of the virtual green roof are more effective in high latitudes climate than in mid ones.

The long period runoff reduction in Mediterranean climate is almost half the ones in Oceanic climate. For the former climate regime, it can reach reductions up to 57% while in the latter climate regime the reduction amounts to about 90%.

The seasonal simulations show a comparable efficiency during summer and spring in which for both climate areas, a complete mitigation of run-off occurs but better performances take place for northern latitude climates in Winter and Autumn where reduction of runoff is larger than 50% compared to Mediterranean conditions.

The single event simulations provide a total reduction of the overflow for events with all the chosen durations and for both Northern as well as Southern Europe climate areas. For a comprehensive interpretation of the results, improvements in the simulations would be needed. It would be indeed necessary to understand if the outperformance in Oceanic climate is driven by an evapotranspiration process which has different characteristic from the one that takes place in Mediterranean climate, or if the green roof performance is instead driven by geometrical construction issues. It has appeared in fact that to achieve the green roof performances obtained with a minimum soil depth of 15 cm in northern latitude climates, the thickness of the soil layer should be considerably increased in Mediterranean climate, reaching a total depth of about 80 cm. This would be an inconvenient solution because it would entails an huge overload for the existing laying structure for which expensive structural reinforcements should be necessary.

Even though the hydraulic benefits of green roof technology are better under Oceanic climatic it remains a valid option for runoff reduction in urban areas if compared to a traditional concrete roof in Mediterranean areas too, where however the reduction ranges from a minimum of 33% in Autumn to total mitigation of overflow in Summer and Spring.

References:

[1] Fletcher T.D., et al., SUDS, LID, BMPs, WSUD and more- The evolution and application of terminology surrounding urban drainage. Urban Water Journal, Vol.12, 2015, pp. 525-542

[2] Voll H., Erkki S., Mati S., Analysis of Passive Architectural Roof Cooling Potential to Decrease the Cooling Demand for Northern European Office Buildings Based on Energy Modelling and Laboratory Tests, WSEAS Transactions on Environment and Development Vol.7, 2011, pp. 136-145.

[3] Lacrodc R.N., Stamatiou E., Green roofs- a 21 st century solution to the urban challenges of green space, air pollution, flooding & energy conservation, WSEAS Transactions on Environment and Development Vol. 2.6, 2006, pp. 909-918.

[4] Trinh D.H., Chui T.F.M., Assessing the hydrologic restoration of an urbanized area via an integrated distributed hydrological model, Hydrology and Earth System Sciences, Vol.17, 2013, pp. 4789-4801.

[5] Gibler, M.R., Comprehensive Benefits of Green Roofs. In World Environmental and Water Resources Congress 2015: Floods, Droughts, and Ecosystems, 2015, pp. 2244-2251

[6] Yanling L., Babcock R.W., Green roof hydrologic performance and modeling: a review, Water Science & Technology Vol. 69, 2014, pp. 727-738.

[7] Bengtsson L., Grahn L., Olsson J., Hydrological function of a thin extensive green roof in southern Sweden. Nordic Hydrology, Vol.36, 2005, pp. 259–268.

[8] Guo Y., Zhang S.& Liu S. Runoff Reduction Capabilities and Irrigation Requirements of Green Roofs, Water Resources Management, Vol. 28, 2014, pp. 1363–1378.

[9] Hilten R.N., Lawrence T.M., Tollner E.W., Modeling storm water runoff from green roofs with HYDRUS-1D, Journal of Hydrology, Vol. 358, 2008, pp. 288–293.

[10] Kohler M., Schmidt M., Grimme W., Urban water retention by greened roofs in temperate

and tropical and climate. Technology Resource Management and Development, 2001, pp. 151-162.
[11] Sartor J., The significance of the water balance in sustainable storm water management *(in German)*, Flood control today - sustainable water management, Erich Schmidt Publishers, Berlin, 2001, pp. 287-308
[12] Dvorak B., Volder A., Rooftop temperature reduction from unirrigated modular green roofs in south-central Texas Urban, Urban Green, Vol.12, No.1, 2013, pp. 28-35
[13] Farrell C., Mitchell R.E., Szota C., Rayner J.P., Williams N.S.G., Green roofs for hot and dry climates: Interacting effects of plant water use, succulence and substrate, Ecological Engineering, Vol.49, 2012, pp. 270-276
[14] Fioretti R., Palla A., Lanza L.G., Principi P., Green roof energy and water related performance in the Mediterranean climate, Building and Environonment, Vol.45, 2010, pp. 1890-1904
[15] Halmova D., Pekarova P., Pekar J., Miklanek P., Uncertainties in Runoff Components Modelling and Frequency Analysis, WSEAS Transactions on Environment and Development, Vol.10, 2014, pp. 374-381.
[16] Jarrett A.,Hunt W., Berghage R., Annual and individual-storm green roof stormwater response models, In Annual International Meeting. Sponsored by ASABE, Oregon Convention Center, Portland, Oregon, Vol. 12. 2006.
[17] Moran A.C., Hunt W.F., Smith J.T., Green roof hydrologic and water quality performance from two field sites in North Carolina. In Proceedings of the 2005 Watershed Management Conference-Managing Watersheds for Human and Natural Impacts: Engineering, Ecological, and Economic Challenges, 2005, pp. 1175-1186
[18] Carter T., Jackson C.R., Vegetated roofs for stormwater management at multiple spatial scales, Landscape and urban planning, Vol. 80, 2007, pp. 84-94.
[19] Getter K.L., Rowe D.B., Andresen J.A., Quantifying the effect of slope on extensive green roof stormwater retention, Ecological Engineering, Vol. 31, 2007, pp. 225-231.
[20] Palla A., Gnecco I., Lanza L. G., Compared performance of a conceptual and a mechanistic hydrologic models of a green roof, Hydrological Processes Vol. 26.1, 2012, pp. 73-84.
[21] Hakimdavar R., et al., 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, Vol.73 ,2014, pp. 494-508.
[22] LiuY., Bralts V.F., Engel B.A., Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model, Science of The Total Environment, Vol. 511, 2015, pp. 298-308.
[23] Guo Y., Shouhong Z., Shuguang L., Runoff Reduction Capabilities and Irrigation Requirements of Green Roofs, Water resources management, Vol. 28, 2014, pp.1363-1378.
[24] Stovin V., Vesuviano G., Kasmin H., The hydrological performance of a green roof test bed under UK climatic conditions, Journal of Hydrology, Vol. 414, 2012, pp.148-161.
[25] Mentens J., Raes D., Hermy M., Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century?, Landscape and urban planning, Vol. 77, 2006, pp. 217-226.
[26] Villarreal E.L., Bengtsson L., Response of a Sedum green-roof to individual rain events, Ecological Engineering, Vol. 25, 2005, pp. 1-7.
[27] Zimmer U., Geiger W.F., Model for the design of multilayered infiltration systems, Water science and technology, Vol.36, 1997, pp. 301-306.
[28] Kasmin H., Stovin V., Hathway E., Towards a generic rainfall-runoff model for green roofs, Water Science and Technology, Vol. 62, 2010, pp. 898-905.
[29] Bengtsson L., Peak flows from thin sedum-moss roof, Nordic Hydrology, Vol.36, 2005, pp. 269-280.
[30] Locatelli L., Markb O., Mikkelsena P.S., Arnbjerg-Nielsena K., Jensenc M.B., Binninga P.J., Modelling of green roof hydrological performance for urban drainage applications, Journal of Hydrology, Vol. 519, 2014, pp. 3237-3248.
[31] Versini P.A., Petrucci G., De Gouvello B., Green-roof as a solution to solve stormwater management issues? Assessment on a long time period at the parcel scale, IAHS, Vol.364, 2014, pp. 536-543
[32] Alfredo K., Montalto F., Goldstein A., Observed and modeled performances of prototype green roof test plots subjected to simulated low-and high-intensity precipitations in a laboratory experiment, Journal of

Hydrologic Engineering, Vol.15, 2009, pp. 444–4

[33] Gottesch, G.; Zimmer, M., Evaluation criteria for concepts of sustainable storm water management (in German), Trier University of Applied Sciences, 2002, pp. 30-81

[34] Nilles, S., Aspects of sustainable storm water management (in German), Trier University of Applied Sciences, 2003, pp. 59-64

[35] Mobilia M., Longobardi A., Sartor J.F., Impact of green roofs on stormwater runoff coefficients in a Mediterranean urban environment. In: N. Mastorakis, F. Batzias and C. Guarnaccia (eds) Recent advances in urban planning, sustainable development and green energy, 2014, pp. 100-106.

[36] Guida D., Longobardi A., Villani P., Hydrological modelling for river basin management in an highly hydro-geological conditioned environment. In: Geo-Environment & Landscape Evolution II. J.F. Martin-Duque, C.A. Brebbia, D. Emmanouloudis, U. Mander (eds), WIT Press, Southampton, Boston, 2006, pp. 283-292.

[37] Longobardi A.. Observing soil moisture temporal variability under fluctuating climatic conditions. Hydrology and Earth System Sciences Discussion, Vol.5, 2008, pp. 935-969.

[38] Longobardi A., Khaertdinova E., Relating soil moisture and air temperature to evapotranspiration fluxes during inter-storm periods at a Mediterranean experimental site. Journal of Arid Land, Vol.7, 2015, pp. 27-36.

[39] Longobardi A. and Villani P., The use of micrometeorological data to identify significant variables in evapotranspiration modeling, Procedia environmental sciences,Vol.19, 2013, pp.267-274