Toward an assessment of the hydrological components variability in green infrastructures: Pilot site of the Green Wave (Champs-sur-Marne)

Pierre-Antoine Versini, Auguste Gires, George Fitton, Ioulia Tchiguirinskaia, Daniel Schertzer

Pierre-Antoine Versini, Auguste Gires, George Fitton, Ioulia Tchiguirinskaia, Daniel Schertzer. Toward an assessment of the hydrological components variability in green infrastructures: Pilot site of the Green Wave (Champs-sur-Marne). La Houille Blanche - Revue internationale de l'eau, 2018, 4, pp.34-42. 10.1051/lhb/2018040 . hal-02060151

HAL Id: hal-02060151
https://hal-enpc.archives-ouvertes.fr/hal-02060151

1DOI 10.1051/lhb/2018040 La Houille Blanche, n° 4, 2018, p. 34-42

Toward an assessment of the hydrological components variability in green infrastructures: Pilot site of the Green Wave (Champs-sur-Marne)

Pierre-Antoine VERSINI, Auguste GIRES, George FITTON,
Ioulia TCHIGUIRINSKAIA, Daniel SCHERTZER

Hydrologie Météorologie et Complexité, Ecole des Ponts ParisTech, e-mail: pierre-antoine.versini@enpc.fr

ABSTRACT. – The Green Wave (GW) site is located in the heart of the Paris-East Cluster for Science and Technology (Champs-sur-Marne, France). Initially designed on aesthetic criteria, this large wavy-form vegetated roof (1 ha) is a particularly interesting case study regarding hydrological and thermic issues. Since 2013, several measurement campaigns have been conducted during the Blue Green Dream project to investigate and better understand its hydrological behaviour. Rainfall, humidity, wind velocity, water content and temperature have been particularly studied. The data collected have been used to study the spatio-temporal variability of these variables. Results have shown they are all characterized by a non-gaussian distribution and a scaling behaviour.

These results have justified the implementation of a continuous monitoring of the GW. It will serve to develop a specific model simulating its hydrological behaviour and able to assess green roof performances.

Key-words: green roof, spatio-temporal variability, Monitoring, stormwater management

Vers une évaluation des variabilités du bilan hydrologique d’une infrastructure verte : site pilote de la vague verte de Champs-sur-Marne

RÉSUMÉ. – La Vague Verte (GW) se situe au cœur du cluster de Sciences et Technologies Paris-Est (Champs-sur-Marne, France). Initialement conçue sur des critères esthétiques, cette vaste structure ondulée et végétalisée (1ha) représente un cas d’étude particulièrement intéressant pour aborder des questions liées à l’évaluation des bilans hydriques et énergétiques. Depuis 2013, plusieurs campagnes de mesures ont été conduites dans le cadre du projet Blue Green Dream pour mieux comprendre son fonctionnement hydrologique. Précipitations, humidité, vitesse du vent, teneur en eau, température ont ainsi été particulièrement étudiées. Les données collectées ont été utilisées pour appréhender les variabilités spatio-temporelles de ces variables. Les analyses menées ont permis de démontrer que celles-ci sont caractérisées par des distributions non gaussiennes et des comportements scalants. Ces résultats ont justifié la mise en œuvre d’un suivi expérimental continu de la Vague Verte. Celui-ci permettra de développer un modèle spécifique capable de simuler son comportement hydrologique et d’évaluer les performances de structures végétalisées.

Mots-clés : toiture végétalisée, variabilité spatio-temporelle, instrumentation, gestion des eaux pluviales

I. INTRODUCTION

Rapid urbanization and adverse impacts of climate change may severely impact urban ecosystems services and functions. Consequences may be numerous: reduction of available water resources, increase of hydrological extremes, pollution of water bodies, poor energy efficiency of buildings, or increase of urban heat island. Blue (storage ponds, detention ponds…) and green (green roofs, bioretention swales, rain gardens, infiltration trenches…) infrastructures can provide solutions to these threats. Such assets encompass technologies developed earlier for hydrological purposes, such as SUDS (Sustainable Urban Drainage System) and WSUD (Water Sensitive Urban Design) but go beyond them. These infrastructures provide effective and multifunctional support to urban adaptation to climate change [Maksimovic *et al.*, 2013]: flood protection, water supply, thermal energy collection, air quality improvement, urban heat island management, amenity increase, biodiversity… Following this line of thought, European Blue Green Dream (BGD) project (http://bgd.org.uk/, funded by Climate-KIC) aimed to promote a change of paradigm for efficient planning and management of new urban developments and retrofitting of existing ones to maximize ecosystem services and increase resilience to climate change.

Among existing blue and green infrastructures, green roofs are surely the most popular, and for this reason have been particularly studied [Voyde *et al.*, (2010), Stovin *et al.*, (2012), Bouzouidja *et al.*, 2013, Yilmaz *et al.*, 2016 among other]. Indeed, they are currently widely implemented all over the world (annual growth between 0.1 to 2 km^2 in Spain, Brazil, Canada, Korea, UK, Japan or France, and higher than 10 km^2 in Germany, eg Lassalle, [2012]), and can provide several benefits strongly linked to thermo-hydrology: e.g. managing urban runoff [Palla *et al.*, 2008, Versini *et al.*, 2015], reducing the heat island by increasing evapotranspiration [Takebayashi and Moriyama, 2007; Santamouris, 2012], building thermal-insulation [Jim, 2014], or protecting biodiversity [Madre *et al.*, 2013].

Despite these works, green roofs still suffer a lack of monitoring and methods for precise assessment of their performances. For this reason, thermo-hydrological processes driving surface energy balance and water budget at both parcel and infrastructure scales (suitable for an urban project) are usually averaged for instance. Regarding the latter for a typical green roof (Eq.1), the discharge flowing out of the structure (Q) is function of precipitation (P), evapotranspiration (ET) and water stored in the substrate (S). Note that evapotranspiration can be related to several meteorological variables (air temperature, wind velocity, relative humidity and radiation for instance) and represents a major factor in urban heat island attenuation by consuming energy.

$$Q = P - ET - S \tag{1}$$

Small-scale -i.e. typically below few hundred meters in time and few minutes in space- variability and complexity of atmospheric fluxes such as precipitation [Mandapaka *et al.* 2009, Gires *et al.* 2014] and wind, are indeed usually underestimated and consequently misjudged. It represents also a significant element of uncertainty introduced in the models. Accordingly, the estimated frequency of some extreme events could also be inappropriate and their consequences badly anticipated. It is thus essential to capture these flows in all their complexity. Multi-scale analysis appears as an efficient tool to account for the high variability of hydro-meteorological fields on a wide range of scale.

Based on these considerations, this paper aims to detail the first experiments conducted on a unique site (containing among others a large green roof of 1 ha) implemented in the heart of the Paris-East Cluster for Science and Technology (Champs-sur-Marne, France). Temporal variability, and in a lesser extent spatial variability, of some of the thermo-hydrological variables directly or indirectly mentioned in Eq. 1 have been particularly studied by using multi-scale analysis tools. This work has not the ambition to characterize the whole water budget but to make a step forward in this direction by presenting some relevant methodologies applied on some particular geophysical variables. It aims to establish a preliminary basis for the implementation of a further and in-depth monitoring setup.

II. EXPERIMENTAL PILOT SITE

II.1. The Green Wave

The French Blue Green Dream demonstration site is located in front of Ecole des Ponts ParisTech (Champs-sur-Marne, France). Since 2013 a large (1 ha) wavy-form vegetated roof (also called "Green Wave" and GW for simplification) is implemented (see Figure 1). It represents a pioneering site where an initially amenity (decorative) design project has been transformed into the BGD research oriented one.

Two types of vegetation has been planted: green grass and a mix of perennial planting, grasses and bulbous. They are based on a substrate layer (210 mm depth for the grass, 280 mm depth for the mix of vegetation respectively), a filter layer (synthetic fiber) and a drainage layer (expanded polystyrene of 3.6 cm). The substrate is composed of volcanic soil completed by organic matter (around 13%) and is characterized by a density of 1446 g/l and a total porosity of 60%.

The site (green roof and impervious areas) is connected to a large retention basin - designed considering that the green roof (around 50% of the total contributive area) is impervious – to collect excess volumes of water during a rainfall event before being routed to the rainwater network. Indeed, for now in France, there is no guideline concerning basin sizing that takes into account the retention properties of green roof. However, such guidelines exist in US for example. The New York City Department of Environmental Protection suggests a modification in the rational method used to design stormwater management systems (NYC, 2012).

II.2. Experiments to measure the (spatio-)temporal variability of Hydro-meteorological components

Several measurement campaigns have been conducted since 2013 on the GW. They aim to investigate and better understand the hydrological and thermal behaviours of such a structure by measuring their temporal variability (and also the spatial variability when it was possible). Rainfall, air humidity, wind velocity, soil water content and temperature – directly or indirectly involved in Eq. 1- have been particularly studied (but also additional environmental variables such as CO_2 concentration). They are detailed in the following.

II.2.1. Precipitation, humidity and IWV measurements

Local rainfall is analysed with the help of data collected by an optical disdrometer Campbell Scientific PWS100. It is made of two receivers, which are not aligned with a transmitter. From the light refracted by each drop passing through the 50 cm sampling area, their size and velocity are estimated. From this, a rain rate is computed every 30 s. The type of hydrometeors (drop, snowflake, hail…) is also distinguished. Disdrometers are now considered as reliable [Frasson *et al.*, 2011, Thurai *et al.*, 2011] and their use is quickly expanding. Numerous drop size distribution studies have been carried out [Thurai *et al.*, 2011, Jaffrain and Berne, 2012b]. It is possible to estimate from their raw data polarimetric radar parameters [Jaffrain and Berne, 2012a], which can be used for ground validation of radar data.

The device is installed since September 2013 on the roof of the Ecole des Ponts ParisTech building (see Fig. 1) and data analysed in the paper was recorded until March 2014. More information on the measurement campaign can be found in Gires *et al.* [2016]. The PWS100 is actually operating with a collocated relative humidity sensor (CS215), which measures the ratio between the partial pressure of water vapour in an air-water mixture and the saturated vapour pressure of water at a prescribed temperature. This data is generated at the same 30 s time step.

A fixed GPS ground receiver operated by the Ecole Nationale des Sciences Géographique (www.ensg.eu) is also installed on the same roof few meters away from the disdrometer. The GPS signal from the satellite to the ground receiver is delayed in the atmosphere with regards to expectation if the propagation was occurring at light celerity. This delay can be related to the Integrated Water Vapour content (IWV in kg.m-2), which is the total amount of water vapour present in the vertical atmospheric column of unit section. Water is mainly located in the troposphere (i.e. below roughly 10 km); see Bevis *et al.* [1994] for more details. This side product of GPS ground stations is commonly assimilated in numerical weather models or used for validation [Guerova *et al.*, 2003; Ducrocq *et al.*, 2014]. This station is operational since 2001 and provides data with a 30 s time step. In this paper, mainly the periods during which rainfall is recorded are used. There is obviously a

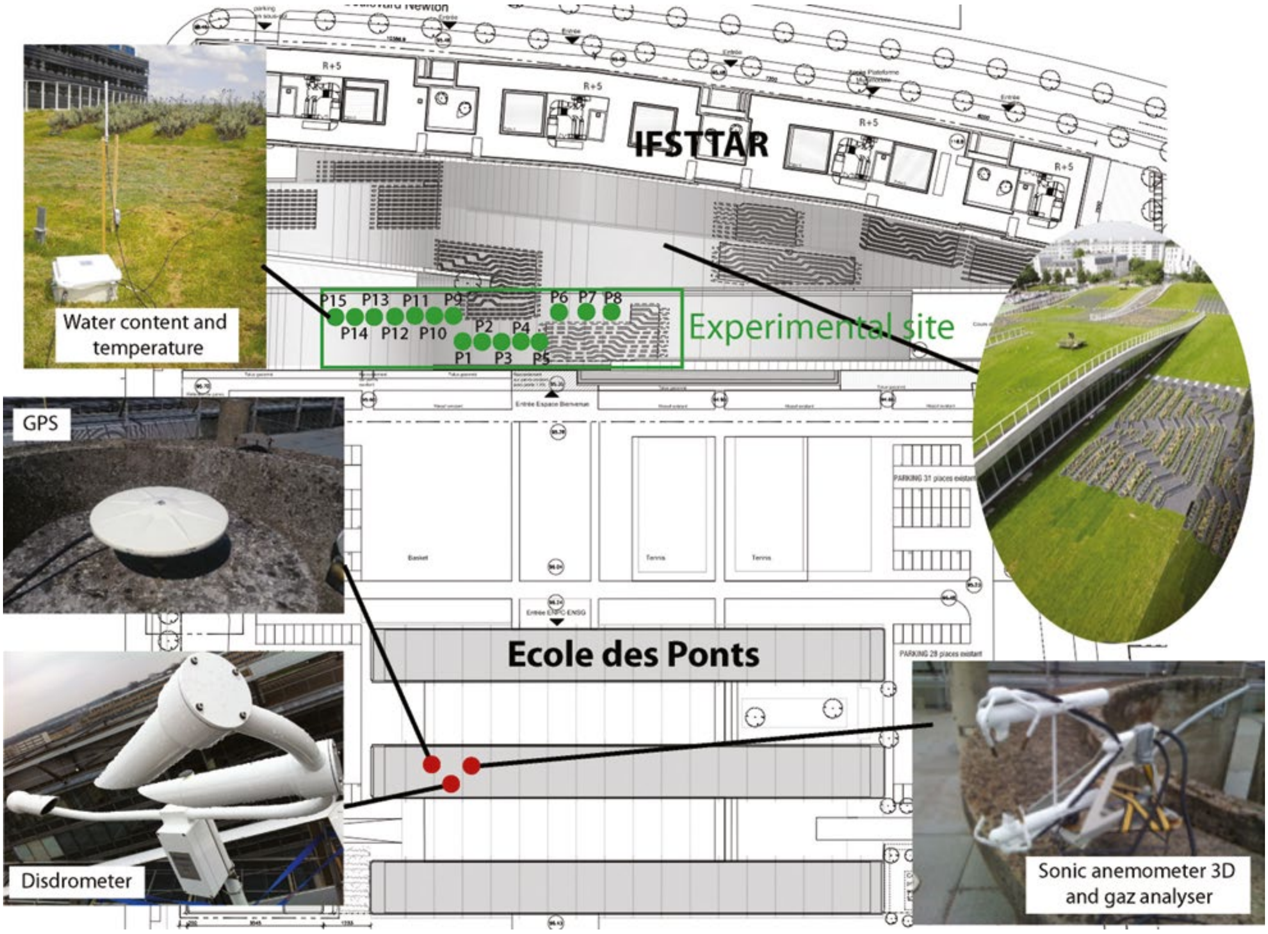

Figure 1: *The GW in the Paris-East Cluster for Science and Technology and the different tested measuring instruments. P1 to P15 represent the different locations where soil water content and temperature were measured.*

large gap between the observation scale of this measurement and the disdrometer one. Hence IWV content will only be used to check whether it is correlated with rainfall as it has been suggested in Ralph *et al.* [2006].

II.2.2. Wind velocity, air temperature and concentration of gases measurements

Ecole des Ponts operated a Campbell Scientific IRGASON (integrated gas analyzer and sonic anemometer) eddy-covariance system to study atmospheric quantities: three-dimensional wind speeds and air temperature were measured with sonic anemometers and thermometers, while CO_2 and H_2O densities with an infrared gas analyzer (IRGA). While the quality of sonic anemometer and infrared gas measurements is a long and well studied topic [Auble and Meyers, 1992] -the reliability of the measurements therefore is of perhaps less concern than those of disdrometers- large uncertainties arise when these quantities are used to estimate surface-layer fluxes. Eddy-covariance (EC) methods are a long established means for measuring, for example, latent and sensible heat fluxes for the computation of surface energy balance budgets. Under the following assumptions: fluctuations are statistically stationary when time averaging and net turbulent transfer is due mainly to turbulent eddies, the vertical flux density may be computed by decomposing the vertical wind component and another variable (usually gas concentration, temperature or momentum) into their mean and fluctuating components (see Ueyama *et al.*, 2012 for a more detailed discussion on this topic). The flux density is then proportional to the covariance of the fluctuating component of the vertical wind and the fluctuating component of the other desired variable, gas concentration say.

In order therefore to capture the variability due to atmospheric turbulence for the computation of vertical fluxes, it is suggested [Aubinet *et al.*, 2012] that atmospheric variables be measured at time resolutions higher than 1–10 Hz depending on the surface characteristics. EC systems are a necessary and fundamental tool for understanding the physical properties of green roofs. The device was installed on the roof of Ecole des Ponts ParisTech, i.e., at a height of 20 m from ground level (see Figure 1). Over 10 days in June 2013 a total of 28 hours were measured at a frequency of 15 Hz (or 0.067 s).

II.2.3. Soil water content measurements

As presented in the sub-section 2-1, green roof substrate is often an engineering soil mix containing a large majority of expanded slate completed by organic matter. This mix differs from traditional soils and can be considered as a typical volcanic media. Several studies related to green roof (see Hilten *et al.*, 2008 and Palla *et al.*, 2009 for instance) have already performed *in situ* measurements including volumetric moisture content by time domain reflectometry (TDR). The fundamental principle for TDR water content measurement is that the velocity of electromagnetic wave propagation along the probe rods is dependent on the dielectric permittivity of the material surrounding the rods: as water content increases, the propagation velocity decreases because of increasing dielectric permittivity. Dielectric permittivity is related to volumetric water content in mineral by using an empirical relationship proposed by Topp *et al.* [1980]. As observed by Tomer *et al.* [1999] the coarser samples of volcanic soil has a typical dielectric behaviour, and dielectric constant – water content relation has to be established cautiously. Implemented vertically, the punctual integrated value of water content provided by the sensor can be used to assess the water storage (*S* in Eq. 1).

For this study a Campbell Scientific a CS655 sensor was implemented vertically on the Green Wave to monitor soil water content along its 12-cm rods in different locations of the substrate (see Figure 1). It is an improved TDR sensor that combines measurements of moisture, temperature and conductivity to automatically give soil volumetric water content. These experiments were conducted from 29th July 2014 to 6th August 2014 with a time resolution of 5 minutes. Note that for this experiment, the TDR sensor was not especially calibrated for this particular substrate, as we focused our study on the space-time variability.

II.2.4. Soil temperature measurements

Potential evapotranspiration (PET) refers to the expected rate of evapotranspiration associated with a crop under well-watered conditions, which is approximately the case of the GW. Transformed in actual evapotranspiration (AET), PET is related to surface energy balance and water budget. Many alternative PET formulae have been proposed [Oudin *et al.*, 2005]: temperature-based approaches, energy-based approaches or combination approaches. For example, the Thornthwaite equation, requiring only the local temperature, has already been used for green roof applications [Stovin *et al.*, 2013]. Temperature sensors are then used to measure temperature at the ground level or in several substrate depths to obtain a temperature profile [Fioretti *et al.*, 2010, Chan and Chow, 2013].

For now, only green roof surface temperature has been monitored by such a sensor on the GW. The Campbell Scientific CWS900 temperature wireless sensor has been used for this purpose. It consists of a thermistor encapsulated in an epoxy-filled aluminium housing. It measures the range of – 35° to + 50° C. This kind of wireless system allows making measurements in locations where the use of cabled sensors is problematic. It can also be useful to increase the number of measurements being made when the datalogger does not have enough available channels left for attaching additional sensor cables. As water content measurements, these experiments were conducted on several locations from 29th July 2014 to 6th August 2014, but with a time resolution of 1 minute.

II.3. Variability and Randomness

After a data quality assessment, a large majority of the collected data were conserved (> 95%). Some different time periods of 30 minutes (as measurements were not carried out simultaneously) are showed in Figure 2 to illustrate the temporal variability for each device. Continuous measures and their corresponding increments (see Eq. 2) are depicted.

$$\Delta\varphi(t) = \varphi(t + \tau) - \varphi(t) \qquad (2)$$

Where $\Delta\varphi$ is the increment, φ is the quantity being analysed, t is time and, τ is a time-scale separation.

Studied hydro-meteorological variables appear to significantly vary in time, even on a short period. A unifying theme across all of the measurement campaigns performed at Ecole des Ponts ParisTech is also the non-local and wildly varying increments at small-scales. Several tools and techniques are usually used to assess this spatio-temporal variability. In this paper, temporal variability of obtained measures were analysed by studying increments spectra and distribution when sufficient data was available (it was not the case concerning water content for which more basic study was conducted). These two approaches are presented in the following.

II.3.1. Scaling

A scaling analysis provides information regarding the non-locality of the increments. The second-order scaling

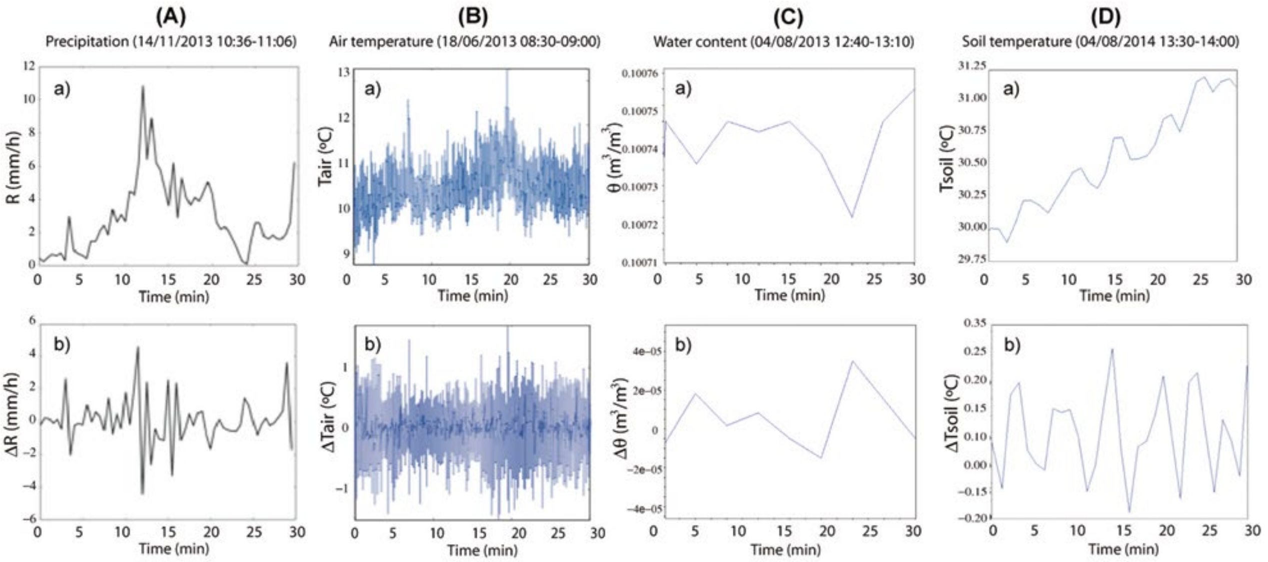

Figure 2: *Measurements (a) and increments (b) computed on a 30-minute time period for rainfall (A), air temperature (B), water content (C), soil temperature (D).*

properties of a sample can be analysed by transforming the sample into frequency-space using the Fourier transform; the frequency ω is inversely proportional to the time-scale separation τ, i.e., τ = 1/ω. If the quantity is scaling, its energy spectrum, E(ω) (the absolute square of the Fourier transformed sample), will follow a power-law behaviour:

$$E(\omega) \propto \omega^{\beta} \quad (3)$$

The numerical value of the exponent β can be computed from the log-log plot of the energy spectrum versus frequency, thus providing information about the long-term memory/or non-locality of the sample. If β > 1, the studied field is considered as non-conservative, that is to say its mean is different regarding the considered scale.

II.3.2. Small-scale variability

Small-scale increments can be analysed by computing the empirical probability distribution (EPD) of the measurements. A simple method for computing the EPD non-parametrically is to normalise the histogram of the sample data such that its area is one. Alternatively, the empirical probability of non-exceedance (denoted Pr) may be computed as the rank divided by the number of elements. In both cases the EPD can be compared to the equivalent Gaussian distribution, estimated with the help of the empirical mean and standard deviation of the studied sample. The comparison with the Gaussian model is done to highlight the heavy-tails of the EPDs (note to further highlight this feature the logarithmic probability may be used). The heavy-tails represent the wild part of the randomness of the field; the much more frequent occurrence of extremes characteristic of a multiplicative cascade process.

III. PRESENTATION OF THE RESULTS

III.1. Precipitation, humidity and IWV measurements

The analysis is carried out on 67 rainfall events from the studied period from September 2013 to March 2014. They correspond to a total rainfall depth of 205 mm and the maximum recorded rain rates are 128, 69.7 and 12.7 mm/h with temporal time steps of respectively 30s, 5min and 1 h. 64 min (128 time steps long series) were extracted from these events. This length, which should be a power of 2, is a trade off between using long series that would enable to confirm scaling on extended range of scales, and “wasting” available data. Here 77% of available data is used. Each sample is then considered as an independent realization of the same process and ensemble analyses are performed. The same time steps are extracted for precipitation, humidity and IWV.

Figure 3 (a to c) displays the power spectra analysis (i.e. Eq. 2 in a log-log plot) obtained by averaging the 67 event-based spectra for the three studied fields. It appears that they all exhibit a good scaling behaviour on the range of scales 0.5-64 min. This confirms previous results obtained for rainfall [de Montera *et al.* 2010; Royer *et al.*, 2008], but was not showed for relative humidity and IWV to the knowledge of the authors. It means that theses fields in which the GW is embedded exhibit variability across scales during rainfall events. The values of the spectral slope are slightly greater for relative humidity (β = 2.46) than for rainfall (β = 1.93) but they both corresponds to non-conservative fields. With regards to IWV we find a β = 2.36, which is closer to the relative humidity. It should be noted that for IWV content the analysis was also carried out on longer series since this field does not contain any zero values, which might bias the analysis. A similar scaling behaviour is retrieved from 30 s to 34 h, the maximum sample duration tested.

The Gaussianity of the rainfall increments, ΔR = R(t + τ) – R(t), are also tested and results are shown in Fig. 3 (g). The non-gaussianity is explicit, and fat tail reflects that assuming Gaussian statistics would lead to severe underestimation of the extreme rainfall increments.

Finally the potential correlation of the IWV content with rainfall is investigated to check whether this field could be used as a tool for short term forecasting of rainfall events. It was found that IWV has a general tendency to decrease during rainfall events, which is expected since a portion of the water vapour is actually converted into rainfall. However no obvious correlations were found between the quantitative decrease of IWV content and the strength of the rainfall event measured locally. A possible explanation of these discrepancies is the gap between the observation scales of the two devices; indeed IWV is an average over a roughly 10 km column whereas the rainfall measurement is point wise.

III.2. Wind velocity, air temperature, and concentration of gases measurements

Figure 3 (d) shows the log-log plot of the spectral analysis of the horizontal wind velocity components u and v, and temperature, T. The linearity (while broken), between the logarithm of the energy spectrum and the logarithm of the frequency, confirms that all three quantities are scaling. Moreover, the superposition of the spectra confirms that the temperature acts as a passive scalar.

Figure 3 (h) is a log-linear plot of the empirical probability density of the increments of the temperature, ΔT, measured by the IRGASON, over half an hour with time-scale τ = 0.066s. The heavy-tails of the fluctuations of the temperature are characteristic of the non-Gaussian statistics of a turbulent velocity (see for example Morales, 2012). The heavy-tails mean that extremes are much more frequent (in some cases over 10 σ between observations and the Gaussian model). These results highlight the fact that passive scalars must be treated as turbulent quantities, wildly varying and non-local. Attempting to characterise this variability with respect to the benefits of green roofing will be difficult using standard statistical methods, e.g., the mean and variance.

Note, we have chosen to focus on the temperature because it is a scalar quantity that has been measured in every experiment allowing us to easily compare results. The statistics of humidity, CO_2, and other variables exhibit equally intermittent fields.

III.3. Soil water content measurements

The water content sensor was implemented on the GW and moved every 1 or 2 hours on the 15 different locations (see Figure 1) during 3 days (attention was particularly paid to do not modify substrate structure with TDR rods). Each day, measurements were made at the lowest point up to the highest point. It has to be noticed that time series were too short to compute the power spectra. For this reason, water content variability is analysed only by using their fluctuations (Figure 4 (A)).

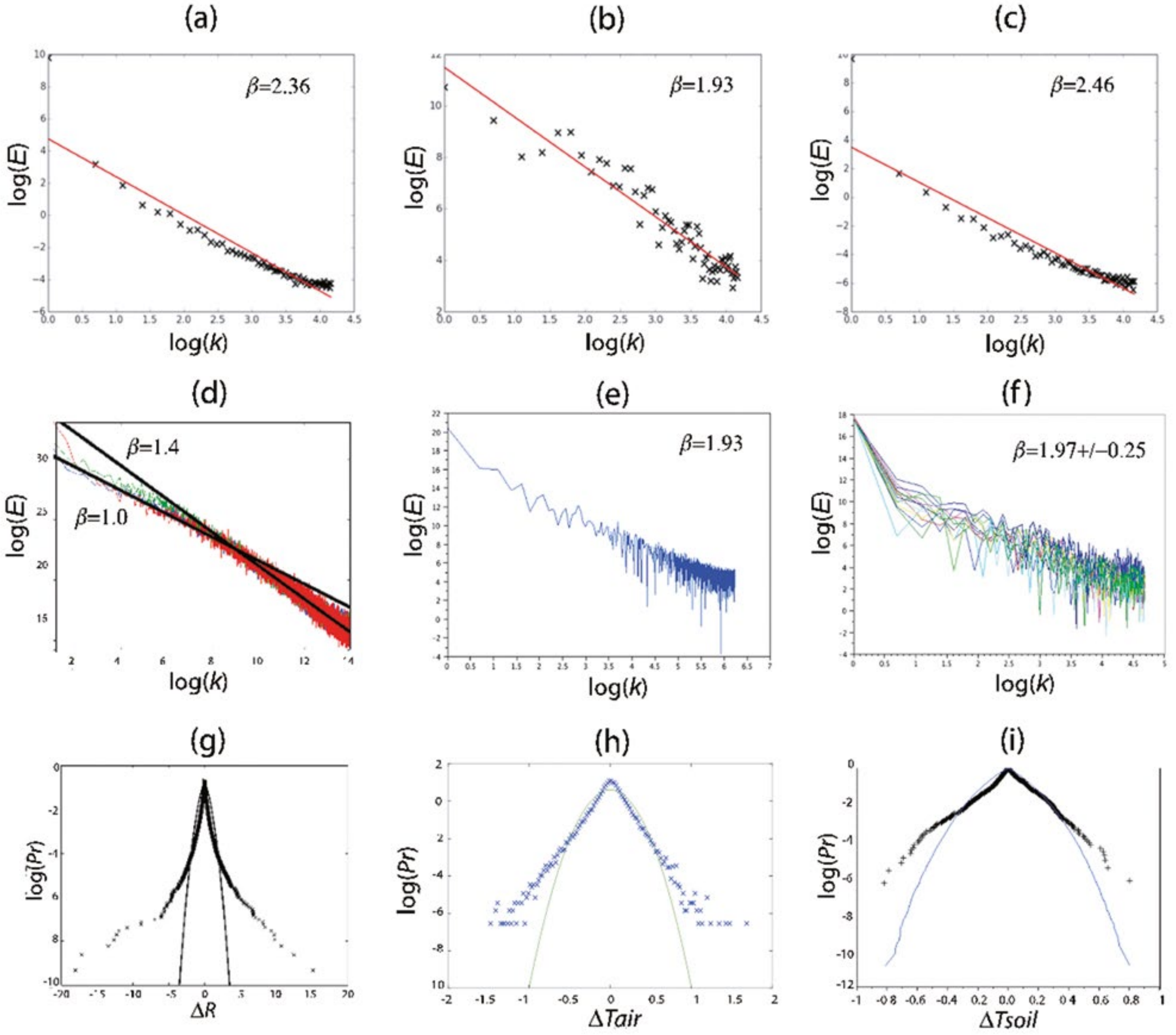

Figure 3: *Spectral analysis for IWV content (a), rainfall (b), relative humidity (c), horizontal wind velocity components u (blue) and v (green), and air temperature T (red) (d), soil temperature for continuous measurement (e) and 15 short measurements (f), log-probability distribution of the increments and comparison with the Gaussian model (solid line) for precipitation (g), air temperature (h), and soil temperature (i).*

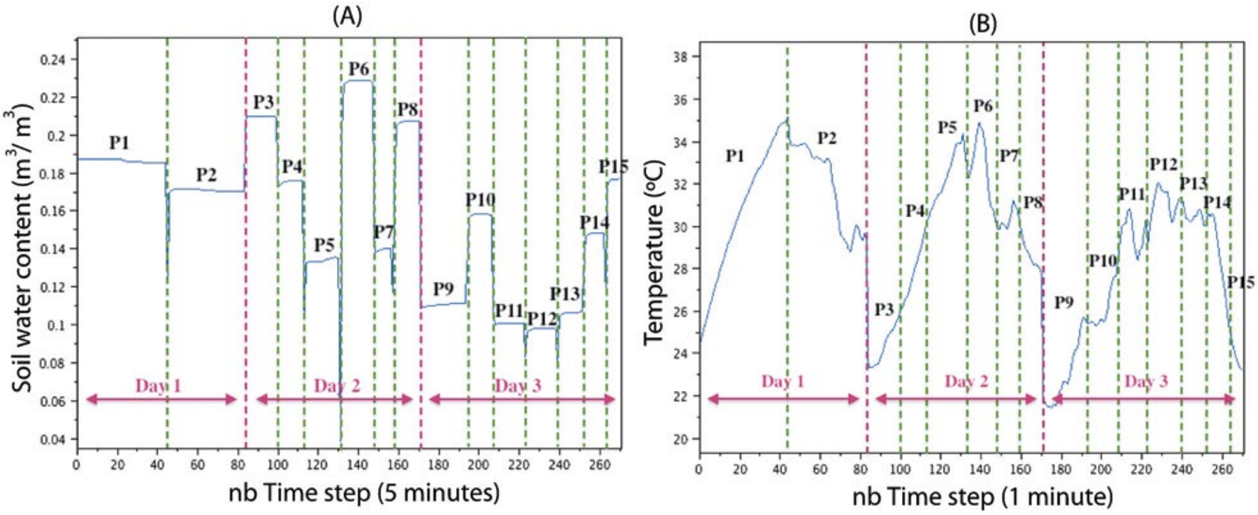

Figure 4: *Water content (A) and temperature (B) measures for the several locations defined on the GW experimental area.*

It is clear that water content spatially varied from one location to another, from 0.10 to 0.23 m^3/m^3. These differences seem to not be linked to topography: there is no apparent relationship between water content values and locations on the Green Wave. These spatial variations of water content should be due to the heterogeneity of sprinkle (or precipitation but it did not rained during these 3 days of experiment), and to the spatial heterogeneity of substrate and vegetation. They also seem to not be related to the diurnal cycle. Contrary to temperature (Figure 4 (B) in the next sub-section), water content measurements did not increase or decrease depending on the time of the day. Moreover there was no variation of water content for a particular location during the observation time step (between 1 or 2 hours).

III.4. Temperature measurements

A similar procedure to the water content one was applied for temperature measurements (6-hour continuous monitoring and displacement of the sensor on 15 locations). Unlike water content measurements, temperature variations were not significant in space (see Figure 4 (B)). They were clearly influenced by the diurnal cycle with a general tendency: increase of temperature in the morning and a decrease from 14:00.

Figure 3 (f) displays the power spectra analysis for the large time series (6 hours) and the 15 short ones. They all exhibit a good scaling behaviour on the entire range of scales. The values of the spectral slope β are quite similar from one location to another (around 1.9) and correspond to non-conservative fields ($\beta > 1$). Note that these values are similar to those obtained for rainfall ($\beta = 1.93$).

The comparison between temperature increments EDP and the Gaussian model is shown in Figure 3 (i). The non-gaussianity does not appear so clearly than for the previous variables. The highest increments values are remote from the Gaussian model, but the small variability of temperature and the absence of significant values do not provide similar results to those obtained for atmospheric data.

IV. CONCLUSIONS AND PERSPECTIVES

The Green Wave is a pioneering site to assess thermo-hydrological performances of such a green infrastructure. Several measurement campaigns conducted since 2013 have aimed to test equipment and characterize the (spatio-)temporal variability of hydro-meteorological variables including precipitation, humidity, wind velocity, temperature and water content. Every studied data has exhibited a significant variability in time characterized by a non-gaussian distribution and a scaling behaviour. These results encourage the use of additional tools based on Universal Multifractals framework to analyse and simulate geophysical field extremely variable over a wide range of scales (see Schertzer and Lovejoy, 2011 for a review). Water budget results from the complex non-linear interactions between numerous processes ranging from rainfall, and evapotranspiration influenced by wind, temperature and humidity, to runoff and infiltration. This paper highlights that basically all the input data exhibit some multifractal behaviour. Understanding and accounting for the full complexity and variability of these fields is a required step for better representing and simulating the whole green roof water budget. Such framework furthermore open the path to stochastic approach, notably to account for data unknown at the needed resolution. Unfortunately there was not enough data here to test this framework, but it would be relevant to do so in future investigations. In parallel, a continuous in-depth monitoring has to be implemented to capture this high variability (in space and time) on a longer time period. This large scale monitoring is planned through the development of the multi-scale Fresnel platform at Ecole des Ponts (https://hmco.enpc.fr/portfolio-archive/blue-green-wave/). This fully monitoring of the GW includes:

Precipitation

Rainfall spatial variability has not been studied for now. It can be significant [Gires *et al.*, 2016] at the scale of the GW and should be taken into account to model its hydrodynamic response. A way to handle it could be to install a network of disdrometer on it. On the other hand, a X-band radar is installed nearby the GW. It produces rainfall estimates characterized by a high spatial (100 m) and temporal resolution (150 s).

Wind

In order to compute the effect of green roofs on the surface energy balance budget, the sensible and latent heat fluxes have to be computed. These quantities are classically estimated using eddy-covariance methods. We have shown however that the assumptions needed for EC-methods are no-longer valid when the measured quantities (velocity for example) are wild and non-local. Future work should also focus on understanding near-surface fluxes without the need of a Reynolds decomposition. The IRGASON should also be moved closer to the green roof to better capture the evapotranspiration it produces. For now, this punctual measurement of heat fluxes is certainly affected by the contribution of surrounding (impervious) land uses (called footprint effect).

Soil temperature and water content

Water content monitoring has also to be pursued to study both substrate infiltration and evapotranspiration processes for a large panel of contexts (extreme wet and dry conditions). Several temperature and water content sensors will be implemented to capture the spatial variability (due to GW slope, vegetation layer and substrate heterogeneity, sprinkle…).

Discharge

To be able to estimate the different components of the GW water balance, several stream gauges will be implemented. Every outlet will be instrumented to measures in real time runoff produced by stormwater. Note that the combination of drop size and fall velocity (provided by disdrometers) gives access to the kinetic energy of drops at ground level, which means that such device has potential to be used for studying erosion or water quality (splash effect).

Measures collected by the previously presented instruments on the GW will enable the estimation of the main equations' terms conducting thermal (cooling and estimation of heat flux) and hydrological (water balance) behaviours. They will be used to:

Model development

The hydrological and thermal data provided by this experimental set-up will be very useful for future modeling applications, especially devoted to the evaluation of green roof modules in hydrological and thermal models. It is for instance the case of Multi-Hydro [El Tabach *et al.* 2009, Giangola-Murzyn 2014], a distributed rainfall-runoff model developed at Ecole des Ponts Paristech (open access from https://hmco.enpc.fr/Page/Multi-Hydro/en), which is able to simulate green roof behaviour at the basin scale (see Versini *et al.* [2016] for details). In a general way, this data could contribute to develop more physical models allowing to test the impact of different green roof configuration differentiating by their substrate porosity and thickness, plant species, drainage layer…

Blue and Green assets promotion and policies

Based on monitoring and modelling results, green roof performances could be quantified. For example, it will be possible to estimate how they can reduce stormwater runoff and how these performances can vary in space and in time depending on green roof configuration, rainfall event characteristics and antecedent conditions. These quantified impacts will be used to interfere in the regulation policies at the parcel scale. In the particular case of the presence of a retention basin in the considered parcel, the influence of green roof will be studied during the sizing of the basin in order to possibly reduce its size. It should be possible to extend these results in order to develop specific policies in collaboration with planners, architects, infrastructures designers and local authorities.

Optimization of blue and green infrastructures' management and maintenance

The modelling system will enable to support water storage capacities management by using rainfall-runoff modelling and rainfall forecast. Simulate and forecast the hydrological behaviour of the green roof -but also the entire parcel- will enable to optimize the management of the retention basin making possible to empty it before a coming event. Moreover, the long and continuous monitoring of such a structure will also contribute to adopt maintenance best practices in order to provide suitable services to maintain the performances over time.

V. REFERENCES

Aubinet M., Vesala T., Papale D. (Eds.). (2012) — Eddy covariance: a practical guide to measurement and data analysis. Springer.

Auble D. L., Meyers T. P. (1992) — An open path, fast response infrared absorption gas analyzer for H_2O and CO_2. *Boundary-Layer Meteorology*, **59(3)** : 243-256.

Bevis M., Businger S., Chiswell S., Herring T.A., Rocken C., Ware R.H. (1994) — GPS meteorology: Mapping Zenith Wet Delays onto Precipitable Water. *Journal of Applied Meteorology*, **33** : 379-386.

Bouzouidja R., Sere G., Claverie R., & Lacroix D. (2013) — Characterization of the thermo-hydric functioning of in situ green roof. *La Houille Blanche*, **5** : 62-69.

Chan A.L.S., Chow T.T. (2013) — Energy and economic performance of green roof system under future climatic conditions in Hong Kong. *Energy and Buildings*, **64** : 182-198.

De Montera L., Verrier S., Mallet C., Barthes L. (2010) — A passive scalar-like model for rain applicable up to storm scale. *Atmospheric Research*, **98(1)** : 140-147.

Ducrocq V., Et Al. (2014) — HyMeX-SOP1, the field campaign dedicated to heavy precipitation and flash flooding in the northwestern Mediterranean. *Bul. of the American Meteo. Society*, **95** : 1083-1100.

El Tabach E., Tchiguirinskaia I., Mahmood O., Schertzer D. (2009) — Multi-Hydro: a spatially distributed numerical model to assess and manage runoff processes in peri-urban watersheds. In: Pasche, E., Evelpidou, N., Zevenbergen, C., Ashley, R. & Garvin, S. (eds). Final Conference of the COST Action C22, Road map towards flood resilient Urban Environment. Paris, France.

Fioretti R., Palla A., Lanza L.G., Principi P. (2010) — Green roof energy and water related performance in the Mediterranean climate. *Building and Environment*, **45(8)** : 1890-1904.

Frasson R.P.D.M., Da Cunha L.K., Krajewski W.F. (2011) — Assessment of the Thies optical disdrometer performance. *Atmospheric Research*, **101(1-2)** : 237-255.

Giangola-Murzyn A. (2014) — Modélisation et paramétrisation hydrologique de la ville, résilience aux inondations. PhD thesis, Université Paris-Est, 260 pp.

Gires A., Tchiguirinskaia I., Schertzer D., Schellart A., Berne A., Lovejoy S. (2014) — Influence of small scale rainfall variability on standard comparison tools between radar and rain gauge data. *Atmospheric Research*, **138** : 125-138. ISSN 0169-8095.

Gires A., Tchiguirinskaia I., Schertzer D. (2016) — Multifractal comparison of the outputs of two optical disdrometers. *Hydrological Science Journal*, **61(9)** : 1641-1651.

Guerova G., E. Brockmann E., Quiby J., Schubiger F., Matzler Ch. (2003) — Validation of NWP mesoscale models with Swiss GPS Network AGNES. *J. Appl. Meteorol*, **42 (1)** : 141–150.

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

Jaffrain J., Berne A. (2012) — Influence of the Subgrid Variability of the Raindrop Size Distribution on Radar Rainfall Estimators. *Journal of Applied Meteorology and Climatology*, **51(4)** : 780-785.

Jaffrain J., Berne A. (2012) — Quantification of the Small-Scale Spatial Structure of the Raindrop Size Distribution from a Network of Disdrometers. *J. of App. Meteorology and Climatology*, **51(5)** : 941-953.

Jim C.Y. (2014) — Building thermal-insulation effect on ambient and indoor thermal performance of green roofs. *Ecological Engineering*, **69** : 265-275.

Lassalle F. (2012) — Panorama technique, historique et géographique, Paris (France), 20th November 2012.

Madre F., Vergnes A., Machon N., Clergeau P. (2013) — A comparison of 3 types of green roof as habitats for arthropods. *Ecological Engineering*, **57** : 109-117.

Maksimovic C., Stankovic S., Liu X., Lalic M. (2013) — Blue green dream project's solution for urban areas in the future. In: *International science conference reporting for sustainability*. Recici, Montenegro, May 7-10 2013.

Mandapaka P.V., Lewandowski P., Eichinger W.E. Krajewski W.F. (2009) — Multiscaling analysis of high resolution space-time lidar-rainfall. *Nonlinear Processes in Geophysics*, **16(5)** : 579-586

Morales A., Wächter M., Peinke J. (2012) — Characterization of wind turbulence by higher-order statistics. *Wind Energy*, **15(3)** : 391-406.

Nyc (2012) — Guidelines for the Design and Construction of Stormwater Management Systems. NYC Environmental Protection, 137 pp: http://www.nyc.gov/html/dep/pdf/green_infrastructure/stormwater_guidelines_2012_final.pdf.

Oudin L., Hervieu F., Michel C., Perrin C., Andréassian V., Anctil F., Loumagne C. (2005) — Which potential evapotranspiration input for a lumped rainfall–runoff model?: Part 2—Towards a simple and efficient potential evapotranspiration model for rainfall–runoff modelling. *Journal of Hydrology*, **303 (1–4)** : 290-306.

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)** : 193-204.

Ralph F.M., Neiman P.J., Wick G.A., Gutman S., Dettinger M., Cayan D., White A.B. (2006) — Flooding on California's Russian River-Role of atmospheric rivers. *Geophys. Res. Lett*, **33** : 5.

Royer J.-F., Biaou A., Chauvin F., Schertzer D. And Lovejoy S. (2008) — Multifractal analysis of the evolution of simulated precipitation over France in a climate scenario. *C.R Geoscience*, **340** : 431-440.

Santamouris M. (2012) — Cooling the cities – a review of reflective and green-roof mitigation technologies to fight heat island and improve comfort in urban environments. *Solar Energy*, **103** : 682-703.

Schertzer D., Lovejoy S. (2011) — Multifractals, generalized scale invariance and complexity in geophysics. *International Journal of Bifurcation and Chaos*, **21(12)** : 3417-3456.

Šimůnek J., Van Genuchten M.T., Šejna M. (2008) — Development and applications of the HYDRUS and STANMOD software packages, and related codes. *Vadose Zone Journal*, **7(2)** : 587-600.

Stovin V., Vesuviano G. And Kasmin H. (2012) — The hydrological performance of a green roof test bed under UK climatic conditions. *Journal of Hydrology*, **414-415** : 148-161.

Stovin V., Poë S., And Berretta C. (2013) — A modelling study of long term green roof retention performance. *Journal of Environmental Management*, **131(15)** : 206-215.

Takebayashi H., Moriyama M. (2007) — Surface Heat Budget on Green Roof and High Reflection Roof for Mitigation of Urban Heat Island. *Building and Environment*, **42(8)** : 2971-2979.

Thurai M., Peterson W.A., Tokay A., Schutz C., Gatlin P. (2011) — Drop size distribution comparisons between Parsivel and 2-D video disdrometers. *Advances in Geosciences*, **30** : 3-9.

Tomer M.D., Clothier B.E., Vogeler I., Green S. (1999) — A dielectric–water content relationship for sandy volcanic soils in New Zealand. *Soil Sci. Soc. Am. J*, **63(4)** : 777-781.

Topp G.C., J.L. Davis, Annan A.P. (1980) — Electromagnetic determination of soil water content: measurements in coaxial transmission lines. *Water Resources Research*, **16(3)** : 574-582.

Ueyama M., Hirata R., Mano M., Hamotani K., Harazono Y., Hirano T., Miyata A., Takagi K., Takahashi Y. (2012) — Influences of various calculation options on heat, water and carbon fluxes determined by open-and closed-path eddy covariance methods. *Tellus B*, 64.

Versini P.-A., Jouve P., Ramier D., Berthier E., De Gouvello B. (2015) — Use of green roofs to solve storm water issues at the basin scale – Study in the Hauts-de-Seine county (France). *Urban Water Journal*, **13(4)** : 3372-381.

Versini P., Gires A., Tchiguirinskaia I., Schertzer D. (2016) — Toward an operational tool to simulate green roof hydrological impact at the basin scale: a new version of the distributed rainfall-runoff model Multi-Hydro. *Water Science and Technology*, **74(8)** : 1845-1854, DOI 10.2166/wst.2016.310.

Voyde E., Fassman E. And Simcock R. (2010) — Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *Journal of Hydrology*, **394(3-4)** : 384-395.

Yilmaz D., Sabre M., Lassabatère L., Dal M., & Rodriguez F. (2016) — Storm water retention and actual evapotranspiration performances of experimental green roofs in French oceanic climate. *European Journal of Environmental and Civil Engineering*, **20(3)** : 344-362.