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A Comparison between Conceptual and Physically Based Models in Predicting the Hydrological Behavior of Green Roofs

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Abstract: The evolving climate conditions contribute to increase flooding risk in urban areas. Green roofs are effective tools to control and manage stormwater runoff. With the aim to prevent these damaging events, an accurate modelling of the response of green roofs to storm events becomes essential. The goal of this research is to compare the accuracy of two hydrological models in predicting the behavior of two green roof test beds in terms of runoff production. The test beds are located in the campus of University of Salerno, in a typical Mediterranean climate and they differ for the composition of the drainage layer. The selected models are the SWMM model and the Nash model. They have been calibrated against hourly data of twenty-five rainfall-runoff events observed at the experimental site and compared using a number of goodness of fit indices. The Nash cascade model results to be a very simple but effective approach. No substantial differences can be observed in the behavior of the two green roof plots though they differ for the design characteristics. Finally, the existence of a relationship between the errors and the rainfall characteristics has been found.

Keywords: SWMM; Nash model; Green roofs; Mediterranean climate

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1. Introduction

One of the consequences of the climate change is the increase in the occurrence and intensity of heavy rainfall events. This condition leads to more frequent and severe urban flooding caused by the increasing stormflow volumes that exceed the sewers capacity [1-3]. In order to mitigate the risk of flooding in urban areas, sustainable urban drainage strategies have been proposed, and among these the green roofs [4-6]. The potential of green roofs to manage urban stormwater has largely been proved [7]. In light of this, modeling the hydrological behavior of vegetated covers appears a crucial issue for urban planners, policymakers and developers so as to quantify stormwater management ability of the green infrastructures before retrofitting existing buildings or planning new settlements. To predict the hydrological performances of a green roofs, different models with different levels of complexity have been introduced by several authors [8-10]. Among these, the SWMM model has been here selected due to its widespread use and demonstrated efficiency [11,12]. It has been compared, using a number of goodness of fit indices, with a basic transfer function approach, the Nash model [13], typically used to simulate the hydrological behavior of natural river basins and not yet fully explored for what concerns its implementation in predicting the runoff production from green roof systems [14,15] . The two models have been calibrated against hourly data of twenty-five rainfall-runoff events observed at two experimental green roofs, located in southern Italy, in a typical Mediterranean climate. They are characterized by different composition of the drainage layer that is expanded clay for GR1 and plastic trays filled with expanded clay for GR2. The present research aims, behind a comparative assessment of the ability of conceptual and physically based to simulate the hydrological performance of green roofs, to investigate whether the hydrological behavior of the two experimental plots, in terms of runoff production, differs and quantify this difference, if any. Finally, with a multiple regression analysis, the existence of a relationship between the errors and the rainfall characteristics has been analyzed.

2. Materials and Methods

2.1. Case study

The study site consists of two green roof test beds installed in the campus of University of Salerno [16,17]. They are placed on steel benches with a slope of 1% and an area of 2.5 m^2 (1 x 2.5 m) that are surrounded by perimetral channels. The latter convey the runoff fluxes into a tank located on a scale which measures the weight of the rainwater with 5-minutes time interval. The two green roofs are made up of three layers for a total thickness of 15 cm: the vegetation layer where succulents grow, 10 cm deep support substrate of peat and zeolite required for the root development and a water storage layer of approximately 5 cm. The two benches differ for the construction material of the drainage layer, that is expanded clay for GR1 and a commercial drainage panels with trays filled with expanded clay for GR2 (Figure 1). The meteorological conditions are monitored with a 5 minutes resolution by a weather station equipped with a raingauge, a thermohygrometer and a pyranometer, in addition two soil moisture sensors have been installed in the support layers of each bench. The monitoring campaign has started on 16th February 2017 and it is still ongoing.

(**a**) (**b**)

Figure 1. (**a**) The experimental site; (**b**) Composition of the drainage layers.

2.2. Datasets

Twenty-five rainfall-runoff events have been considered for this study. The events with the highest quality have been selected since they don't have missing values due to temporary failure of the instruments. For each storm event the following three parameters have been evaluated: Rain duration "d", cumulative rainfall "C" and the mean storm intensity "I", while the retention capacity "RC" has been used as indicator of the hydrological performance of the roofs. The events present a minimum and a maximum duration respectively of 60 and 1800 min while the cumulative rainfall ranges between 0.8 mm and 30.2 mm. The average intensity in never less than 0.5 mm/h and never higher than 10.2 mm/h. Finally, the retention capacity reaches at least 6.6% and 2.8% and at most 96.2% and 90.3% respectively for GR1 and GR2. In the table 1, an overview of above cited parameters for each event has been shown:

Table 1. Rainfall/runoff characteristics of the selected events.

Date	25/07/2017	07/09/2017	07/11/2017	10/01/2018	11/01/2018	12/01/2018	16/01/2018	17/01/2018	17/01/2018
d (min)	420	540	360	540	960	300	900	180	60
C (mm)	2.8	4.6	15.2	30.2	20.1	5.3	15.5	1.3	3.6
I (mm/h)	2.0	2.3	9.4	10.2	9.4	2.0	2.8	1.0	3.6
RC_{GR1} (%)	82.4	68.9	36.8	45.2	22.4	85.4	6.6	77.5	77.6
RC_{GR2} (%)	84.0	68.9	2.9	49.0	25.0	88.0	14.4	77.2	83.4

Date	01/02/2018	03/02/2018	07/02/2018	13/02/2018	14/02/2018	18/02/2018	20/02/2018	02/03/2018	03/03/2018
d (min)	300	1200	840	60	240	1800	1080	240	720
C (mm)	3.3	12.4	11.2	0.8	4.8	11.2	11.4	3.3	11.4
I (mm/h)	1.5	3.8	4.8	0.8	2.5	1.3	2.3	1.8	2.3
RC_{GR1} (%)	80.5	36.6	7.0	84.3	81.4	82.5	18.9	38.2	17.7
RC_{GR2} (%)	74.4	42.0	5.6	90.3	76.7	77.6	29.4	40.0	39.1
Date	09/04/2018	17/04/2018	03/05/2018	04/05/2018	23/05/2018	05/10/2018	07/11/2018		
d (min)	180	360	180	300	300	240	360		
C (mm)	6.1	5.8	7.1	1.3	13.0	2.8	16.0		
I (mm/h)	3.6	5.3	4.8	0.5	4.8	1.3	6.4		
RC_{GR1} (%)	80.3	82.7	78.1	96.2	11.4	84.8	25.2		
RC_{GR2} (%)	80.2	79.9	73.9	78.6	40.5	76.0	20.0		

2.3. SWMM and NASH model

The Nash cascade model and the storm water management model (SWMM) have been selected in this study to reproduce the hydrological response at the event scale of the two green roof test rigs in terms of runoff production. The rainfall–runoff conceptual model introduced by Nash [13] considers a linear cascade of n reservoirs with equal storage constant k for derivation of the instantaneous unit hydrograph (IUH). The IUH of the Nash model is given by:

$$h(t) = \frac{t^{n-1}}{(n-1)!k^n} e^{-\frac{t}{k}} \tag{1}$$

where t is the time step.

In this research, the Nash model parameter "n" has been a priori set to 2 by analyzing the hydrograph patterns while the "k" parameter results from the calibration of the model.

The SWMM is a dynamic rainfall–runoff simulation model. It performs a moisture balance tracking the movement of water through each layers of the system. The Bio-Retention module has selected among the LID (Low impact development) controls to simulate the green roofs. It consists of three layers (surface, substrate, and drainage layer). SWMM uses a routing equation to quantify water flow through the surface:

$$Q_s = \left(\frac{S_1}{nA}\right) W D^{\frac{5}{3}} \tag{2}$$

While the Green-Ampt equation is used to simulate the infiltration of the water into the substrate:

$$f = k_{sat}\left[1 + \frac{(\phi-\theta)\psi}{F}\right] \tag{3}$$

Q_s is the surface overflow rate, S_1 represents the surface slope, n is depth of depression storage, A is flow area, W is the subcatchment width, D corresponds to the depth of water above the subcatchment, f stands for the infiltration rate, ksat represents the saturated hydraulic conductivity, ϕ is the soil porosity; θ equals the water content; ψ corresponds to the suction head and F is the cumulative amount of infiltrated water. All the required parameters have been estimated from field measurements, literature, or taken from defaults values, while the suction head has been subject to calibration process.

2.4. Model evaluation

The Nash–Sutcliffe efficiency (NSE) index, the root mean square error (RMSE) and the mean absolute error (MAE) have been used to quantitatively assess how well the observed runoff vales have been reproduced by the applied models for each event. The k and ψ parameters have been iteratively adjusted until the NSE reaches the highest value. The indices have been calculated as follows:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(R_{obs.i}-R_{mod.i})^2}{\sum_{i=1}^{n}(R_{obs.i}-\bar{R}_{obs.i})^2} \quad (4)$$

$$\mathrm{RMSE(mm)} = \left[\frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}}(R_{\mathrm{mod.i}} - R_{\mathrm{obs.i}})^2\right]^{\frac{1}{2}} \quad (5)$$

$$MAE\mathrm{(mm)} = \frac{1}{\mathrm{n}}\sum_{\mathrm{i=1}}^{\mathrm{n}}|R_{\mathrm{mod.i}} - R_{\mathrm{obs.i}}| \quad (6)$$

where n represents the length of the sample, $R_{mod,i}$ and $R_{obs,i}$ respectively represent the modeled and the observed runoff.

An efficiency index equal to one and a value of RMSE and MAE close to zero indicate a perfect match between the simulated and observed runoff.

3. Results and Discussion

The goodness of fit indices reported in Table 2, show the agreement between the modelled and the observed values of runoff. The average values of NSE, higher than 60%, indicates an acceptable level of performances for both models and test benches. The errors are slightly lower for SWMM than for Nash cascade model. Indeed, SWMM returns mean RMSE and MAE of about 0.30 mm and 0.22 mm compared to 0.38 mm and 0.25 mm of Nash cascade model. For what concerns the comparison between the two experimental beds, the indices show very similar errors for GR1 and GR2 which suggests no substantial differences between their hydrological behavior.

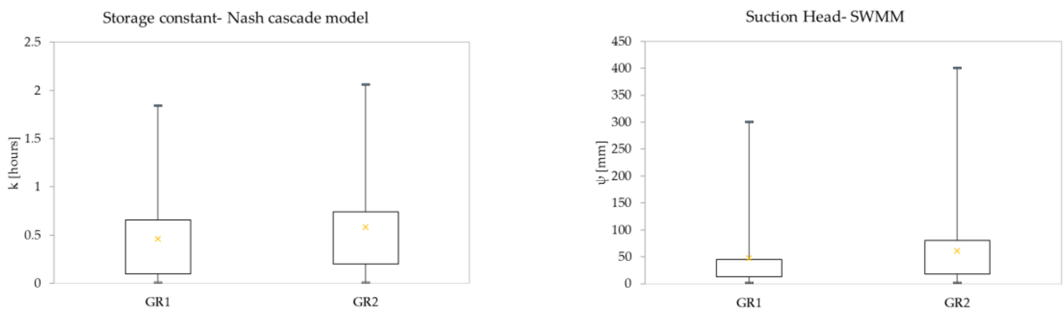
Table 2. The goodness-of-fit indices for the two models.

Event	SWMM-GR1			SWMM-GR2			NASH-GR1			NASH-GR2		
	NSE (-)	RMSE (mm)	MAE (mm)	NSE (-)	RMSE (mm)	MAE (mm)	NSE (-)	RMSE (mm)	MAE (mm)	NSE (-)	RMSE (mm)	MAE (mm)
25/07/2017	0.80	0.04	0.03	0.87	0.03	0.02	0.87	0.03	0.02	0.95	0.02	0.01
07/09/2017	0.78	0.13	0.07	0.74	0.15	0.08	0.39	0.22	0.13	0.51	0.21	0.12
07/11/2017	0.95	0.89	0.78	0.94	1.07	0.85	0.95	0.71	0.47	0.81	1.76	1.07
10/01/2018	0.86	1.14	0.72	0.87	1.01	0.68	0.55	2.03	1.46	0.47	2.01	1.59
11/01/2018	0.89	0.56	0.43	0.82	0.60	0.41	0.91	0.50	0.35	0.93	0.37	0.27
12/01/2018	0.04	0.09	0.07	0.35	0.06	0.05	0.83	0.04	0.02	0.28	0.06	0.05
16/01/2018	0.35	0.86	0.48	0.67	0.47	0.35	0.49	0.76	0.35	0.71	0.43	0.28
17/01/2018	0.54	0.03	0.02	0.25	0.03	0.03	0.81	0.02	0.01	0.82	0.01	0.01
17/01/2018	0.85	0.17	0.12	0.78	0.09	0.07	0.77	0.13	0.10	0.96	0.03	0.02
01/02/2018	0.51	0.11	0.11	0.47	0.08	0.06	0.74	0.06	0.04	0.81	0.04	0.03
03/02/2018	0.90	0.20	0.14	0.90	0.19	0.13	0.82	0.26	0.18	0.78	0.28	0.19
07/02/2018	0.93	0.25	0.21	0.73	0.42	0.29	0.93	0.26	0.18	0.82	0.34	0.23
13/02/2018	0.92	0.01	0.00	0.96	0.01	0.00	0.99	0.00	0.00	-0.12	0.03	0.02
14/02/2018	0.88	0.06	0.05	0.91	0.05	0.03	0.90	0.06	0.03	0.95	0.04	0.02
18/02/2018	-0.23	0.08	0.05	-0.31	0.09	0.06	0.80	0.03	0.02	0.89	0.03	0.02
20/02/2018	0.58	0.34	0.22	-0.16	0.42	0.29	0.92	0.15	0.11	0.83	0.16	0.11
02/03/2018	0.56	0.17	0.10	0.73	0.08	0.06	0.54	0.16	0.09	0.44	0.12	0.05
03/03/2018	0.76	0.35	0.22	0.83	0.20	0.09	0.72	0.37	0.23	0.71	0.26	0.16
09/04/2018	0.54	0.19	0.14	0.73	0.20	0.17	0.97	0.05	0.03	0.87	0.10	0.07
17/04/2018	0.85	0.13	0.08	0.99	0.03	0.02	1.00	0.02	0.02	0.96	0.07	0.04
03/05/2018	0.93	0.11	0.07	0.66	0.24	0.13	0.96	0.08	0.05	0.95	0.09	0.07

04/05/2018	-0.05	0.01	0.01	-0.21	0.03	0.02	0.18	0.01	0.00	0.09	0.025	0.019
23/05/2018	0.91	0.49	0.42	0.83	0.52	0.37	0.12	1.54	1.00	0.38	0.91	0.63
05/10/2018	0.22	0.06	0.04	0.35	0.09	0.05	0.86	0.03	0.02	0.87	0.04	0.03
07/11/2018	0.68	1.16	0.85	0.47	1.64	1.17	0.04	1.88	1.21	0.06	1.94	1.05
MEAN	0.64	0.30	0.22	0.61	0.31	0.22	0.72	0.38	0.25	0.67	0.38	0.25

Concerning the calibrated values of the storage coefficient for Nash model, it can be observed (median values in boxplot of Figure 2a) that the average value of k is higher for GR2 (0.5) than for GR1 (0.46). This result proves that the detention capacity of GR2 is a slightly higher, probably because of the existence of the plastic trays in the panels which stores, retains and delays water until the maximum capacity has reached and runoff begins. The distance between the first and the third quartile illustrated by the boxplot are furthermore similar for the two experimental roofs highlighting a similar variability for the K parameter. Maximum values are also comparable and no outliers have been detected.

As regards the calibration process of SWMM, GR2 exhibits an average value of ψ (61 mm) higher than GR1 (48 mm) (median values in boxplot of Figure 2b). One reason might be that the expanded clay in the modular panels of GR2 are confined within the trays. The compaction in these trays causes a lower porosity than the expanded clay in the drainage layer of GR1 and it is known that under the same water content, the larger the pores, the lower the suction to drain the soil. The interquartile distance in the case of SWMM for GR1 and GR2 is quite different with also quite different maximum values calibrated for the two experimental sites, highlighting a different behavior in terms of calibration for the two GRs.



(**a**) (**b**)

Figure 2. (**a**) Boxplot of calibrated K (Nash model); (**b**) Boxplot of ψ (SWMM model) for both roofs.

In order to improve the descriptive capability of the applied model and taking into consideration the uncertainty in the performances of GRs retention models generated by the specific rainfall properties at the event scale, a multiple regression analysis has been performed in order to investigate the statistical relationships between the errors and the rainfall characteristics (Table 3). The p-value for each term tests the null hypothesis that no correlation exists between dependent and independent variables.

Table 3. P-values of the multiple regression analysis.

Dependent variable	**Indipendet variable**	**P-value (SWMM-GR1)**	**P-value (SWMM-GR2)**	**P-value (NASH-GR1)**	**P-value (NASH-GR2)**
RMSE	d	9.0E-03	1.6E-01	3.0E-04	1.2E-02
	C	3.5E-05	2.2E-02	4.2E-06	2.0E-03
	I	4.6E-01	5.3E-01	4.3E-02	8.3E-01
MAE	d	4.4E-02	2.0E-01	2.3E-04	1.4E-03
	C	1.6E-03	4.5E-02	3.8E-06	7.2E-05

	I	6.6E-01	4.1E-01	6.7E-02	8.5E-01

The low p-values (<0.05) for the cumulative rainfall and the event duration indicates that the null hypothesis can be rejected and, in other words, that rainfall duration and cumulative values appear significant variables with respect to model errors. This circumstance opens the necessity to improve the GRs modelled hydrological behavior especially in the case of large events. On the other side, no effect or relationship appears between the mean intensity and the errors.

4. Conclusions

The aim of this paper is to evaluate the accuracy of two different hydrological models in simulating the hydrological response of two green roofs plots to storm events. The performances of a conceptual model namely the Nash cascade model and of SWMM falling within the class of the physically based models, in predicting the hydrological behavior of green roofs have been tested and compared. The case study is an experimental site including two GR benches located in Mediterranean climate. The test beds differ for the material used in the drainage layer that is expanded clay for GR1 and commercial plastic panels filled with expanded clay for GR2. The selected models have been calibrated comparing the observed values of runoff related to twenty-five rainfall-runoff events recorded at the experimental site and the observed ones, so as to optimize three goodness of fit indices which are the NSE, RMSE, MAE. The parameters subjected to calibration are the storage coefficient "k" for the Nash model and the suction head "ψ" for SWMM. The mean values of k and ψ resulting from the calibration process underline that the drainage layer of GR2 has a slightly higher detention capacity and a lower porosity than GR1. The analysis has proved that both the considered models have good capabilities in simulating the runoff production from green roofs as demonstrated by the high values of NSE so despite the Nash model, is a simple model, it appears very suitability for the event scale simulations. Furthermore, the low difference in the values of error for GR1 and GR2 shows that the two green benches exhibit a similar hydrological behavior. A more detailed study has revealed the existence of a relationship between the errors and the rainfall characteristics. Specifically, a multiple regression analysis has demonstrated that the MAE and RMSE increase with increasing cumulative rainfall and duration of the events.

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