



HAL
open science

Seasonal and annual performance of green roof: Impact of thermal and hydraulic behaviour

Ryad Bouzouidja, G. Séré, R. Claverie, David Lacroix

► To cite this version:

Ryad Bouzouidja, G. Séré, R. Claverie, David Lacroix. Seasonal and annual performance of green roof: Impact of thermal and hydraulic behaviour. Green Infrastructures: : Nature Based Solutions for Sustainable and Resilient Cities, Apr 2017, Orvietto, Italy. hal-01983450

HAL Id: hal-01983450

<https://hal.science/hal-01983450>

Submitted on 16 Jan 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Seasonal and annual performance of green roof : Impact of thermal and hydraulic behaviour,

R. Bouzouidja^{a,b,c,*}, G. Séré^a, R. Claverie^b, D. Lacroix^c

^aUniversité de Lorraine, LSE UMR 1120, 2 avenue de la Forêt de Haye BP 172 F-54505
Vandœuvre-lès-Nancy

^bCEREMA DTer Est / LRN, 71 rue de la grande haie F-54510 Tomblaine

^cUniversité de Lorraine, LEMTA UMR 7563, 2 Avenue de la Forêt de Haye TSA 60604 F-54518
Vandœuvre-lès-Nancy cedex

Abstract

Performance of vegetated roofs are investigated in terms of their expected benefits for the building and the urban environment, due to their recognised thermal and water management potential scores. A review of related worldwide experiences is reported for comparison purposes. The investigation is here performed within the specific climatic context of the European region. Full-scale experimental results are provided from one case study, located in north-east of France, involving in two fully monitored green roofs plots on top of public buildings. The attenuation of solar radiation through the vegetation layer is evaluated as well as the thermal insulation performance of the green roof structure. The daily heat flow through the roof surface is quantified showing that the green roof outperforms the reference roof, therefore reducing the daily energy demand. As for water management, it is confirmed that green roofs significantly mitigate storm water runoff generation even in a Mediterranean climate in terms of runoff volume reduction, peak attenuation and increase of concentration time, although reduced performance could be observed during high precipitation periods.

Keywords: green roof, substrate, hydraulic performances, thermal behaviour

1. Introduction

In developed countries, the level of urbanization is still rising and expected to reach 83% in 2030 (Nations, 2015). Risks of flooding due to overload of the drainage system, and pollution due to combined sewer overflows and diffuse pollution, consequently increase significantly. Questions about biodiversity promotion and urban heat islands are also emerging as major issues in the construction of sustainable cities (Berretta et al., 2014). Even if vegetation was planted on the roofs of buildings in several European countries for hundreds of years, the widespread use of the roof vegetation – with the emerging of extensive green roof

*Corresponding author

Email address: ryad.bouzouidja@gmail.com (R. Bouzouidja)

(GR) - has been recently developed to tackle these environmental issues (DeNardo et al., 2005).

Several authors focused only on the hydrodynamic behaviour water flow (e.g. Stovin (2010)) and evapotranspiration (e.g. Stovin et al. (2012)) and have specifically shown that GR effectively control the runoff in urban drainage by reducing overall volumes and peak flows. Studies mentioned the fact that water retention contributes also to peak flow attenuation and delay runoff (Carter and Rasmussen, 2005; Mentens et al., 2006; Stovin et al., 2012). Moreover, Berretta et al. (2014) shows volume retention depends on rainfall intensity distribution, the initial moisture conditions and GR characteristics (layer thickness, slope, materials, etc.). According to many authors, runoff delay times varied, according to many authors, around 30 min (e.g. Carter and Rasmussen (2005); Stovin et al. (2012)).

Other authors focused on the thermal behaviour to explain the GR performance. They reduce building energy demand through improvement of thermal performance of buildings (e.g. Santamouris et al. (2007); Alexandri and Jones (2008)). A study in Greece showed that, depending on the area covered by GR, cooling energy can be reduced by 2% to 48% and daytime indoor temperature drop of 4°C (Niachou et al., 2001). The authors also identified that GR can reduce indoor energy consumption (heating in winter and cooling in summer time). Furthermore, maximum energy savings depend strongly on thickness of growth medium (Kotsiris et al., 2012). During winter, GR acts as insulators decreasing external heat flow; however this benefit is often under debate as some studies claimed GR as a medium to save energy with a thicker soil layer (e.g. Sailor (2008); Jaffal et al. (2012); Jim and Peng (2012)). For instance, Jaffal et al. (2012) founded in winter time an elevation of the substrate temperature of 5.6°C compared to air temperature caused by the vegetation which acts as an insulation barrier. In summer time, they observed decrease of the substrate temperature 12.8°C below compared to air temperature. The authors explained that the evapotranspiration phenomena plays a major role during summer period. Other authors identified that GR has no influence during winter (Santamouris et al., 2007) and some of them showed that it may increase energy consumption (Jim and Tsang, 2011b). Jim and Tsang (2011a) monitored building in subtropical region (Hong Kong) with intensive and extensive GR. They founded an excellent thermal performance of the intensive GR with 100 cm thick substrate and with a thin soil layer of 10 cm which is sufficient to reduce heat penetration into building.

Only few studies interested thermal and hydrodynamic coupling behaviour in GR. It is possible to mention some works made by Fioretti et al. (2010), Ouldboukhitine et al. (2012) and de Munck et al. (2013). They discussed the thermal and hydraulic performances separately. Fioretti et al. (2010) monitored two case studies in Mediterranean region located in north-west and central Italy, consisting in two fully monitored GR on top of public buildings. They founded that the GR can reduce the daily solar radiation by $85.0 \pm 3.6\%$ due to the presence of vegetation. In fact, foliage creates shadow on the soil, which allows decreasing the incident solar irradiance on the external surface of the roof, therefore reducing the surface temperature and the heat gain through the cover. The authors attributed this reduction to the the plant shading, insulation and evapotranspiration of the foils apparatus. At the same time, the authors discussed the stormwater management performance

separately from the thermal performance. No correlation has been established between water content inside the substrate, evapotranspiration and the temperature through the GR. de Munck et al. (2013) conducted a validation study of a numerical model compared to an experimental study located in Nancy (France) which consists of an instrumented extensive sedum GR and substrate and drainage layers that are widely used. The authors started to highlight a relationship between substrate water content and temperature. They explained that a better understanding of hydraulic modelling can improve the thermo-hydraulic modelling of GR. Sun et al. (2013) showed in their study a dependence of surface temperature, heat flux crossing the building and GR hydrological conditions. The results indicate that incoming solar radiation and medium layer moisture are the main determinants of the GR performance.

The hydraulic performance of the GR is strongly dependent upon substrate humidity characteristics, weather and antecedent moisture conditions. Understanding the hydrological process and characteristics of the different GR components is the key to the high GR performances (Palla et al., 2008; Stovin et al., 2012). From a thermal standpoint, the performance of the GR deal with vegetation coverage (Kumar and Kaushik, 2005), substrate thickness (Wong et al., 2003) and evapotranspiration rate (Tsang and Jim, 2011). Considering these results, it is necessary to conduct more investigation on impact of water presence within the substrate on reduction its temperature and impact of weather conditions on thermal and hydraulic performance of GR depending on seasonal variations, and some questions remain unanswered: What are the GR thermo-hydraulic performances over long periods of time and what kind of evolution may be expected as time goes on?

The main objectives of this study is to understand the coupled thermal and hydrodynamic behaviour of GR under real weather conditions, and also to propose a technical innovations aiming to optimize the GR functionality through experiment and data observations.

2. Materials and methods

2.1. Experimental design

This work was based on an *in situ* experimental GR plot located in Nancy (north-east of France, under temperate climate, N48°41'11.8716" E6°13'7.0716"). The local climate is driven by an average annual precipitation of 763 mm and a mean temperature 10 °C with high amplitude of variations between summer and winter (Bouzouidja et al., 2013).

The GR platform, built in July 2011, is placed above an approximately 6 m height flat roof building. The overall GR surface area is 600 m², with different plot compositions. GR platform is made of a supporting element in concrete (Figure 1). Vegetation plants that were installed are classically: sedum album, sedum reflexumlarix, sedum reflexum germanium, sedum sexangulare, sedum floriferum (Bouzouidja et al., 2013). These plants do not exceed 10 cm height. In this study, the changes of the GR was observed and monitored over two years 2012 and 2014 (January to December) on two plots designed as Expanded Clay (*EC*) and *Gravel* designed as reference. The study plots are designed as EC and Gravel, with respectively an overall surface area of 75 m² and 64 m². The composition is detailed in

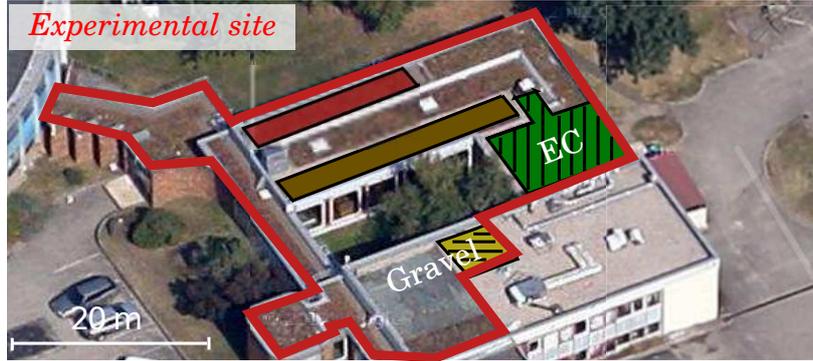


Figure 1: Overview of the experimental platform, comprising two GR plots including *EC* (green and vertical lines) and *Gravel* (yellow and horizontal lines).

Table 1: Details of the two experimental GRs plots use in the study.

GR name	Vegetation	Layer			
		Substrate	Drainage		
	Species	Composition	Height[mm]	Type	Height[mm]
EC	Sedum album, sedum reflexumlarix, sedum reflexum germanium, sedum sexangulare, sedum floriferum	60 % poz-zolana(7/15) 20 % poz-zolana(3/6)	100	Expanded Clay(10/20)	50
Gravel				Gravel(20/25)	50

Table 1. The EC plot is equipped with several sensors. A meteorological station is placed on the roof at 0.3m above vegetation (for rainfall data, external temperature and humidity, wind speed and direction and air pressure measurements). Inside the GR substrate two TDR (Time Differential Reflectometry) per pilot-scale and soil temperature record using five Platinum thermometers (PT100) sensors at different depth for continuous water content and soil temperature monitoring along vertical profile. Finally, the excess water, drained out of the substrate and drainage layer is measured with tipping bucket water gauge at the base of the roof (water outflow) with a resolution of 0.04 mm. Run-off flow from each roof compartment is measured continuously at the outlet of the downspouts with tipping buckets (Figure 2 a). The Gravel plot is equipped with the same meteorological station as EC plot at 0.3m. Inside the Gravel plot two temperature sensors (PT100) are placed at the top and at the base of the gravel (Figure 2b).

Automatic acquisitions are made at 60 minutes frequency. There were dysfunctions on Gravel temperature data logger between 01/07/2014 and 31/12/2014 and no data was acquired on that period.

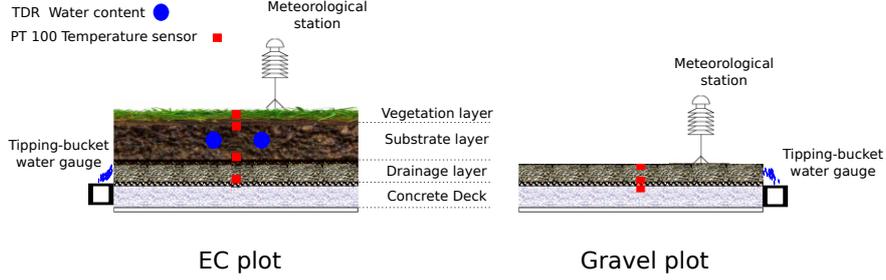


Figure 2: Design of the GR experimental plot, showing the positions of the various sensors (red squares for temperature sensors, blue circle for water content sensor and black square for drainage water gauge). Left sketch represents EC plot and right sketch Gravel plot.

2.2. Performances evaluation

The hydraulic performances of a GR are complex to address in a unique way. Depending on the observed parameters and on the expected behaviour, several indicators can be relevant. Most of studies aimed at modelling the hydrology of GR (Hilten et al., 2008; Palla et al., 2009; Fioretti et al., 2010; Metselaar, 2012). These authors have used indicators related to the storage. In the present work, the performances of GR are estimated using the retention capacity (RC) parameter giving by the following (Eq. 1) defined by Bouzouidja et al. (2016b).

$$RC = \int_{t_i}^{t_f} \left(1 - \frac{Q_{out}}{Q_{in}} \right) dt \quad (1)$$

Where t_i is the start time of the rain event and t_f is final time for GR drainage. In fact, RC can be defined as the amount of water which is not evacuated to the rainfall water collection network during a period under action of gravity.

Considering a rain event, the water balance at the GR scale can be expressed as in Equation (2).

$$Q_{out} = Q_{in} + \Delta S \quad (2)$$

In which Q_{in} [mm h^{-1}] is the incoming rainwater precipitation (P) plus irrigation (if considered), Q_{out} [mm h^{-1}] is the drainage water. ΔS is the quantity of water stored in the substrate and the vegetation. In the following experiments, the evapotranspiration water is included in drainage water (Q_{out}) term.

The thermal performance of GR was chosen in this study according to hot (June to August) and cold (January to February and October to December) periods, which are represented of a summer and winter seasons in Nancy (France). In fact, the rooftop thermal performance is controlled by reducing the surface and internal temperature with vegetation and without vegetation (Niachou et al., 2001; Parizotto and Lamberts, 2011; Ouldboukhitine et al., 2012).

Two temperature variables were derived as indicators of green roof thermal effect according Jim and Peng (2012):

- Temperature of EC plot (T_{EC}) Gravel temperature (T_{Gr})

Table 2: Substrate characteristics according to FLL testing method released 30 months after installation, based on Bouzouidja et al. (2016a) and Bouzouidja et al. (2016b) studies.

	Units	EC substrate		EC drainage	
		Mean	St. Dev.	Mean	St. Dev.
Particle size < 2 mm	(%)	12.5	2.9	0.0	-
Dry density	(kg m ⁻³)	789.5	29.8	273.8	27.4
Wet density	(kg m ⁻³)	820	10.4	320.1	30.7
Total pore volume	(%)	70.0	0.9	86.2	1.8
MWHC (field capacity)	(m ³ m ⁻³)	0.46	0.03	40.0	0.8
Air content at MWHC	(m ³ m ⁻³)	0.07	0.01	0.11	0.08
Organic content	(%)	2.10	0.65	0.5	0.04

- Daily maximum (DM) temperature of EC plot (T_{EC}) Gravel temperature (T_{Gr});
- Average daily maximum temperature (ADM) of EC plot (T_{EC}) Gravel temperature (T_{Gr}).

Both energy and water recorded performances of the GR were analysed by comparing at the same time the value of hydraulic parameter given by (Eq. 1) and the reduction of temperature through the GR in the different seasons.

2.3. Substrate characteristics

EC substrate is an extensive commercial substrate which consists of mineral (80%) and organic parts (20%). Pozzolana materials are extracted in a quarry located in the "Massif Central" mountain, in the center of France. The pozzolana aggregate size distribution is the following: 20% of the pozzolana aggregate diameters ranged from 3 to 6 mm, and 60% from 7 to 15 mm. The organic part is composed of 10% of peat dust and 10% of maritime pine barks (Bouzouidja et al., 2016a) (Table 1). Laboratory tests of these substrates were carried out according to the *Guidelines for the Planning, Construction and Maintenance of Green Roofing of the German Landscape Development and Landscaping Research Society* (FLL, 2008) and previous works (Bouzouidja et al., 2016a,b). The tests performed included Particle Size Distribution (PSD), apparent density (dry condition and at max water capacity), total pore volume, maximum water holding capacity (MWHC), permeability and organic content (Table 2). To address the uncertainty of testing substrates consisting of heterogeneous mixtures of different materials, tests were conducted using different samples of substrate and drainage (expanded clay). It was observed that individual samples of each specific material provided different results (Stovin et al., 2012; Berretta et al., 2014; Bouzouidja et al., 2016b). Often the raw materials composing the substrates are sourced by different suppliers, resulting in material characteristics per sample that vary from the nominal expected values. For this reason, the results presented in this paper refer to the specific samples used in the field installation.

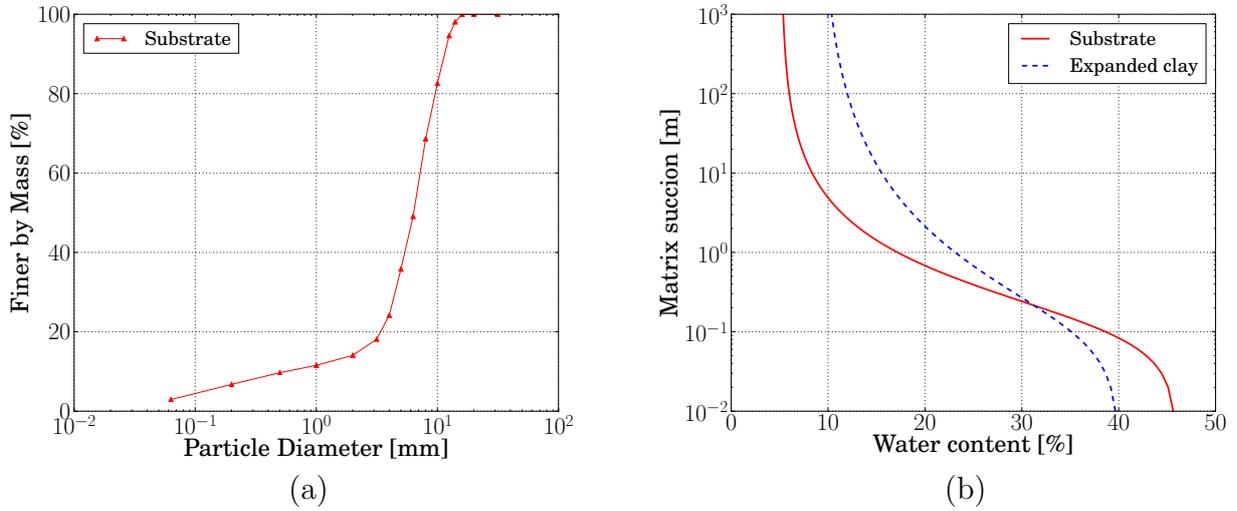


Figure 3: Particle size distribution (PSD) of the three tested substrates (a) and moisture release curves resulting from the pressure plate extraction test (b).

3. Results and discussion

3.1. Green roof physical and hydraulic characteristics

The physical characteristics of the substrates are reported in Table 2, while the PSD and moisture release curve are shown in Figure 3.

In general the substrate, although different in composition and material, is characterized by a higher proportion of finer particles (18%). This characteristic is not surprising considering that the substrate was developed according to the FLL guidelines, which restrict the range of permissible granulometric distributions. The MWHC of substrate from the laboratory test is $0.46 \text{ m}^3 \text{ m}^{-3}$, slightly higher than the expanded clay ($0.39 \text{ m}^3 \text{ m}^{-3}$) due to its higher organic content and finer gradation.

The EC drainage is a lightweight, low density (273.8 kg m^{-3}) characterized by higher porosity (86.2%) and neglected organic content. The substrate and the drainage have not retention curve, consistent with their characteristics. The wilting point is reached at 9.0% and 11.4% volumetric moisture content respectively for EC substrate and drainage. The shape of two EC substrate and drainage are different due to a difference of porosity (very high for drainage) and the organic levels of substrate.

3.2. Characterization of the monitored weather periods

The 2012 period record contained 774 mm with 122 d rainfall events ($P > 1 \text{ mm}$) and 15 d of DWPs. The climate in Nancy (France) is generally temperate with an average 656.1 mm of rain per year (source Météo France office data series 1930–2015).

The aim of this study was to investigate the moisture content behaviour during dry (DWP) and wet weather periods (WWP). Four periods were selected in which with rainfall (WWP) and no rainfall (DWP) or runoff was observed for a continuous period of at least

Table 3: Selected climatic characteristics and initial moisture content conditions (θ_0) together with mean, median and standard deviation of the daily moisture loss calculated for EC plot

-	-	Moisture loss (mm day ⁻¹)	T(°C)	Wind speed (m s ⁻¹)	RH(%)	Solar radiation (MJ m ⁻²)	
01-15 January (15 days)	Jan- uary 2012	θ_0 (m ³ m ⁻³)					
		Median	0.42	5.62	3.12	86.08	1.34
		Mean	0.42	5.31	3.51	85.75	1.81
		St. Dev.	0.01	3.75	2.41	8.2	1.20
1-13 2012 days)	May (13	θ_0 (m ³ m ⁻³)					
		Median	0.39	13.15	2.70	76.00	11.13
		Mean	0.38	15.38	2.97	71.84	12.08
		St. Dev.	0.02	4.85	1.67	16.50	3.97
10-22 2012 days)	July (12	θ_0 (m ³ m ⁻³)					
		Median	0.39	16.95	2.00	70.76	12.61
		Mean	0.38	18.55	2.45	70.11	12.07
		St. Dev.	0.03	3.22	1.40	15.96	4.42
13-29 Septem- ber 2012 (16 days)		θ_0 (m ³ m ⁻³)					
		Median	0.12	13.54	0.70	78.40	8.64
		Mean	0.19	14.25	1.05	73.42	8.53
		St. Dev.	0.11	4.56	1.20	19.37	3.22

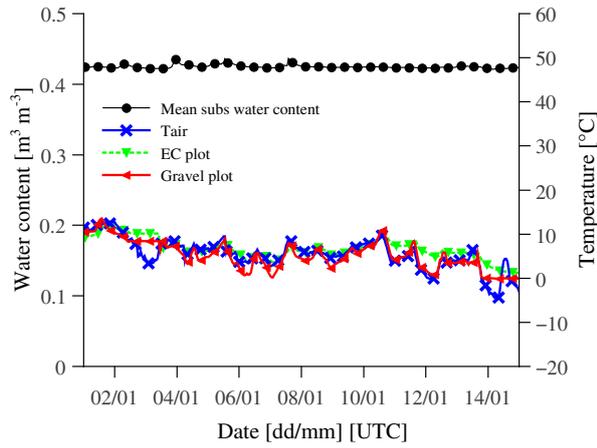
twelve days. The periods were classified as corresponding to either cooler or warmer periods. This conditions are in the two cooler periods (January and September 2012) correspond to typical conditions in winter and fall with mean temperatures of 5.6 and 13.5 °C. Conditions during the two warmer periods (May 2012 and July 2012) were comparable to typical spring and summer conditions in Nancy (mean temperatures between 15.5 and 18.5 °C). According to Stovin et al. (2012); Berretta et al. (2014), we supposed the initial moisture content, θ_0 , is expected to influence moisture loss rates. For each of the period (DWPs and WWPs) considered, the absolute values of θ_0 , and the ratios of θ_0 vary between period (warm and cold). The two cooler periods were characterized by high and low θ_0 respectively, whilst the two warmer periods corresponded to high and medium θ_0 . The characteristics of the selected DWPs and WWPs are represented in Table 3.

3.3. Moisture content fluctuations during selected periods

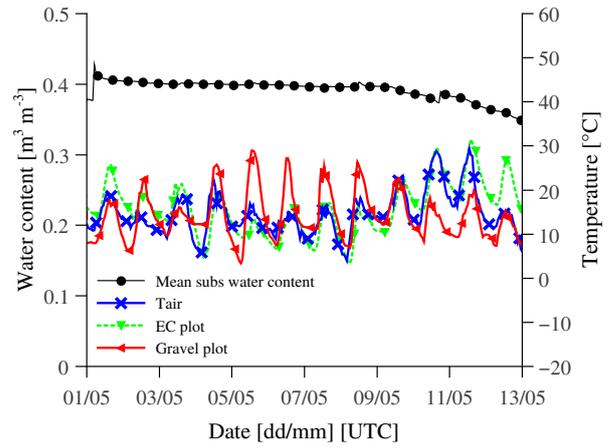
Figure 4 shows the temporal variations in moisture content at 66 mm depth and the temperature at 100 mm from the substrate surface during the month of January, May, July and September 2012 for the tested GR (EC) and non-vegetated roof (Gravel) configurations.

In general it can be seen that the substrate water content slowly decreases during DWPs, and that water content are restored to their maximum value (i.e. field capacity–MWHC) during the WWPs, which also result in runoff. Some of the smaller rainfall events result of an increases in the substrate water content, but are insufficient to restore moisture to field capacity or to generate runoff from the GR. One of the most important effects created by the presence of water is the reduction of the temperature inside the GR and the attenuation of temperature fluctuations. In traditional roof, made of high absorption materials, the surface layer reach high temperature due to the combination of the relative humidity and the solar radiation, which determines an important thermal storage. It can be clearly seen that the water content variation reflects the rainfall events in 'medium' and 'low' initial water condition respectively in July and September 2012. Between the two cooler periods of January and May 2012, the rainfall events with a total depth of 39.7 mm and 'high' initial water condition did not alter the moisture content within the EC plot. In contrast, during September 2012 with a total rainfall depth of 42.8 mm and 'low' initial water condition alter the moisture content within the EC plot. The weather conditions and initial moisture content can explain the contrasted GR behaviour. Other studies showed that the antecedent soil moisture conditions impact the amount of water in substrate (Palla et al., 2009; Stovin, 2010; Stovin et al., 2012). Berretta et al. (2014) observed that the rate of moisture loss or gain is also due to the plant's transpiration.

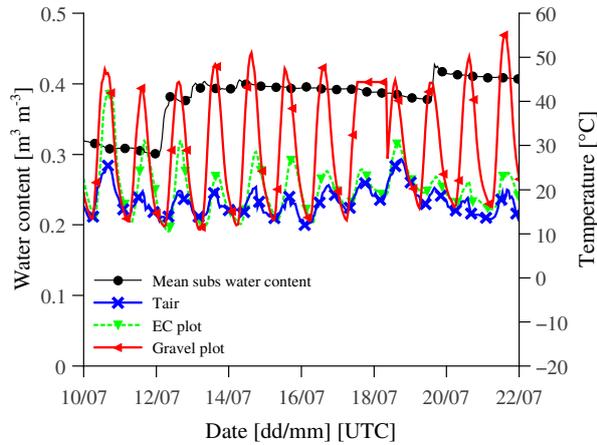
The thermal performance of the GR structure was evaluated by comparison between the internal temperature on the no vegetated roof (Gravel) and the temperature inside the substrate layer. By this analysis it was possible to evaluate the reduction due to the GR presence represented in Figure 6. It seems that the EC plot has a lower temperature level during 'warm' period in July 2012 compared to Gravel plot and the difference between them are 9.9 °C. This reduction is due to the amount of water after the rainfall event (after July, 12th 2012). This scenario is repeated in September 2012 ('low' initial water condition). Sun et al. (2013) founded a reduction between 3.2 and 4.2 °C due to presence of GR installed in



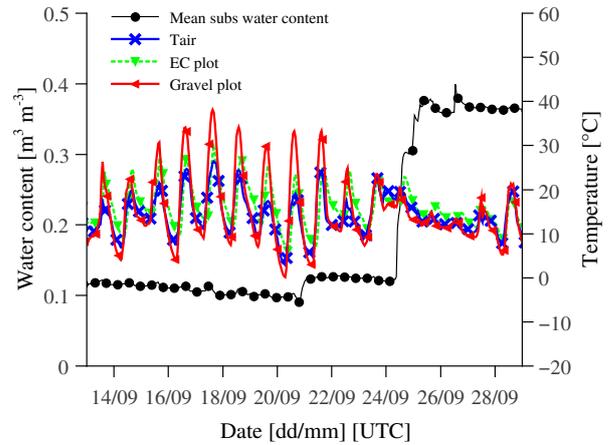
(a)



(b)



(c)



(d)

Figure 4: Moisture content (black round and continuous line) (left axis) and temperature (right axis) behaviour for the EC (green inverted triangle and dotted line) and Gravel plots (red horizontal triangle and continuous line) and selected conditions: low (d), medium (c) and high (a and b) moisture content during one year in 2012.

Tsinghua University campus, Beijing, China and Princeton University campus, New Jersey, US. Both sites are located at a similar latitude (40°N). From the results it can be deduced that, during warm periods with significant solar radiation, the shade effect of vegetation (Leaf area Index and albedo), the transpiration of the plants, and the evaporative cooling effect from substrate contributes to reduce the external surface temperatures during daytime. These results confirm those of (Tabares-Velasco and Srebric, 2012; Coma et al., 2016)

3.4. Storm water management performances

The hydrological behaviour of the experimental GR in the temperate town of Nancy was examined on a number of rainfall events basis over a twelve-months period. Seven out of the sixteen rainfall events monitored did not produce any subsurface outflow, seven produced subsurface outflow with a peak flow lower than 1 mm h^{-1} and three produced subsurface outflow lower than 0.04 mm h^{-1} which is the tippet bucket accuracy, and only three events produced a significant subsurface outflow with peak flows greater than 1 mm h^{-1} . In all events the rainfall volume was completely infiltrated (no surface runoff occurred) and only partially exfiltrated. The synthetic index (retained volume) used for describing the GR and traditional roof hydraulic performances are listed in Table 4. The retained volumes for the EC and Gravel plot were calculated as the percentage difference between the volume of rain and the discharged volume according (Equation (1)), and ranges between 56.5 % and 100 %, with an average value of 86.9 % and a standard deviation of 13.8 % for EC plot and ranges between 1 % and 100 %, with an average value of 81.3 % and a standard deviation of 31.8 %. Speak et al. (2013) founded when comparing GR and traditional roof that average retention is higher on the GR (65.7 %) than on the traditional roof (33.6 %) and the difference is highly significant. Despite this result, there is a lot of variation within the retention data, with the GR retaining between 22 % and 100 % and the traditional roof between 8 % and 72 %. Mentens et al. (2006) founded ranges between 27 % and 81 %, with an average value of 50 % for GR and ranges between 9 % and 38 %, with an average value of 19 % for traditional roof.

The hyetograph and the corresponding GR hydrographs (EC plot) and impervious rooftop hydrographs (Gravel plot) for four periods rainfall events are illustrated in Figure 5. From the comparison of GR measured hydrographs with the reference impermeable roof simulated hydrographs it clearly shows the ability of GR to attenuate stormwater runoff peaks with respect to the impervious roof (see Figure 5).

3.5. Seasonal impact on water retention and temperature

The runoff from the GR and non-vegetated roof in North-East France was measured from January to December 2012 and 2014. The monthly water balance from the GR and the non-vegetated roof for a full year is given respectively for 2012 and 2014 in Figure 6a and Figure 6b. For the whole period the monthly average precipitation was respectively 64 mm in 2012 and 55 mm in 2014. The monthly runoff quantities during the observation period are relatively low due to the above mentioned fact that about 50 % of the precipitation fell in spring and summer, this is caused by an important substrate temperature during summer and a hot weather conditions (Figure 4 and Table 3). The seasonal data show the differences

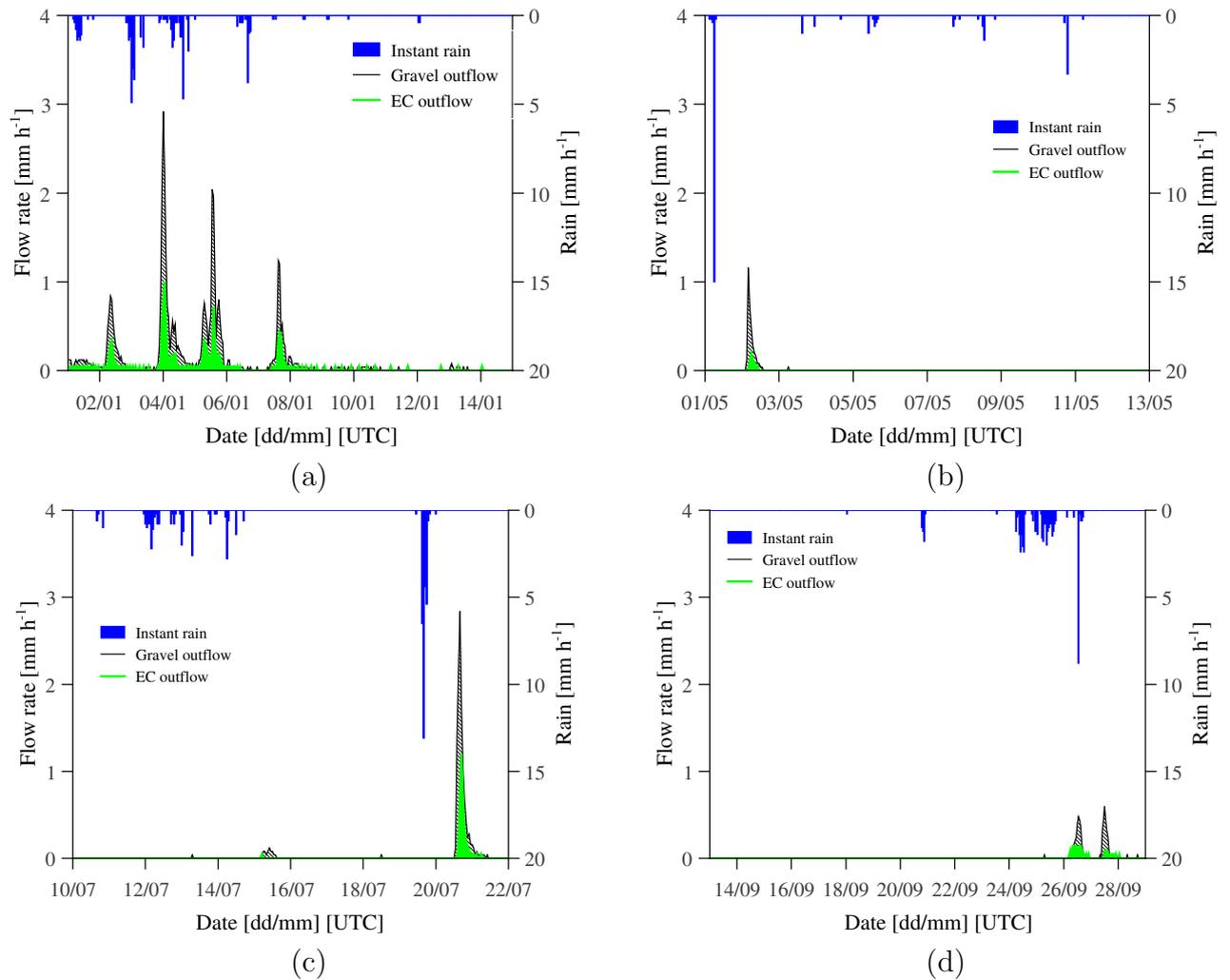


Figure 5: hydrograph of the EC (green solid area) and Gravel (grey dotted area) plot systems during one year in 2012 for selected conditions: low (d), medium (c) and high (a and b) moisture content. The left axis represents the outflow rate in mm h^{-1} and the right axis the rain flow rate in mm h^{-1} .

Table 4: Events observed at the GR of the Nancy laboratory (France) for the whole GR during the first phase of the monitoring campaign and percentage of retained volume and peak flow reduction.

Event [dd/mm/yyyy]	Rain depth [mm]	Max flow peak [mm h ⁻¹]	Retained volume	
			Gravel	EC
			[%]	
03-08/01/2012	39.7	1.0	0.8	70.5
18-23/01/2012	29.8	0.6	14.4	74.5
09/04/2012	10.3	No outflow	100.0	100.0
01-03/05/2012	17.6	0.3	80.6	97.1
06/06/2012	10.0	No outflow	100.0	100.0
11/06/2012	24.2	No outflow	100.0	100.0
12/07/2012	11.1	No outflow	100.0	100.0
19-21/07/2012	30.6	1.3	63.7	86.6
24-28/09/2012	42.8	0.3	87.6	94.6
03/10/2012	13.0	0.04	100.0	99.6
13/10/2012	12.3	0.04	97.0	74.7
01-05/11/2012	51.1	0.7	57.6	80.7
09/11/2012	10.1	0.04	99.6	93.0
15/12/2012	13.0	No outflow	100.0	92.3
21-23/12/2012	12.9	No outflow	100.0	56.5
26-27/12/2012	17.9	No outflow	100.0	70.9
mean	–	–	81.3	86.9
Dev. Std.	–	–	31.8	13.8

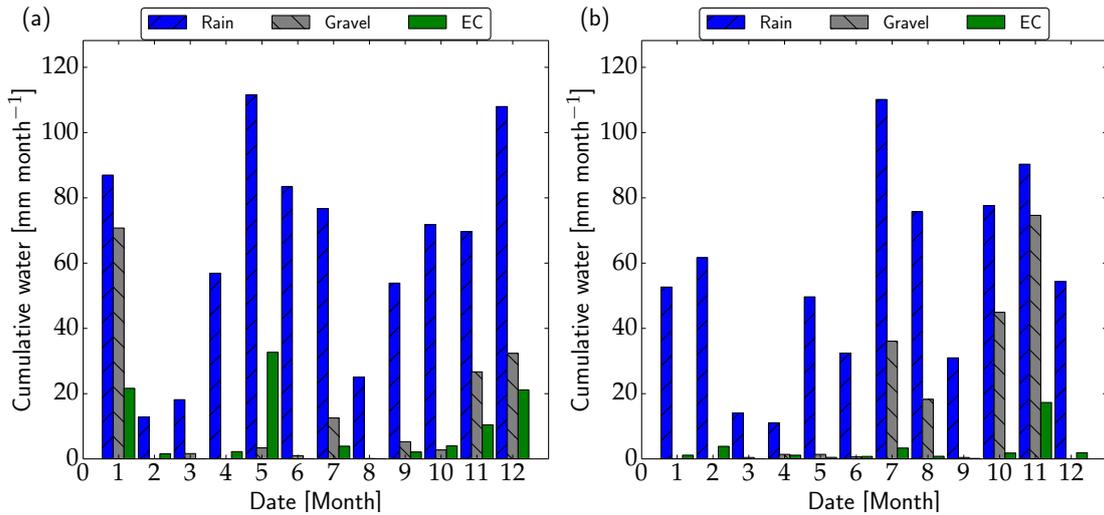


Figure 6: Evolution of EC (solid green bar without diagonal line) and Gravel (solid gray bar with left to right diagonal line) plots drainage outlet water and rain incoming (solid blue bar with right to left diagonal line) during 12 months between January to December 2012 (a) and January to December 2014 (b).

which favor GR runoff during winter period (20 to 25 %) comparing to gravel roof (30 to 82 %). In summer period, as a result of hot weather conditions (hot temperature and low rainfall intensity), both GR and gravel roof runoff is slightly different respectively 5 % and 15 %.

The concept of seasonality differs from one author to another and were differently interpreted. Kaufmann (1999); Mentens et al. (2006) considered two seasons (winter (1 October-30 March) and summer (1 April-30 September). Kaufmann (1999) has examined data on a 5 cm gravel roof and a GR with 10 cm. Pairwise comparisons of the percentage of runoff during the two periods showed that the runoff was significantly higher during winter. This was both the case for the gravel roof (86 % winter runoff versus 70 % summer runoff) and the GRs (80 % winter runoff versus 52 % summer runoff).

Figure 7 and Figure 8 compares the daily maximum (DM) substrate temperature for the vegetated and non-vegetated roof respectively in 2012 and 2014. In the 2012 session, Gravel plot has consistently higher DM than EC plot. The temperature peaks and troughs of the two plots are emphasis, but the amplitude at Gravel plot exceeds EC plot. In fact, DM for Gravel plot stays high in hot period (Figure 7c), with 20 % (19 out of 92) of the days exceeding 40 °C. In contrast, DM temperature for EC plot drops notably with only three days (3 % exceeding 40 °C and 41 days (44 %) exceeding 30 °C. In cold period (Figure 7a and Figure 7d), DM temperature for Gravel plot is warmer than EC plot by an average of 3.3 °C.

On the contrary, in 2014 (Figure 8), DM temperature for Gravel plot is respectively slightly warmer than DM temperature for EC plot by 2.9 °C in cold period (Figure 8a) and in hot period (Figure 8b) by 12 °C.

4. Annual variation of water retention capacity and reduction of temperature

The runoff from the vegetated and non-vegetated roof in North-East France was measured from January to December 2012 and 2014. The annual water balance for a full year is given respectively for 2012 and 2014 in Figure 6. For the whole period the precipitation was respectively 774 mm in 2012 and 660 mm in 2014. The runoff was respectively 100 mm and 33 mm for the vegetated roof in 2012 and 2014 and respectively 156 mm and 178 mm for the non-vegetated roof in 2014, which means that the GR is capable to retain precipitations.

5. Conclusion REFAIRE LA CONCLUSION

With the purpose of investigating the hydrological and thermal processes within GR systems a comparative long term field monitoring program has been carried out between two laboratories of the University of Lorraine (LEMTA and LSE-INRA) and a laboratory of Environmental Minister (Cerema) since July 2011. This paper focused on the soil moisture and temperature behavior in extensive GR during dry and wet periods due to weather conditions. The study is supported by 24 months monitoring in 2012 and 2014 (January to

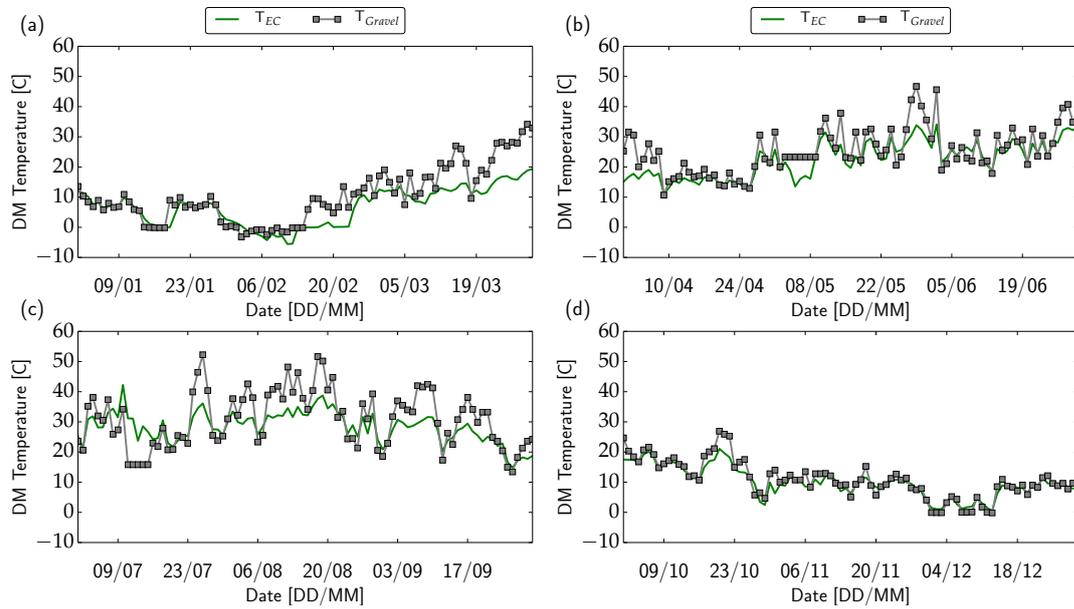


Figure 7: Daily maximum (DM) inside temperature in: i) cold period (a and d), ii) hot period (c) and iii) temperate period (b) between EC and Gravel plot in 2012.

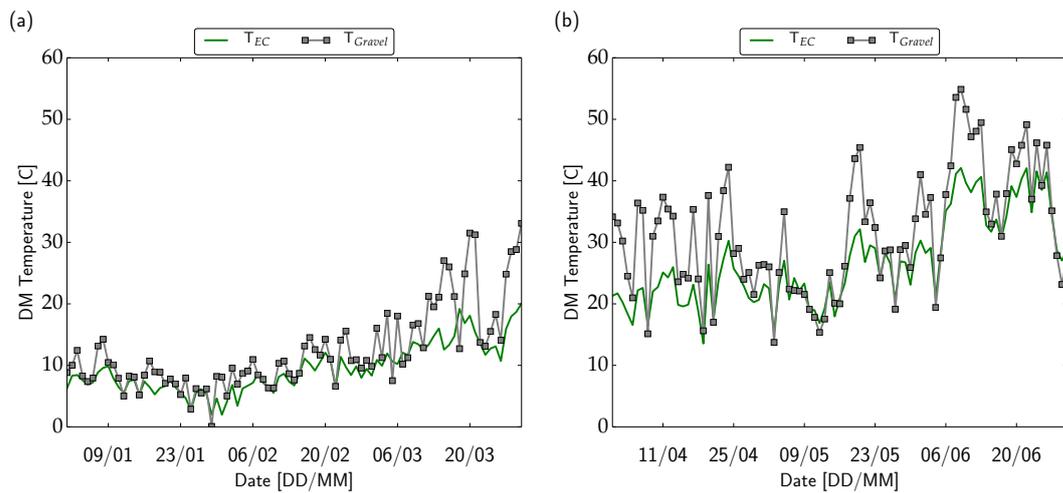


Figure 8: Daily maximum (DM) inside temperature in: i) cold period (a) and temperate period (b) between EC and Gravel plot in 2014.

December) of the moisture content and temperature within substrate and drainage layers of one vegetated roof and non-vegetated roof. Water content reflectometers and Platinum resistance thermometers located at different soil depths were used to measure the soil moisture and temperature behavior and to record temporal changes in moisture content at a one-hour resolution.

Green roof can reduce the annual and seasonal rainfall precipitations considerably. The annual retention capacity ranged between 50 % and 83 % during summer $83.4 \pm 6.9 \%$ and $50.2 \pm 15.0 \%$ during winter were observed. The antecedent weather condition and the soil moisture conditions dominates the retention effect clearly compared to other construction details. In fact, even if we have not observed and measured the real impact of evapotranspiration on GR water performance, we supposed that the soil moisture and retention is predominantly influenced by evapotranspiration and the sequence of rainy and dry periods.

Green roof demonstrates great variations in diurnal thermal performance. On average, GR effect could reduce daily maximum temperature through the roof by 3.3 to 12 °C in hot period and 0.5 to 2.9 °C in cold period,

Acknowledgements

This work was supported by the French National Association of research and technology (ANRT) through a CIFRE grant (Conventions Industrielles de Formation par la Recherche) research funded by an association and a company (NIDAPLAST). The authors would like to thank

References

- Alexandri, E., Jones, P., 2008. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. *Building and Environment* 43 (4), 480 – 493, part Special: Building Performance Simulation.
- Berretta, C., Poë, S., Stovin, V., 2014. Moisture content behaviour in extensive green roofs during dry periods: The influence of vegetation and substrate characteristics. *Journal of Hydrology* 511 (0), 374 – 386.
- Bouzouidja, R., Claverie, R., Séré, G., Lacroix, D., 2013. Characterization of the thermo-hydric functioning of *in situ* green roof. *La Houille Blanche* 5, 62 – 69.
- Bouzouidja, R., Rousseau, G., Galzin, V., Claverie, R., Lacroix, D., Séré, G., July 2016a. Green roof ageing or isolatic technosols pedogenesis? *Journal of Soils & Sediments*, 1–8.
- Bouzouidja, R., Séré, G., Claverie, R., Nuttens, L., Lacroix, D., 2016b. Green roof ageing: quantifying the impact of substrate evolution on hydraulic performances. submitted to *Water Resources Management*.
- Carter, T., Rasmussen, T., 2005. Use of greenroofs for ultra-urban stream restoration in the georgia piedmont (usa). In: *Proceedings of 3rd North American Green Roof Conference: Greening Rooftops for Sustainable Communities*.
- Coma, J., Pérez, G., Solé, C., Castell, A., Cabeza, L. F., 2016. Thermal assessment of extensive green roofs as passive tool for energy savings in buildings. *Renewable Energy* 85, 1106 – 1115.
- de Munck, C. S., Lemonsu, A., Bouzouidja, R., Masson, V., Claverie, R., 2013. The greenroof module (v7.3) for modelling green roof hydrological and energetic performances within teb. *Geoscientific Model Development* 6 (6), 1941–1960.
- DeNardo, J., Jarrett, A., Manbeck, H., Beattie, D., Berghage, R., 2005. Stormwater mitigation and surface temperature reduction by green roofs. *Transactions of the ASAE* 48 (48), 1491–1496.

- Fioretti, R., Palla, A., Lanza, L. G., Principi, P., AUG 2010. Green roof energy and water related performance in the Mediterranean climate. *Building and environment* 45 (8), 1890–1904.
- FLL, 2008. Guidelines for the planning, construction and maintenance of green roof. Green roofing guideline.
- Hilten, R. N., Lawrence, T. M., Tollner, E. W., 2008. Modeling stormwater runoff from green roofs with hydrus-1d. *Journal of Hydrology* 358, 288–293.
- Jaffal, I., Ouldboukhitine, S., Belarbi, R., 2012. A comprehensive study of the impact of green roofs on building energy performance. *Renewable Energy* 43, 157–164.
- Jim, C., Peng, L. L., 2012. Weather effect on thermal and energy performance of an extensive tropical green roof. *Urban Forestry & Urban Greening* 11 (1), 73 – 85.
- Jim, C., Tsang, S., 2011a. Biophysical properties and thermal performance of an intensive green roof. *Building and Environment* 46, 1263–1274.
- Jim, C., Tsang, S., 2011b. Modeling the heat diffusion process in the abiotic layers of green roofs. *Energy and Buildings* 43 (6), 1341 – 1350.
- Kaufmann, P., 1999. Extensiv begrünte Flachdächer – ein Gewinn für die Siedlungsentwässerung. *hochschule für technik und architektur, Burgdorf*.
- Kotsiris, G., Androutsopoulos, A., Polychroni, E., Nektarios, P., 2012. Dynamic u-value estimation and energy simulation for green roofs. *Energy and Buildings* 45 (0), 240 – 249.
- Kumar, R., Kaushik, S., 2005. Performance evaluation of green roof and shading for thermal protection of buildings. *Building and Environment* 40, 15051511.
- 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, 217–226.
- Metselaar, K., JUL 2012. Water retention and evapotranspiration of green roofs and possible natural vegetation types. *Resources conservation and recycling* 64 (SI), 49–55.
- Nations, U., 2015. World population 2015 wallchart. Tech. rep., Department of Economic and Social Affairs, Population Division.
- Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., Mihalakakou, G., 2001. Analysis of the green roof thermal properties and investigation of its energy performance. *Energy and Buildings* 33 (7), 719 – 729.
- Ouldboukhitine, S.-E., Belarbi, R., Djedjig, R., 2012. Characterization of green roof components: Measurements of thermal and hydrological properties. *Building and Environment* 56, 78–85.
- Palla, A., Berretta, C., Lanza, L., La Barbera, P., 2008. Modelling storm water control operated by green roofs at the urban catchment scale. In: *11th International Conference on Urban Drainage*, Edinburgh, Scotland, UK.
- Palla, A., Gnecco, I., Lanza, L., 2009. Unsaturated 2d modelling of subsurface water flow in the coarse-grained porous matrix of a green roof. *Journal of Hydrology* 379, 193–204.
- Parizotto, S., Lamberts, R., 2011. Investigation of green roof thermal performance in temperate climate: A case study of an experimental building in Florianopolis city, southern Brazil. *Energy and Buildings* 43 (7), 1712 – 1722.
- Sailor, D., 2008. A green roof model for building energy simulation programs. *Energy and Buildings* 40 (8), 1466 – 1478.
- Santamouris, M., Pavlou, C., Doukas, P., Mihalakakou, G., Synnefa, A., Hatzibiros, A., Patargias, P., 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), 1781 – 1788.
- Speak, A., Rothwell, J., Lindley, S., Smith, C., 2013. Rainwater runoff retention on an aged intensive green roof. *Science of The Total Environment* 461462 (0), 28 – 38.
- Stovin, V., 2010. The potential of green roofs to manage urban stormwater. *Water and Environment Journal* 24 (3), 192–199.
- Stovin, V., Vesuviano, G., Kasmin, H., 2012. The hydrological performance of a green roof test bed under {UK} climatic conditions. *Journal of Hydrology* 414415 (0), 148 – 161.
- Sun, T., Bou-Zeid, E., Wang, Z.-H., Zerba, E., Ni, G.-H., 2013. Hydrometeorological determinants of green roof performance via a vertically-resolved model for heat and water transport. *Building and Environment*

60, 211–224.

Tabares-Velasco, P., Srebric, J., 2012. A heat transfer model for assessment of plant based roofing systems in summer conditions. *Build. Environ.* 49, 310–323.

Tsang, S., Jim, C., 2011. Theoretical evaluation of thermal and energy performance of tropical green roofs. *Energy* 36, 3590–3598.

Wong, N., Cheong, D., Yan, H., Soh, J., Ong, C., Sia, A., 2003. The effects of rooftop garden on energy consumption of a commercial building in singapore. *Energy and Buildings* 35 (4), 353 – 364.