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THERMAL AND HYDROLOGICAL MODELING OF GREEN ROOFS: APPLICATION TO STORMWATER MANAGEMENT ASSESSMENT

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Abstract

This paper focuses on the potential of green roofs in stormwater management. Through their water retention capacity and to the evapotranspiration phenomena, green roofs are capable of improving urban drainage by reducing stormwater runoff. In this work, a green roof model able to simulate the complex hygrothermal behavior of green roofs, including coupled mechanisms of heat and mass transfer, is used to simulate the hydrological performance of non-tilted green roofs.

Keywords:

Hygrothermal modeling; numerical simulation, hydrological behavior, green roofs

1 INTRODUCTION

Green roofs have gradually become a solution to connect the city to the wildlife in the architecture of the 20th century. With the introduction of light and resistant waterproofing membranes and lightweight mixes of substrates, extensive green roofs have experienced significant growth over the 1980s. In Germany, for example, 14% of flat roofs were vegetated with this technique [Castleton 2010]. Green roofs have considerable potential to reduce building energy consumption. Several studies show various benefits associated with the use of these bio-based architectural components in terms of thermal comfort and energy saving [Djedjig 2015; Jaffal 2012; Fioretti 2010; Santamouris 2007], urban microclimate [Djedjig 2013; Smith 2011; Ng 2012], stormwater management [Mentens 2006a; Czemiel 2010; Berndtsson 2009a], sound insulation [Van Renterghem 2009; Van Renterghem 2008] and psychological social aspects [Raffan 2002; White 2011; Van Den Berg 2007]. Furthermore, green roofs change the pollutants concentrations of water that seep in. According Berndtsson et al. [Berndtsson 2009b], the substrate used in intensive and extensive green roofs remove some pollutants as nitrates and heavy metals but release other pollutants such as phosphorus used in fertilizers.

From hydrological point of view, green roofs increase the permeability of urban surfaces which help to reduce the risk of flooding. Thanks to their water storage capacity, vegetated roofs can significantly reduce runoff stormwater peaks. According to Mentens et al. [Mentens 2006], this runoff reduction reach 54%. This helps prevent water clogging of sewage systems. It is very useful to develop green wall models capable of predicting such experimental results. In this context, Palla et al. [Palla 2009] applied a SWMS_2D model based on Richards' law and the Van Genuchten–Mualem functions to simulate the variably saturated flow within the green roof system. The model was calibrated using rainfall– runoff events observed experimentally. Although this approach provides a detailed modeling of water transport phenomena in the substrate, it is limited as for global flows simulation over long periods, as for considering the role of vegetation and as for evapotranspiration modeling. Indeed, this approach does not take into account the heat transfer that affect at long-term water transfer notably through the evapotranspiration phenomena.

Volder and Dvorak [Volder 2014] undertook an experimental approach to correlate the storm water retention efficiency of un-irrigated extensive green roof with event size (rainfall rate and duration), with water content and with the presence or not of vegetation. An earlier study [Ouldboukhitine 2012] has evaluated water loss by evapotranspiration by means of weighing vegetated modules placed outdoors, and comparing the measurements to the predictions of the Penman Monteith equation. The latter showed that the use of the Penman Monteith equation for green roofs led to overestimation of the evapotranspiration.

In the following, we present a modeling approach to calculate the stormwater runoff rate (or Drainage D [kg.m^{-2}.Δt^{-1}]) on extensive green roof over long periods of simulation. This approach represents a compromise between refine hydrological modeling approaches that not consider the coupling with heat transfer and the simply thermal modeling not considering the water transfer.

2 GREEN ROOF MODEL

2.1 Thermal model

The model used in this paper has been mainly developed to simulate green roofs or green walls impacts on building thermal behavior [Djedjig 2012; Djedjig 2015]. Although this model deals with a more detailed heat transfer compared to water transfer, it should be useful in hydrological simulation on horizontal green roofs since it models quite good the evapotranspiration phenomena.

The model is based on energy and water balances. The energy balances account for the radiative, the sensible and for the latent heat transfer on the foliage and through the substrate. The water balance takes into account the water intake related to precipitation or watering and water losses by evapotranspiration.

The heat balances are written in the following form:

$$(\rho c_p)_f \, d_f \, F \frac{dT_f}{dt} = Rn_f - H_f - L_f \tag{8}$$

$$\frac{\partial}{\partial t}\left[(\rho c_p)_{g,\omega_g} T\right] = \frac{\partial}{\partial z}\left(k_{\omega_g} \frac{\partial T}{\partial z}\right) \tag{9}$$

Where Rn_f, H_f and L_f (all in $W.m^{-2}$) are respectively the net radiative flux, the sensible heat flux and the latent heat flux on the foliage (see ***Fig. 1***). Here (F) is the leaf area index, (d_f) is the mean leaf depth, (ρc_p) is the volumetric heat capacity. Equation (9) expresses the 1D heat diffusion through the substrate layer whose thermal conductivity ($k_{\omega g}$) and volumetric thermal capacity $(\rho c_p)_{\omega g}$ are depend on the volumetric water content of the substrate layer (ω_g [$kg_w.m^{-3}$]).

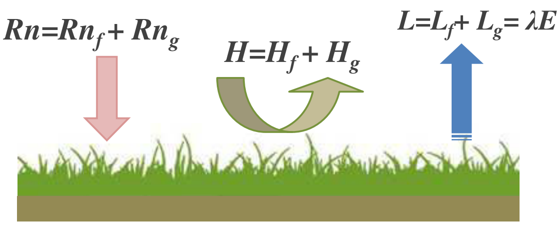

Fig. 1: Modeled heat fluxes on green roofs

To solve the PDE (9), the following boundary conditions are considered for the upper and the inner surfaces respectively:

$$-k_{\omega_g} \left.\frac{\partial T}{\partial z}\right|_{z=0} = Rn_g - H_g - L_g \tag{10}$$

$$-k_{\omega_g} \left.\frac{\partial T}{\partial z}\right|_{z=-h_g} = \varphi_{in} \tag{11}$$

Where Rn_g, H_g and L_g (all in $W.m^{-2}$) are respectively the net radiative flux, the sensible heat flux and the latent heat flux on the substrate surface. Besides, the heat flux (φ_{in}) transferred to the building is considered when the green roof model is coupled to the building model. In this paper, we are only studding hydrological behavior of green roofs, for these purposes, this heat flux is set to zero (φ_{in}=0 W.m^{-1}). In this way, we suppose that the building is perfectly insulated.

The latent heat fluxes (L_f) and (L_g) used in equations (8) and (10) are calculated considering partial vapor deficit relative to the ambient air:

$$L_f = F \frac{(\rho c_p)_a}{\gamma (r_a + r_s)} \left(p_{v_{f,sat}} - p_{v_a}\right) \tag{12}$$

$$L_g = \frac{(\rho c_p)_a}{\gamma (r_{sub} + r_a)} \left(p_{v_{g,sat}} - p_{v_a}\right) \tag{13}$$

In these equations: p_{va} is the vapor pressure in the ambient air, $p_{vf,sat}$ and $p_{vg,sat}$ are respectively the saturation pressure of water vapor at the foliage and at the substrate temperatures, r_a that depend on the wind velocity represent the aerodynamic resistance to heat transfer, r_s and r_{sub} are the resistances to vapor diffusion that characterize the leaves and the substrate respectively. The two resistances r_s and r_{sub} depend on the water content ω_g, they decrease as this one increase.

For more detail about the calculation of the radiative, sensible and latent heat fluxes on the foliage and on the substrate (Rn_f, Rn_g, H_f, H_g, L_f and L_g), see reference [Djedjig 2012].

2.2 Hydrological model

The heat balance equations presented above are coupled to the water balance on the roof since the heat fluxes related to plant transpiration (L_f) and to direct evaporation (L_g) depend on the water content (ω_g) and also the thermophysical properties of the substrate. If not for other reason, it is crucial to simulate the water content evolution over time. That being said, it is always interesting to analyze the water balance in order to assess green roofs potential for stormwater management, especially when little or no literature model consider coupled heat and water transfers on green roofs.

The green wall model used in this paper establishes a global water balance (***Fig. 2***) in which the water content (ω_g), supposed spatially homogenous, is tracked over time depending on water supply (precipitation, irrigation) and water losses (evapotranspiration, drainage). The homogeneity assumption is justified for thin substrate layers as those of extensive green roofs.

The water balance of a green roof is written as the following:

$$h_g \frac{\partial \omega_g}{\partial t} = P - D - E \tag{14}$$

Where (h_g [m]) is the substrate layer depth, (P) the water supply (mainly rainfall), (D) the drainage and (E) the evapotranspiration. P, D and E are in [kg.m^{-2}.s^{-1}]. The evapotranspiration rate is calculated according to the latent plant transpiration and to the substrate evaporation rates as the following:

$$E = \left(L_f + L_g\right) / l_v \tag{15}$$

Where (l_v) is the water latent heat of vaporization.

The green roof model has been already validated through measurements carried out on extensive green roofs with real weather conditions [Djedjig 2012]. The issue was to compare numerical simulation to measurements for water content and temperature variations. In the referred publication, both precipitation and drainage rates were measured and used as input data in performed simulations.

The current study deals with simulating the capability of a green wall to reduce storm water runoff. So, in this paper the drainage rate is not known a priori. Precisely, the objective now is to evaluate the drainage after rainfall events accounting for water losses by evapotranspiration.

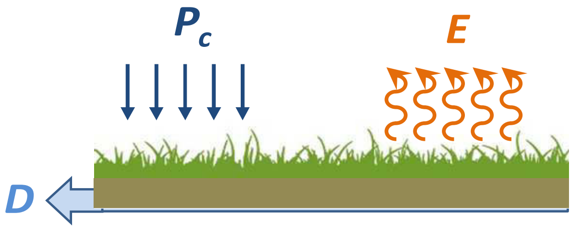

Fig. 2: Water balance on a waterproof and insulated non-tilted extensive green roof

To ensure that the numerical code runs as normally as possible, the water content ω_g was limited between two values $\omega_{g,min}$ and $\omega_{g,max}$. While $\omega_{g,min}$ is very close to zero, $\omega_{g,max}$ is a substrate parameter that represent the maximum water retention. This parameter can be measured experimentally [Ouldboukhitine 2012]. Since the hydrological model considers a global water balance without drainage delay, numerically it is as if drainage can take place only if, simultaneously, it rains and the water content is maximal. Therefore, the drainage during one time step (k) of calculation can be deduced from equation (14) as follows (in kg.m^{-2}):

$$D^{(k)} = \begin{cases} P^{(k)} - E^{(k)} - h_g\left(\omega_g^{(k)} - \omega_g^{(k-1)}\right); & \text{when } \omega_g = \omega_{g,\max} \\ 0 \;; \quad \text{when} & \omega_g < \omega_{g,\max} \end{cases} \quad (16)$$

3 RESULTS AND DISCUSSION

The results presented in this paper use real weather data collected in May 2012 by a weather station located at the University of La Rochelle. These real weather data are used to simulate the hydrological behavior of a green roof characterized by the properties listed in ***Tab. 1***.

Tab. 1: Main structural and thermo-hydrological parameters of the studied green roof

Fractional vegetation coverage	$\sigma_f = 1$
Leaf area index	$F = 4$
Leaf canopy height	$h_f = 0.07$ m
Minimum leaf stomatal resistance	$r_{s,min} = 200$ s.m^{-1}
Maximum water content retention	$\omega_{g,max} = 260$ kg.m^{-1}
Substrate solar reflectivity	$\rho_g = 0.2$
Substrate thermal conductivity	$k_{\omega g} = [0.1,0.5]$
Substrate depth	$d_g = 0.1$ m

The ideal is to compare the model results with experimental hydrological data. However, this does not prevent analyzing, as a first step in this article, the results of the proposed model according to the simulated hydrological behavior.

The results of performed numerical simulation are presented on Fig. 3. This figure shows on its upper graph a summary of the meteorological data used in this paper including solar radiation on horizontal, ambient temperature, relative humidity, sky temperature and wind velocity. The red curve of the lower part of the figure show the rainfall (P) [mm.hr^{-1}], the blue curve show the drainage rate (D) also in in [mm.hr^{-1}] and the black one shows the water content variation.

As can be seen on this figure, Simulation period, which correspond to three week of May 2012, was chosen because it alternates rainy and sunny days. In fact, the weather conditions of this period illustrate quite well the hydrological behavior of the proposed model.

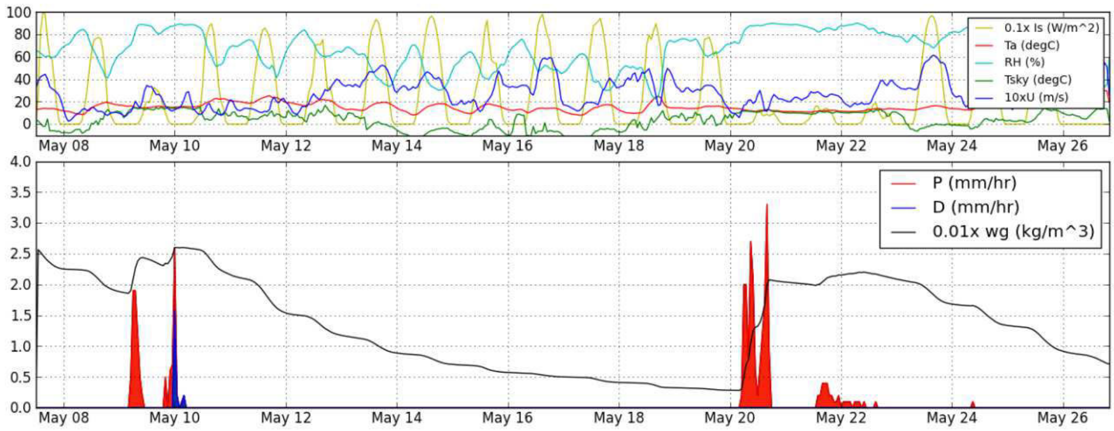

Fig. 3: Upper graph: Summery weather conditions measured on May 2012 and used in numerical simulations; Lower graph: Measured rainfall (P) and the time variation of the water content (ω_g) and the drainage (D) obtained with initial (ω_g) equal to ($\omega_{g,max}$)

4 CONCLUSION

In this paper a thermos-hydrological model for green roofs was used to simulate the hydrological behavior of a hypothetical non-tilted extensive green roof submitted to real weather conditions in order to assess its stormwater runoff management. The model, presented as a compromise between purely hydrological or thermal models, has proved capable for simulating the green roofs hydrological behavior over long periods. The simulation results showed also that the drainage amount, although lowered by green roofs; it depends on the water retention capacity of the substrate, on the size, the duration but also on the frequency of rainfall events. The next step will be to compare the drainage amount prediction to experimental data carried out on real green roofs.

5 REFERENCES

[Berndtsson 2009a] Berndtsson, J.C., Bengtsson, L. & Jinno, K., 2009. Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering*, 35(3), p.369−380.

[Berndtsson 2009b] Berndtsson, J.C., Bengtsson, L. & Jinno, K., 2009. Runoff water quality from intensive and extensive vegetated roofs. *Ecological Engineering*, 35, p.369−380.

[Castleton 2010] Castleton, H.F. et al., 2010. Green roofs; building energy savings and the potential for retrofit. *Energy and Buildings*, 42, p.1582−1591.

[Czemiel 2010] Czemiel Berndtsson, J., 2010. Green roof performance towards management of runoff water quantity and quality: A review. *Ecological Engineering*, 36(4), p.351−360.

[Van Den Berg 2007] Van Den Berg, A.E., Hartig, T. & Staats, H., 2007. Preference for Nature in Urbanized Societies: Stress, Restoration, and the Pursuit of Sustainability. *Journal of Social Issues*, 63(1), p.79–96.

[Djedjig 2012] Djedjig, R. et al., 2012. Development and validation of a coupled heat and mass transfer model for green roofs. *International Communications in Heat and Mass Transfer*, 39, p.752−761.

[Djedjig 2015] Djedjig, R., Bozonnet, E. & Belarbi, R., 2015. Analysis of thermal effects of vegetated envelopes: Integration of a validated model in a building energy simulation program. *Energy and Buildings*, 86, p.93−103.

[Djedjig 2013] Djedjig, R., Bozonnet, E. & Belarbi, R., 2013. Experimental study of the urban microclimate mitigation potential of green roofs and green walls in street canyons. *International Journal of Low-Carbon Technologies*. Available at: http://ijlct.oxfordjournals.org/content/early/2013/04/14/ijlct.ctt019 [Consulté le avril 15, 2013].

[Fioretti 2010] Fioretti, R. et al., 2010. Green roof energy and water related performance in the Mediterranean climate. *Building and Environment*, 45(8), p.1890−1904.

[Jaffal 2012] Jaffal, I., Ouldboukhitine, S.-E. & Belarbi, R., 2012. A comprehensive study of the impact of green roofs on building energy performance. *Renewable Energy*, 43, p.157−164.

[Mentens 2006a] Mentens, J., Raes, D. & Hermy, M., 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? *Landscape and Urban Planning*, 77(3), p.217−26.

[Ng 2012] Ng, E. et al., 2012. A study on the cooling effects of greening in a high-density city: An experience from Hong Kong. *Building and Environment*, 47, p.256−271.

[Ouldboukhitine 2012] Ouldboukhitine, S.-E., Belarbi, R. & Djedjig, R., 2012. Characterization of green roof components: Measurements of thermal and hydrological properties. *Building and Environment*, 56, p.78−85.

[Palla 2009] Palla, A., Gnecco, I. & Lanza, L.G., 2009. Unsaturated 2D modelling of subsurface water flow in the coarse-grained porous matrix of a green roof. *Journal of Hydrology*, 379(1-2), p.193−204.

[Raffan 2002] Raffan, J., 2002. *La nature nourricière: une étude du potentiel d'apprentissage dans les cours d'école.*, Toronto: Evergreen.

[Van Renterghem 2008] Van Renterghem, T. & Botteldooren, D., 2008. Numerical evaluation of sound propagating over green roofs. *Journal of Sound and Vibration*, 317(3-5), p.781−799.

[Van Renterghem 2009] Van Renterghem, T. & Botteldooren, D., 2009. Reducing the acoustical façade load from road traffic with green roofs. *Building and Environment*, 44, p.1081−1087.

[Santamouris 2007] Santamouris, M. et al., 2007. Investigating and analysing the energy and environmental performance of an experimental green roof system installed in a nursery school building in Athens, Greece. *Energy*, 32(9), p.1781-1788.

[Smith 2011] Smith, K.R. & Roebber, P.J., 2011. Green Roof Mitigation Potential for a Proxy Future Climate Scenario in Chicago, Illinois. *Journal of Applied Meteorology and Climatology*, 50, p.507-522.

[Volder 2014] Volder, A. & Dvorak, B., 2014. Event size, substrate water content and vegetation affect storm water retention efficiency of an un-irrigated extensive green roof system in Central Texas. *Sustainable Cities and Society*, 10, p.59−64.

[White 2011] White, E.V. & Gatersleben, B., 2011. Greenery on residential buildings: Does it affect preferences and perceptions of beauty? *Journal of Environmental Psychology*, 31(1), p.89−98.