A simple rainfall-runoff model for the single and long term hydrological performance of green roofs

Modélisation de la performance hydraulique des toitures végétalisées, sur le long terme et pour des événements particuliers

Luca Locatelli[1], Ole Mark[2], Peter Steen Mikkelsen[1], Karsten Arnbjerg-Nielsen[1], Barbara Kleinlercher[3], Maria Kerstin Roldin[4], Philip Binning[1]

[1]Technical University of Denmark, DTU Environment, 2800, Lyngby, Denmark
[2]DHI Water & Environment, Agern Allé 5, 2970 Hørsholm, Denmark
[3]Grontmij A/S, Granskoven 8, 2600 Glostrup, Denmark
[4]DHI Water & Environment, Kyrkogatan 3, 222 22 LUND, Sweden
lulo@env.dtu.dk, omj@dhigroup.com, psmi@env.dtu.dk, karn@env.dtu.dk, barbara.kleinlercher@grontmij.dk, maria.roldin@dhi.se, pjbi@env.dtu.dk

RÉSUMÉ

Les toits végétalisés ont été largement implantés pour la gestion des eaux pluviales et la réduction du ruissellement. Afin d’évaluer leur impact, les toits végétalisés doivent être incorporés aux modèles de drainage urbain. Ces modèles devraient nécessiter une faible puissance de calcul ainsi qu’un faible temps de résolution. Cet article vise à développer un modèle de performance hydrologique des toits végétalisés. Ce modèle conceptuel simple pour la performance hydrologique des toits végétalisés lors d’événements uniques de longue durée parvient à reproduire les ruissellements mesurés. Le modèle inclut des composantes de rétention de surfaces et de sous-surface représentant la capacité de rétention globale des toits végétalisés. Le ruissellement du système est décrit par un réservoir non-linéaire alors que la capacité de rétention des toits végétalisés est recalculée de façon continue par l’évapo-transpiration. Les données de ruissellement des toits végétalisés au Danemark sont collectées et utilisées pour la calibration des paramètres.

ABSTRACT

Green roofs are being widely implemented for storm water control and runoff reduction. There is need for incorporating green roofs into urban drainage models in order to evaluate their impact. These models must have low computational costs and fine time resolution. This paper aims to develop a model of green roof hydrological performance. A simple conceptual model for the long term and single event hydrological performance of green roofs, shows to be capable of reproducing observed runoff measurements. The model has surface and subsurface storage components representing the overall retention capacity of the green roof. The runoff from the system is described by the non-linear reservoir method and the storage capacity of the green roof is continuously re-established by evapotranspiration. Runoff data from a green roof in Denmark are collected and used for parameter calibration.

KEYWORDS

Evapotranspiration, Green roofs performance, Modelling, Peak-flow, Runoff, Single events, Urban drainage

1 INTRODUCTION

Green roofs are a Water Sensitive Urban Design (WSUD) technique aimed to improve stormwater management. The concept of water sensitive cities was presented by Wong (2009). Green roofs have the advantage of not occupying new areas; in fact hard roofs can in some cases be converted into green roofs. Green roofs generally lead to a decrease of stormwater volumes and peak flows to sewer systems. They also contribute in reducing the contaminant load to sewer systems, improve the roof insulation, enhance biodiversity and add amenity value of urban areas.

Several studies have presented models for the hydrological performance of green roofs. Zimmer and Geiger (1997), Villarreal and Bengtsson (2005), Hilten, Lawrence et al. (2008), Palla, Gnecco et al. (2009) have proposed different approaches for modelling the hydrological response of green roofs to individual storm events. Kasmin, Stovin et al. (2010) compares different methods for modelling evapotranspiration from green roofs. Sherrard and Jacobs (2012) presented a model with the aim of continuously predicting the daily water balance. Carter and Rasmussen (2006), Getter, Rowe et al.(2007) derived the Curve Number used for modelling the hydrological performance of observed green roofs. However, none of the studies focused on both the single event and long term hydrological performance of green roofs. Peak runoff during single events and runoff volume reduction are of major interest. The single event response is affected by the initial moisture content of the green roof and at the same time the long term performance depends on the single event retention. Therefore continuous simulations are relevant for the hydrological response of green roofs. Moreover, there is need of incorporating green roofs into urban drainage models that require fine temporal resolution and continuous simulations with low computational costs.

The aim of this paper is to present a simple conceptual model used for simulation of both single event and long term hydrological performance of green roofs. This model can provide fine temporal resolution keeping low computational costs. The second goal of the study is to provide a set of parameters to be used for runoff modelling. This set of values is obtained by inverse modelling by fitting the runoff hydrograph measured at a test site.

2 METHOD

2.1 The observation data

A green roof was installed in Odense (Denmark) and runoff was measured. It is an extensive green roof with a surface of 9 m^2 (3 x 3 m) and a slope of 10°. It has sedum vegetation growing on a 40 mm layer substrate drained by a 40 mm of rock-wool layer. Runoff data from this roof are available from august 2010 to may 2012. Figure 1 shows both the different layers and the overall structure of the experimental green roof.

Runoff from the roof is collected in a tank where the water depth is measured by pressure transducers in order to provide a continuous record of runoff. The tank is automatically emptied at varying time intervals. Rainfall is monitored using a classical tipping bucket placed approximately 50 meters away from the green roof. Atmospheric data (wind speed, air temperature, relative humidity, net radiation and air pressure) are collected from a meteorological station at a distance of circa 10 km. The rainfall and runoff data are logged at 1-minute time steps whereas meteorological data have 1-hour resolution. Single rain events are defined by rainfall periods separated by more than an hour.

Figure 1: monitoring green roof. Cross section (left), the substrate is made of a mix of mineral soil. Overall test setup (right).

2.2 Conceptual model

The mass balance model for the green roof is shown in Figure 2 and it has been implemented in MATLAB.

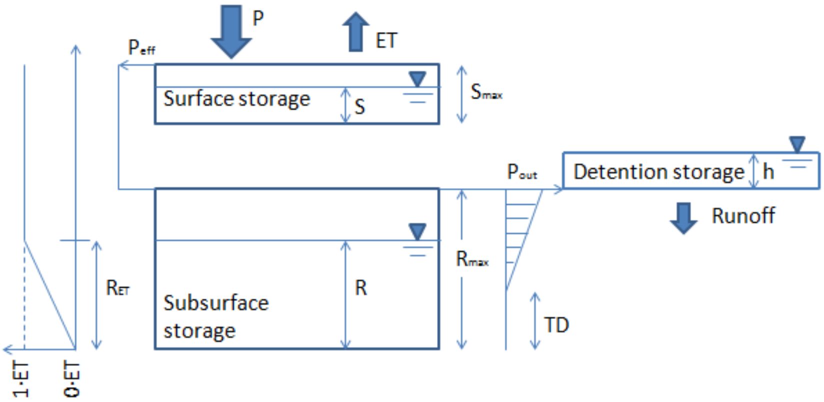

Figure 2: Conceptual mass balance model for the green roof

Rainfall intercepted by the vegetation as well as water trapped in the uppermost, vegetated part of the green roof is referred to as surface storage. S_{max} represents the maximum amount of water in the surface storage. The volume of water in the surface storage is continuously lost through evaporation. When the maximum storage S_{max} is exceeded, P_{eff} is diverted as infiltration into the subsurface storage.

The subsurface storage represents the amount of water that can be stored both in the substrate and in the drainage layer of the green roof. $R=0$ represents the practical minimum water content which may vary in response to atmospheric conditions and it represents the water content at the wilting point. R_{max} is the maximum amount of water that can be held in the subsurface storage, this is the difference between the volume of water at field capacity and the one at wilting point. The volume of water in the subsurface storage is subjected to consumptive loss from evapotranspiration. From the subsurface storage P_{out} is diverted into the detention storage.

The detention storage has a temporary capacity of storing water. The detention storage represents the amount of water that cannot be kept by the system and therefore will runoff. The runoff from the detention storage is described by the non-linear linear reservoir method:

$$\frac{dh}{dt} = P_{out} - Runoff - ET;\ Runoff = k \cdot h^{n}$$

where k and n are the routing parameters. After the end of the rainfall event the detention storage will be drained within 1 to 2 hours. It is assumed that overland flow do not occur for the current case study so maximum detention storage is not considered and water percolate vertically through the substrate and runoff via the drainage layer.

Evapotranspiration is at its maximum rate in the surface storage. If the water content S in the surface storage falls below the minimum level, water is withdrawn by evapotranspiration from the detention storage. If the detention storage is below zero evapotranpiration takes place in the subsurface storage.

The actual evapotranspiration rate is calculated through the FAO Penman-Monteith equation:

$$ET = ET_{FAO} \cdot k_c \cdot F$$

Where k_c is the crop coefficient and F is the reduction factor. Input data for ET_{FAO} are wind speed, air temperature, air relative humidity, atmospheric pressure and global radiation.

The crop coefficient takes into account the stomatal resistance of the leaf and the aerodynamic resistance through the foliage of the plant. The reduction factor takes into account environmental stresses, such as water availability. The reduction factor equals *1* for water content above R_{ET} (see Figure 2) and decreases linearly to zero from the fraction R_{ET} to the minimum water content $R=0$ in the subsurface storage. The ratio R_{ET} can be interpreted as the water content at the stomatal closure point. The reduction factor is expressed by:

$$F = \frac{\min\left(\frac{R}{R_{max}}, R_{ET}\right)}{R_{ET}}$$

The precipitation recharging the detention storage depends on the moisture content ($TD=R/R_{max}$) in the subsurface storage

$$P_{out} = \begin{cases} P_{eff}\dfrac{R/R_{max} - TD}{1 - TD} & , R/R_{max} > TD \\ 0 & , R/R_{max} \leq TD \end{cases}$$

where TD is the threshold value for the detention basin recharge ($0 \leq TD < 1$). TD is a parameter for simulating the hydrograph at the beginning of a rain event. If the subsurface storage is full then $P_{out} = P_{eff}$.

Inverse modelling was applied in order to estimate the different parameters needed for the model. The calibration was made using the Shuffled Complex Evolution Metropolis algorithm (Vrugt, Gupta et al. 2003).

2.3 Results and discussion

Figure 3 shows the accumulated rainfall, observed runoff and computed runoff for a summer and winter season. Both total rainfall and evapotranspiration are higher in the summer period. During the summer period it was registered 493 mm of accumulated rain and 240 mm of runoff (runoff coefficient = 0.49), whereas during the winter 263 mm of rainfall and 188 mm of runoff (runoff coefficient = 0.71). Results show good match between the observed and the computed runoff. However the model for the winter period should be improved by adding snow storage.

The calibrated crop coefficient is 0.78 for summer and 0.62 for winter period. Crop coefficients for sedum were experimentally found to be between 0.15 and 0.65 with varying soil relative humidity and water-stress conditions (Lazzarin, Castellotti et al. 2005); Sherrard and Jacobs (2012) calibrated a crop coefficient of 0.53 using experimental data for their model; Schneider, Wadzuk et al. (2011) experimentally observed average crop coefficients between 1.1 and 1.9. The crop coefficient plays a dominant role in the prediction of the long term water retention of green roofs.

The calibrated value for R_{ET} is 0.45, nevertheless the sensitivity of this parameter in relation to the water balance is much lower compared to the sensitivity of the crop coefficient. Schneider, Wadzuk et al.(2011) observed values between 0.5 and 1 from their experimental green roof.

The calibrated value for TD is 0.4. This parameter is important for the runoff simulation when the field capacity of the roof is not reached. In fact, even though the subsurface storage is not full observations show that runoff does occur. This parameter plays a significant role for the simulation of small rain events however its sensitivity with respect to the water balance is smaller compared to the crop coefficient.

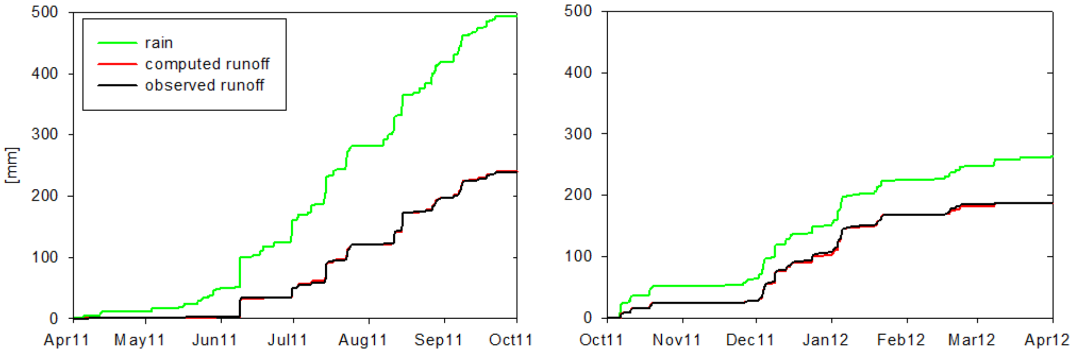

Figure 3: Accumulated rainfall, observed runoff and computed runoff. (left) Summer period, K_c=0.78. (right) Winter period, K_c=0.62.

Figure 4 shows the model fit during two selected rain events. The model shows that runoff peaks can be simulated with satisfactory precision. The calibrated values for the routing parameters *n* and *k* are respectively 0.0041 [min/mm] and 2 [-]. However, it must be noted that these 2 parameters are highly correlated.

The calibrated value for R_{max} is 21 mm. This value seems low for the given green roof. If we assume a porosity of 0.5 for the soil and 0.8 for the drainage layer, we would expect the storage capacity to be approximately 40-50 mm. A reason for this might be that *ET* is not taking place in the drainage layer since there are no roots and it is at least 4 cm below the roof surface.

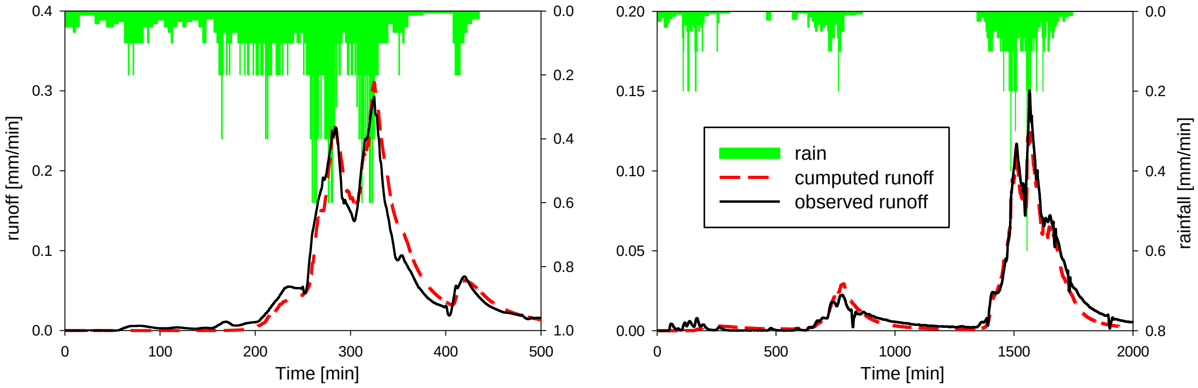

Figure 4: selected rain events. (left) 08/06/2011, rain=50 mm, simulated runoff=31 mm, observed runoff=30 mm. (right) 14/07/2011, rain=45 mm, simulated runoff=29 mm, observed runoff=32 mm.

2.4 Conclusions

Green roofs are often installed for storm water control and runoff reduction. This study has presented a simple mass balance model for the long term and single event hydrological performance of green roofs. This model has low computational cost and can provide a fine temporal resolution, and so it is well suited for incorporation into distributed urban drainage models.

The developed model is shown to reproduce experimental data, both during single events and over a longer continuous simulation period. The model includes a surface, a subsurface and a detention storage. The subsurface storage represents the retention capacity of both the substrate and the drainage layer, but some storage losses during rain events are also taken into account. Evepotranspiration continuously restores the capacity of the green roof.

The model is shown to be suitable for the evaluation of green roof performance, but parameter calibration will be needed to apply it to other roof types than the one studied here.

ACKNOLWLEDGMENTS

The authors wish to thank the Danish Council for Research for financial support through the project BIV (Byer I Vandbalance – Cities in waterbalance) and Annette Brink-Kjær from Vancenter Syd that provided the runoff data from the tested green roof.

LIST OF REFERENCES

Carter, T. L. and T. C. Rasmussen (2006). "Hydrologic behavior of vegetated roofs." Journal of the American Water Resources Association **42**(5): 1261-1274.

Getter, K. L., D. B. Rowe, et al. (2007). "Quantifying the effect of slope on extensive green roof stormwater retention." Ecological Engineering **31**(4): 225-231.

Hilten, R. N., T. M. Lawrence, et al. (2008). "Modeling stormwater runoff from green roofs with HYDRUS-1D." Journal of Hydrology **358**(3-4): 288-293.

Kasmin, H., V. R. Stovin, et al. (2010). "Towards a generic rainfall-runoff model for green roofs." Water Science and Technology **62**(4): 898-905.

Lazzarin, R. A., F. Castellotti, et al. (2005). "Experimental measurements and numerical modelling of a green roof." Energy and Buildings **37**(12): 1260-1267.

Palla, A., I. Gnecco, et al. (2009). "Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof." Journal of Hydrology **379**(1-2): 193-204.

Schneider, D., B. M. Wadzuk, et al. (2011). Using a Weighing Lysimeter to Determine a Crop Coefficient for a Green Roof to Predict Evapotranspiration with the FAO Standardized Penman-Monteith Equation. World Environmental and Water Resources Congress 2011**:** 3629-3638.

Sherrard, J. and J. Jacobs (2012). "Vegetated Roof Water-Balance Model: Experimental and Model Results." Journal of Hydrologic Engineering **17**(8): 858-868.

Villarreal, E. L. and L. Bengtsson (2005). "Response of a Sedum green-roof to individual rain events." Ecological Engineering **25**(1): 1-7.

Vrugt, J. A., H. V. Gupta, et al. (2003). "A Shuffled Complex Evolution Metropolis algorithm for optimization and uncertainty assessment of hydrologic model parameters." Water Resources Research **39**(8).

Wong, T. H. F. and R. R. Brown (2009). "The water sensitive city: principles for practice." Water Science and Technology **60**(3): 673-682.

Zimmer, U. and W. F. Geiger (1997). "Model for the design of multilayered infiltration systems." Water Science and Technology **36**(8–9): 301-306.