Dear Editor,

First of all, we would like to thank both reviewers for their interest to our manuscript and their detailed reviews. Some efforts have been made to improve our paper regarding these comments and suggestions.

Reviewer 1

1. Figure 1 is very difficult to understand, with photographs overlaid on top of a blurred engineering drawing. There are no dimensions. A clearer diagram is required.
4. The monitored area appears to be only a portion (1143 + 2368 m2) of the total roof area (1 ha, line 119). Please indicate the monitored portions clearly on a revised version of Figure 1. Some indication of the longest flow path lengths from catchment boundary to outlet would be useful for interpreting/modelling runoff detention.
5. Line 135 mentions two types of vegetation. Please show where each type of vege- tation occurs on a revised version of Figure 1.
6. In line 209 it is suggested that the moisture content probes were specifically located to study the influence of slope. Therefore, please provide some information about the slope at their location.

Regarding specific comments (1), (4), (5) and (6), Figure 1 has been modified: (i) photographs and the blurred engineering drawing have been separated and simplified (on which a scale has been added), (ii) the monitored area and some indications about flow path lengths have been added, (iii) areas with plants have been indicated, (iv) a profile of the section where the water content sensors were implemented (indicating the slopes) has been added.

2. Insufficient detail of the green roof profile is provided (line 136-7). Please provide a clear vertical section through the system, and confirm that it is consistent over the whole area. What is the actual shape/configuration of the drainage layer?
3. The information provided here on the physical properties of the substrate (lines 137- 9) is insufficient for the validation of physically-based models. Please provide more detail on the particle size distribution, moisture retention characteristics and hydraulic conductivity.

Regarding specific comments (2) and (3), some information has been added to better describe the green roof: (i) a figure (new Figure 2) presenting the vertical profile has been added, (ii) more physical properties of the substrate (Table 1 + previous paragraph) have been provided (It has been recalled that grain size distribution, water retention and hydraulic conductivity curves are available in Stanic et al., 2019).

7. Moisture content probes. Section 2.2.2 contains a lot of information about the general principles of soil moisture measurement, suggesting (Equation 3) that a standard calibration equation for natural soils was applied. There is no indication that these were calibrated for the specific substrate used here. Other

green roof studies have repeatedly emphasised the need to undertake substrate-specific calibrations. The statement later on (lines 385 to 387) is unclear, but suggests that perhaps you don't trust this data. Do the authors recommend use of this data set or not?

Specific comment (7): Indeed Topp equation (Eq. 3) has been defined for natural soil. Moreover it gives the link between the dielectric constant and the volumetric water content which is strongly related to the bulk density (compaction of the substrate). Here it can be assumed that the BGW substrate was coarse enough to not clearly show the dielectric behaviour of a typical volcanic media, and do not reveal a dielectric constant–volumetric water content relation significantly different from the Topp equation (see Palla et al., 2009 for a similar assumption). This justification has been added in Section 2.2.2.

Nevertheless such assumption can also conduct to the mis-estimation of water content. Additional study was done to assess this relationship in lab. A calibration curve obtained with compaction made by applying vibrations has been added (Eq. 4). When comparing with the Topp equation, these curves show that the transformation from dielectric constant into the volumetric water content is not straightforward. For this reason, we provide the dielectric constant data, letting free the reader to use another relationship to convert this data in water content.

The statement "The sensors show a significant spatial variability in terms of absolute values. These differences illustrate the heterogeneousness of the substrate, due to its granular composition and its wavy-form" means the sensors were accurate enough to measure different water content behaviours generating by some different hydrological behaviours (due to the slope and different vertical profiles). By using Topp equation or another relationship, the sensors provide some relevant information about this spatial variability. This is explained in Section 3.2.

8. What are the estimated uncertainties associated with discharge measurements (page 6)?

Specific comment (8): Concerning the water level sensor, the uncertainly represents +/- 1% of the measured value. This information is written in Section 2.2.3 (first paragraph).

9. How did you define a storm event? Line 365. Is this based on a standard inter-event dry period of e.g. 6 hours, or something else?

Specific comment (9): Here, the rainfall events have been defined by analysing both rainfall and discharge data. Following the standard inter-event dry period of 6 hours, 6 rainfall events characterized by a total amount higher than 5 mm can be defined: 7th March (9 mm), 11th March (9.7 mm), 17th March (7.5 mm), 27th and 28th March (13.9 mm), 9th April (9.6 mm), 29 and 30th April (23.5 mm). This has been modified in the manuscript (Section 3.2).

10. Text on line 52 suggests that evapotranspiration can be neglected during storm events. This is a reasonable assumption for short events in cool or temperate cli- mates. However, it may not be correct for longer events and/or hotter climates. In all cases though, ET is a critical component of the overall water balance, as it is ET that generates the roof's retention potential (initial losses) during dry periods. Do you have climate data that would enable ET0 to be estimated (e.g. from Penman-Monteith FAO56 equation)?

Specific comment (10): In Paris region (temperate climate), evapotranspiration can be neglected in the water balance during a rainfall event. It has been specified in Introduction to avoid any confusion. Hot temperature can occur in summer, but storms are very short in such situation. We completely agree that evapotranspiration represents a key-information to assess the retention capacity of the substrate during dry periods. In reality, the monitoring set-up of the BGW has been recently extended to the energy balance components measurement and particularly to the evapotranspiration flux. It is explained in the last paragraph of the manuscript dedicated to perspectives. For now, the evolution of the retention capacity of the substrate during dry periods is assessed by the water content sensors.

11. Given the emphasis on acquiring the complete water balance, it would have been nice to see some evidence that the collected data is capable of demonstrating mass balance by comparing the total volumes of rainfall x catchment area, volumetric change in soil moisture and runoff for several specific storm events. It would also be good to see one or two illustrative hydrograph comparisons over shorter time-scales (< 24 hours). Do you see initial losses after long dry periods? Do you see lag and attenuation of the peak runoff or not?

Specific comment (11): A particular rainfall event is now presented in the new Section 3.3 (figures 7 and 8). It illustrates the ability of green roof to retain and detain rainfall water. The water balance is also computed by assessing the different terms. The water retained by the substrate (estimated by water content measurements) appears to be consistent with the runoff coefficient.

12. I have attempted to retrieve and process some of the data. Data retrieval was straightforward. As I am not a python user, I chose to work with the raw rainfall and pipe discharge data files. The .dat files were read into Excel as csv files, and the data format appears to correspond to the description in the paper. The rainfall data is consistent with Figure 4. However, I have some concerns about the pipe discharge data. Missing data is not clearly indicated in the file. Without smoothing, the data appears noisy, and it doesn't appear to return to zero between events. Pipe slope is not provided in the paper, so Q cannot be independently verified. The Manning-Strickler formula applies to steady uniform flow; its application here for the measurement of time-varying discharge needs more justification.

Specific comments (12): Concerning the discharge measures inside the pipe, only one data is missing (2018-04-28 14:58:33). The slope is equal to 0.74% (it was indicated in the Python script, it is now also the case in the manuscript in Section 2.2.3). This very low slope and the absence of connection before and after the location of the sensor makes relevant the use of the Manning-Strickler formula. This assumption is usually done in stromwater management (see SMWW model developed by the Environmental Protection Agency in USA for instance). It is explained in the manuscript in Section 2.2.3.

Concerning the discharge measures from the storage units, there are 74 time steps characterized by NaN values in the file (19/02/18 at 17:06 and the following for instance). As mentioned in Section 3.1 the 15s-signal produced by the sensor is very erratic. On order to smooth this signal, the data can be averaged on a moving window (whose number of time steps can be modified in the Python script).

Reviewer 2

Data download easily from Zenodo. Good data organisation and formats, easy to open and use both the .dat file and the Python scripts. Good metadata headers in discharge and VWC files but missing (and much needed - you do not want users like me guessing at the data columns) in Arduino and rainfall files. In downloading MacOSX versions I found that changing suffixes from .dat to .csv made files much easier to use in text editors, spreadsheets, GIS software, etc. Consider .csv rather than .dat? Or include a hint for users about changing .dat to .csv?

Headers have been added in both Arduino and rainfall files to recall data source and units. .dat files have been replaced .csv files. Python program has been adapted to this new format.

<u>Overall comments:</u>

The manuscript highlights large areal coverage (e.g. 1 ha) of BGW but in fact the data only cover 3k m2 (e.g. figure 2 and line 252). The area under measurement here still exceeds prior studies by at least a factor of 5, but advertised 1 ha (10k m2) while having data for 'only' 3k m2 seems misleading or perhaps even dishonest?

The present water level sensors measure the discharge flowing out of a third of the BGW (3,500 m^2 on the 10,000 m^2). It is already significantly larger than any prior studies (see references in Introduction section). Moreover, water content sensors can be moved (and have already been moved) over the BGW for additional purposes, as it was the case for evapotranspiration measurements (not presented here). In fact, the whole BGW is used as a pilot site for Blue green solution assessment. Some clarifications have been added in BGW presentation (Section 2.1 and Conclusion) to avoid any misunderstanding and clarify the content of what is presented here as well as the overall context.

The time period of this data set (2018 February to May) misses the usual period of heaviest rainfall for Paris: intense afternoon late-afternoon thunderstorms in mid- to late-summer? Impressive that these authors achieved such high data collection rates (e.g. section 3.2 on times series performance) but do they contend that these measurements cover the full range of precipitation events? If not, they should inform readers about context of these particular months. What would happen (has happened) in heavy (rain rates greater than 20 mm / h) summer rainfall events? Soil / substrate erosion? Aerial flooding? Storage unit 1 fills and overflows to storage unit 2? Ultrasonic proximity/distance sensors in pipe or in storage unit 1 get immersed? Why did the measurements end in May 2018? Particularly curious about this statement at line 381: "this operation is done during a dry period".

Indeed, in May 2018 the water content sensors were moved over the BGW to proceed to several evapotranspiration campaigns (comparison with the measurements made with an evapotranspiration chamber on a small area). For this reason, the continuous dataset ends in May 2018 (added in the first paragraph of Section 3). The authors are aware the 6 presented rainfall events are not representative of the full range of precipitation events. Nevertheless, it has to be mentioned that since the BGW is monitored (2017), intense rainfall has never caused any flooding on the surface, nor pipe filling (the higher water level measured was about 12 cm). This remark has been added in Section 3.2.

The statement at line 381 (now 418): "this operation is done during a dry period" refers to the collection of Arduino data. Arduino data are currently collected manually. During this operation the sensor is disconnected and no measurement is recorded. To avoid the possible loss of relevant measurements, this collection procedure is carried out during "dry periods" characterized by no rainfall and discharge. It has been mentionned.

The authors rightly give high attention to retention / detention issues: water storage and run- off delays due to BGW. But, unfortunately, nowhere does a user find hints that these data might actually allow one to calculate retention or detention. Data providers know area, substrate, depth to impervious layer, soil moisture content, rainfall inputs, etc. But they leave it to users to try to calculate e.g. retention? Or they leave the impression that, despite qualify of measurements, one can not actually derive retention / detention? E.g at the time resolution used in figure 4, discharge looks simultaneous / instantaneous with rainfall. The system provides no detention? Or, the data do not allow user to calculate detention. Having raised the issue often and prominently in the introduction and justification, the authors seem remiss to not address whether their data prove relevant to those questions? Give us an example or address what one would need differently or additionally to actually calculate the BGW impacts on retention / detention? We see reference to these values (as outputs from the Python scripts) at lines 357 to 360 but the authors should give us a graphic example with specified uncertainties? Does the system actually produce useful numbers?

BGW detention and retention properties differ from one event to another depending on the precipitation but also the initial conditions. Detention can be graphically seen at the rainfall event scale (usually 45 minutes between peak rainfall and peak discharge) and retention by computing the runoff coefficient. Both can be done by using the proposed Python script.

As mentioned in response to reviewer 1, the user has to be cautious concerning water retention estimation. We propose to use Topp equation to convert dielectric constant in water content, but we are aware of the possible weakness of this assumption (see response to reviewer 1). Following both reviewers' comments, we have added a second relationship calibrated in lab. Finally, we provide the dielectric constant data, letting free the reader to use another relationship to convert this data in water content.

As also suggested reviewer 1, we have also addes a particular rainfall event in the paper to illustrate the possible hydrological impacts of the BGW, and compute the runoff coefficient for every water content measurement for an example to illustrate the opportunities offered by this data set.

Specific comments:

Line 43 "reaching the network". I believe the authors refer here to the stormwater management network but - unfortunately - the manuscript displays too many possible terms and explanations: sometimes 'network', sometimes 'rainfall network', sometimes 'stormwater network', rarely 'stormwater management network'. Settle on and define a standard language, then use it throughout.

"stormwater management network" should be the appropriate terminology. The text will be homogenised to avoid any confusion.

Line 140, figure 1: In the upper right the figure lists 32 soil moisture sensors but - at left center of the figure and in text lines 200 to 210 - the authors show and explain use of only 16 sensors. Make 16 sensor the default configuration with parenthetical note or footnote about why 32 sensors seemed to exceed logger bandwidth? Fix sensor number in figure 1?

As commented in response to reviewer 1, Figure 1 has been modified. Only 16 sensors are presented.

Line 221: "a nominal range of 250 mm". Clever to use ultrasonic distance / proximity sensors to measure water height but most ultrasonic sensors have dead zone or null zone close to the sensor face. Data sheets for ultrasonic sensors often specify "little or no dead zone" but more careful analysis suggests working dead zone of 2 cm. This represents nearly 10% of the working range of the UM18. Can manufacturers or authors certify linear response outside of that dead zone out to the maximum range? Have authors in this case relied entirely on manufacturer data sheets? If so, tell the user? Do the ultrasonic sensors, particularly in the pipe or in storage unit 1, get wet or get immersed? What happens then? Why do some file names include the term 'Arduino' (which I know well)? Arduino MPU to control the UM18, sending serial data to Campbell data logger? Or, does Arduino refer to the "Unused data coming from a non operational sensor." Evidently the term 'Arduino' applies to storage data but not pipe data? Sensor operated differently or data recorded differently in the two situations?

For UM18 this dead zone is estimated to 5 mm in the datasheet. As the sensor is placed on the top of the conduit, only very high values (higher than 240 mm) could be affected by this dead zone. For this range [0-240 mm], the measures made by the sensor were manually verified with some standards. Note that water levels have never been higher than 120 mm for now. For both conduit and storage units, the ultrasonic sensors have never been immersed. This comment has been added in Section 2.2.3.

Indeed, Arduino refers to the data collected in the storage unit. Campbell data logger collects only the data measured inside the pipe. The reason for which there are two different record systems is due to the fact that the storage unit was instrumented few months after the conduit, and that the distance was too long to make a connection between the storage unit and the existing data logger. This has been specified in Section 2.3.

Line 247 and 252, figure 2: total contributive area of 3511 m^2. See comment above about measured area vs total area.

Additional information has been added in Section 2.1 and in Figure 1 to avoid any confusion.

Line 272 figure 3: If x axis legend of this figure is correct (e.g. Q2 in liter / second) as I think it is, then figure legend ("downstream discharge Q1") seems wrong? Should read 'downstream discharge Q2'?

In fact, it should be indicated "downstream discharge Q2 " in the figure caption.

Line 375, 376: "heterogeneousness of the substrate, due to its granular composition and its wavy-form". Perhaps, but also including sensor-level uncertainties / imprecisions in measuring soil moisture? To the extent "granular composition" and "wavy-form" have an influence, do those represent features of the original BG roof or features that have evolved during time of existence?

For sure, sensor-level uncertainties can be added as an explanation of this spatial variability. The wavy-form has not moved during time as it was an architectural choice, and the roof is included in the concrete structure of the building. Concerning the granular composition, the natural grain size distribution of the substrate (see Stanic et al., 2019) can explain for a large part this spatial variability. It is quite difficult to assess how it has evolved with time. We have only noticed that some of the small particles have been drained out of the substrate. It has been specified in Section 3.2.

The authors

Measurements of the water balance components of a large green roof in Greater Paris Area

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Abstract. The Blue Green Wave of Champs-sur-Marne (France) represents the largest green roof (1 ha) of the Greater Paris Area. The Hydrology, Meteorology and Complexity lab of Ecole des Ponts ParisTech has chosen to convert this architectural building in a full-scale monitoring site devoted to studying the performances of green infrastructures in stormwater management. For this purpose, the relevant components of the water balance during a rainfall event have been monitored: rainfall, water content in the substrate and the discharge flowing out of the infrastructure. Data provided by adapted measurement sensors were collected during 78 days between February and May 2018. The related raw data and a python program transforming them into hydrological quantities and providing some preliminary elements of analysis have been made available. These measurements are useful to better understand the processes (infiltration and retention) conducting their hydrological performances, and their spatial variability due to substrate heterogeneity.

Link to the data set (Versini et al., 2019): https://doi.org/10.5281/zenodo.3687775
(doi: 10.5281/zenodo.3687775)

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Keywords: green roof; stormwater management; water balance

1 Introduction

Considered as Blue Green Solutions (BGS), green roofs are recognized as multifunctional assets able to provide several ecosystem performances (Francis and Jensen, 2017; Oberndorfer et al., 2007) to face climate change and unsustainable urbanization consequences (as biodiversity conservation or thermal insulation). They appear to be particularly relevant in stormwater management as they have the ability to store a more or less significant portion of precipitation (Stovin et al., 2012; Versini et al., 2016). Indeed, at the building scale, green roofs contribute to: (i) reduce runoff volume at the annual scale, and (ii) attenuate and delay the peak at the rainfall event scale. These performances depend on the green roof properties (substrate depth, porosity, or vegetation type), rainfall intensity and antecedent soil moisture conditions (Berndtsson, 2010). Considered as some stormwater Source Control facilities, they can act to manage rainwater at a small-scale (about 10^2–10^3 m^2) to solve or prevent intermediate scale (10^4 – 10^6 m^2) stormwater issues.

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By increasing the storage of water, green roofs contribute to reduce the rainwater reaching the stormwater management network. It is particularly useful to comply with regulation rules that are generally adopted by local authorities in charge of stormwater management, usually divided in two categories: flow-rate based regulation and volume-based regulations (Petrucci et al., 2013). As green roofs perform in both retention (ability to permanently hold back water by storing the water for

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subsequent removal by evapotranspiration) and detention (ability to temporarily hold back the water) (Johannessen et al., 2018), they can be used as relevant tools to ensure both kinds of regulation.

Indeed, for a green roof located in the Greater Paris Area (characterized by a temperate climate), the water balance during a rainfall event can be reduced to 3 components (see Eq. 1) as evapotranspiration can be neglected:

$$P = Q + \Delta S \quad (1)$$

Where P is the precipitation, Q the discharge flowing out of the structure, and ΔS the variation of water stored in the substrate conducting both retention and detention properties. All quantities are expressed in m^3.

Many experimental set-up have been implemented to monitor, assess and understand the hydrological behavior of green roofs (see (Berndtsson, 2010) for a review). Most of them were conducted on small green roof modules or plots (Berretta et al., 2014; Getter et al., 2007; Li and Babcock, 2015; Locatelli et al., 2014; Loiola et al., 2019; Poë et al., 2015; Stovin et al., 2015; Wong and Jim, 2015; Zhang et al., 2015) characterized by an area ranging 0.5 to 3 m^2. These modular structures make possible the modification of green roof configuration and study of the effects of substrate (depth and nature), vegetation type, slope, or climate conditions on their performances. Some of them were also monitored in controlled conditions (Ouldboukhitine et al., 2011; Poë et al., 2015) to assess the respective impacts of temperature, irrigation, and light on green roof behavior for instance.

In addition, few studies were conducted at full-scale green roofs. Indeed, such large infrastructures are harder to monitor, as this operation was not generally planned during their construction. For instance, once built, electric connection is rarely compatible with the conservation of the roof sealing. To the knowledge of the authors, only the following works can be mentioned.

(Palla et al., 2009a) studied an instrumented portion (170 m^2) of a green roof in Genoa (Italy) under Mediterranean climate. This pilot site was equipped to monitor the different components of the water balance with: a meteorological station for rainfall, several Time Domain Reflectometry probes installed horizontally along a vertical profile for retention in the substrate, and a triangular weir and a tipping bucket devices to follow the outflowing discharge.

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(Hakimdavar et al., 2016) used the data collected on three full-scale extensive green roofs in New York City (USA) to validate a modeling approach based on the Soil Water Apportioning Method (SWAM). Under a humid continental climate, these monitored drainage areas were comprised between 310 and 940 m2. The three main components of the water balance were measured: rainfall with a weather station, water content with soil moisture and water content reflectometer sensors, and discharge with a custom designed weir placed in the drain of the green roof.

(Fassman-Beck et al., 2013) assessed several green roofs in Auckland (New Zeland) under sub-tropical climate. Their areas were comprised between 17 and 171 m^2. As the experimental setup was focused on rainfall-runoff relationship, only these components were measured: rainfall with a tipping bucket rain gauge and discharge (deduced from water level) from a water pressure transducer and a custom-designed orifice restricted device.

(Cipolla et al., 2016) analyzed runoff from a 60 m^2 extent green roof in Bologna (Italy) characterized by a humid temperate sub-continental climate. Continuous weather data and runoff were especially monitored for modeling development. Runoff was estimated by using an in-pipe flow meters consisting of a runoff chamber with an outlet weir and an ultrasonic sensor (to detect water level). The site was also equipped with a weather station measuring several meteorological variables (rainfall, wind speed, wind direction, relative humidity, atmospheric temperature, …).

Although these works were focused on the hydrological behavior of green roofs, few of them have actually monitored the 3 components of the water balance. Rainfall and discharge were generally considered as sufficient to assess their performances. Some additional studies can also be mentioned, but as they were focused on other topics (evapotranspiration processes (Feng et al., 2018), or water quality (Buffam et al., 2016)), only one component on the water balance was assessed.

The full-scale monitoring experiments mentioned above also suffer from two limitations. First, they are still dedicated to rather small green roof areas. As the hydrological performance of a green roof is influenced by the size of the plot (water detention depends on water routing in the structure for instance), larger infrastructure should be studied. Second, very few measurements are performed (usually only one!) to assess water content on the whole vegetated surface. Indeed, green roof substrates –which are usually largely composed of mineral components – are very heterogeneous, causing variability in their infiltration and retention capacities. Therefore, large-scale monitoring set-ups able to capture this heterogeneity are required to better understand green roof hydrological behavior and to study the space-time variability of the involved processes.

Based on these considerations, this paper aims to present and make available the water balance data collected on a large green roof (called Blue Green Wave) located close to Paris (temperate climate) in order to study its hydrological behavior and its ability to be used as stormwater management tool. The monitoring set-up has been specifically tailored to take into account the space-time variability of the water balance components.

2 Materials and method

2.1 The Blue Green Wave

The Blue Green Wave (BGW) is a large (1 ha) wavy-form vegetated roof located in front of Ecole des Ponts ParisTech (Champs-sur-Marne, France). For now it represents the largest green roof of the Greater Paris area. From its implementation in 2013, the BGW has been considered as a demonstrative site oriented to Blue Green Solutions research (Versini et al., 2018). This experimental set-up started during the European Blue Green Dream (BGD) project (http://bgd.org.uk/, funded by Climate-KIC) that aimed to promote a change of paradigm for efficient planning and management of new or retrofitted urban developments by promoting the implementation of BGS (Maksimovic et al., 2013). The monitoring was anticipated and the building could be adapted to experimental purpose during its construction. It has also been supported by RadX@IdF, a regional project that notably aimed at analysing the benefits of high-resolution rainfall measurement for urban storm water management. Today the BGW is also part of the Fresnel multi-scale observation and modelling platform created in the Co-Innovation Lab at École des Ponts ParisTech. Fresnel aims to facilitate synergies between research and innovation, as well as the pursuit of theoretical research, the development of a network of international collaborations, and various aspects of data science (https://hmco.enpc.fr/portfolio-archive/fresnel-platform/).

From a technical point of view, the BGW is covered by two types of vegetation: green grass that represents the large majority of its area and a mix of perennial planting, grasses and bulbous (see Figure 1). They are based on a substrate layer of about 200 mm depth (SOPRAFLOR I966), a filter layer made of synthetic fiber (SOPRATEX 650), and a drainage layer made of expanded polystyrene (SOPRADRAIN). The vertical profile of the structure is presented in Figure 2. The substrate was initially composed of volcanic soil (around 85%) completed by organic matter. It can be noticed that 50 % of the grains (in mass) are larger than 1.6 mm and 13 % of fine particles are smaller than 80 µm. The main physical properties of the substrate are synthetized in Table 1 (see Stanic et al., 2019 for a detailed description including grain size distribution, water retention and hydraulic conductivity curves).

Initial composition of the substrate	Porosity	Dry Density	Saturated hydraulic conductivity
85% of mineral matters and 15% or organic matters	40%	1442 g/l	8.11×10^{-6} m/s

Table 1. Physical properties of the BGW substrate

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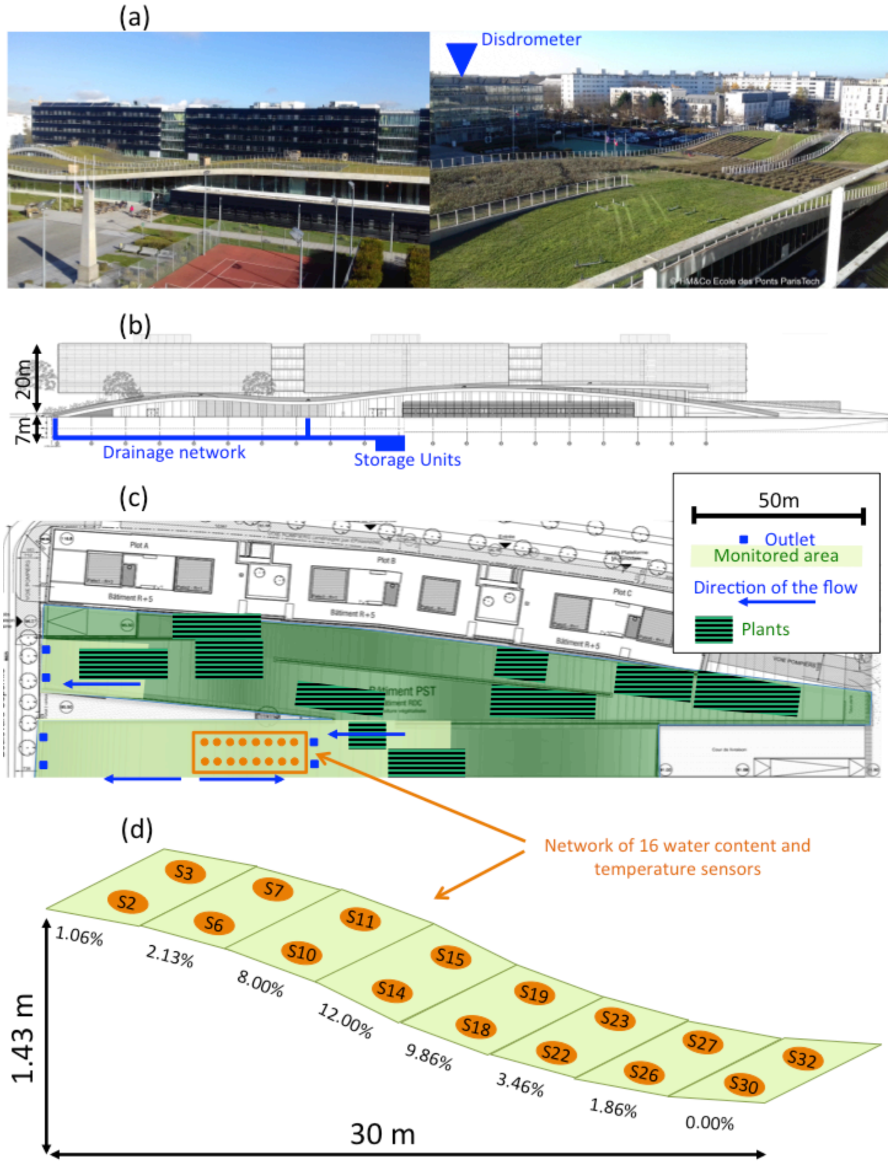

Figure 1. The Blue Green Wave monitoring site of ENPC: (a) pictures, (b) vertical representation and flow path lengths, (c) aerial representation showing the monitored area, (d) profile of the section where the water content sensors were implemented indicating the slopes

From a hydrological point of view, the BGW is connected to three storage units that collect rainwater coming from the roof (with pipes) but also from several impervious parts around the greened building. One of the storage units is preceded by a smaller unit dedicated to irrigation. The water is then routed to a large retention basin to collect excess volumes of water during a rainfall event before being routed to the stormwater management network. This retention basin has been designed (and oversized) as it was considered that the green roof (representing 50% of the total contributive area) was totally impervious without any retention capacity. Until now in France, there is neither rule nor guideline devoted to retention basin sizing that takes into account the retention properties of green areas. That is

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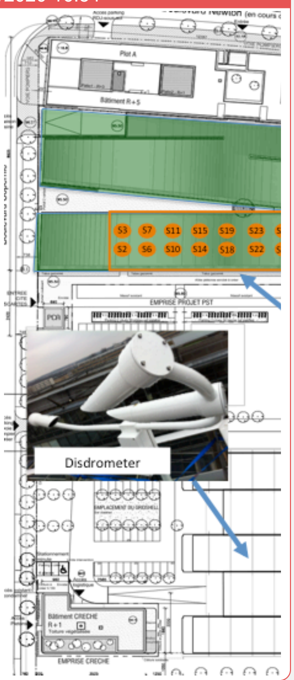

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why the follow-up of such infrastructure is particularly important to develop new guidelines or legislations. For this purpose, the 3 components of the water balance have been monitored on the BGW. It was particularly focused on a significant drained area collecting only green roof contribution (3511 m^2). The implemented set-up is described in the following.

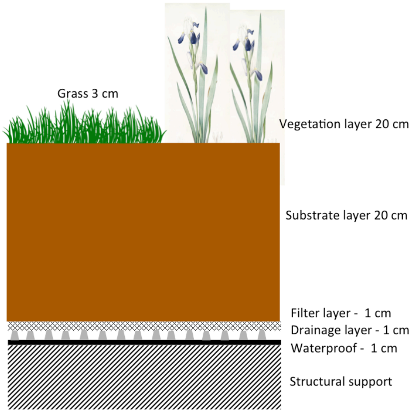

Figure 2. Vertical profile of the green wave structure

2.2 Devices

2.2.1 Rainfall measurement

Local rainfall is analysed with the help of an optical disdrometer Campbell Scientific® PWS100. This device is made of two receivers, which are not aligned with a transmitter generating four laser sheets. By analyzing the signals received from the light refracted by each drop passing through the 40 cm^2 sampling area, their size and velocity are estimated. A rain rate can then be derived. Disdrometers are now considered as a reliable rainfall measurement instrument (Frasson et al., 2011; Gires et al., 2016; Thurai et al., 2011). The device is installed since September 2013 on the roof of the Ecole des Ponts ParisTech building (see Fig.1). This disdrometer and its corresponding data have already been presented in details in a previous data paper (Gires et al., 2018) that summarizes a measurement campaign that took place in January-February 2016. Here, the rainfall data provided by this disdrometer and characterized by a time step of 30 seconds is used.

2.2.2 Water content measurement

Estimation of soil moisture represents a difficult challenge, as it deals with a highly spatially and temporally variable process (Lakshmi et al., 2003), essentially due to soil type and depth. Hence, suitable systems are required to properly assess soil moisture. Nowadays a large number of sensors based on different methods are available for this purpose (Jackson et al., 2008). Among them, indirect methods based on electromagnetic (EM) principles have gained wide acceptance over the last decades. They have the advantage to deliver fast, in-situ, non-destructive and reliable measurements with acceptable precision (Stacheder et al., 2009).

Here Time Domain Reflectometry technique (TDR also known as capacitance) has been selected. It is an EM moisture measurement that determines an electrical property called electrical conductivity or dielectric constant (k_a). It is based on the interaction of an EM field and the water by using capacitance/frequency domain technology (Stacheder et al., 2009). The TDR sensor measures the propagation time of an EM pulse, generated by a pulse generator and containing a broad range of different measurement frequencies. The electrical pulse is applied to the waveguides (traditionally a pair of parallel metallic rods) inserted in the soil. The incident EM travels across the length of the waveguides and then is reflected back when it reaches the end of the waveguides. The travel time required for the pulse to reach the end of the waveguides and come back depends on the dielectric constant of the soil.

$$k_a = \left(\frac{c \cdot \Delta t}{2 \cdot L}\right) \quad (2)$$

Where k_a is the bulk soil dielectric permittivity [-], L the effective probe length [m] Δt is the two-way travel time along the probe (s), and c the velocity of EM wave in free space (c=2.298×10^8 m/s)

Then it is possible to estimate soil moisture content by analyzing the dielectric constant changes into the soil. The usual relationship between volumetric water content and dielectric constant is known as Topp's Equation (Topp et al., 1980). It is adapted to a homogeneous conventional soil. Note that this substrate can be considered as coarse enough to not clearly show the dielectric behaviour of a typical volcanic media (see (Palla et al., 2009b) for a similar assumption). For this reason, it is assumed it does not exhibit a dielectric constant–water content relationship significantly different from the Topp equation:

$$\theta = -5.3\times10^{-2} + 2.92\times10^{-2}k_a - 5.5\times10^{-4}k_a^2 + 4.3\times10^{-6}k_a^3 \quad (3)$$

Where θ is the volumetric soil water content [$m^3.m^{-3}$].

As an alternative to Topp equation, an additional study was conducted to assess this relationship in lab. Here, for information, the calibration curve obtained with compaction representing better the current condition is displayed. This compaction artificially was mimicked by applying vibrations (this causes the segregation of the material similar to what occurs in situ during a long period of time).

$$\theta = -3.01\times10^{-1} + 1.13\times10^{-1}k_a - 5.81\times10^{-3}k_a^2 + 9.85\times10^{-5}k_a^3 \quad (4)$$

Given that the dielectric data is provided, potential users are free to use Topp's Equation as done in this paper, or another one.

Consequently, an ubiquitous wireless TDR sensor network has been implemented on the ENPC Blue Green Wave to measure both water content and temperature. For this purpose 32 CWS665 wireless TDR sensors (produced by Campbell Scientific®) were initially installed. The data were collected by 4 CWB100 wireless bases, able to store each the data of 8 sensors. Then the data was transferred to a data-logger CR6 from Campbell Scientific®. The initial selected time step was 1 minute. It appeared that this first configuration was responsible of many gaps in the time series due to interferences between the different TDR sensors and the bases. To avoid this problem, only 16 TDR sensors were used, all of them connected to the same CWB100 base. For this same reason of possible interferences between the sensors, the time interval has been enlarged to 4 minutes. Indeed, it is recommended to let 15 seconds by sensor to ensure its connection to the base. The final network aimed to capture the space-time variability of water content in a heterogeneous soil as the BGW substrate. It was particularly adapted to assess the influence of the slope on infiltration and evapotranspiration processes.

2.2.3 Discharge measurement

Direct discharge measures are difficult to obtain in drainage pipes. For this reason, indirect measures using water level measurements are usually carried out. Here, water level inside the pipes was measured by a UM18 ultrasonic sensor (SICK, 2018) produced by SICK®. This sensor has been especially developed to perform non-contact distance measurement or detection of objects. The sensor head emits an ultrasonic wave and receives the wave reflected back from the target. Ultrasonic sensors measure the distance to the target by measuring the time between the emission and reception. Implemented face to the water surface, it also measures the variation of the water level. The UM18 sensor is characterized by a nominal range of 250 mm, and an accuracy of 1% on this measurement range. For UM18 ultrasonic sensor, the dead zone is estimated to 5 mm. As the sensor is placed on the top of the conduit, only very high values (higher than 240 mm) could be affected by this dead zone. Since its implementation, water levels have never been higher than 120 mm.

One UM18 sensor has been implemented inside a pipe located in the garage in the building basement (see Figure 1). With a diameter of 300 mm, this pipe collects the water coming from a large part of the BGW (approximately 1143 m^2). A standard 4–20 mA current loop is used to monitor or control

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remotely these analogue sensors. The current is then transformed in voltage by a resistance of 100 Ω. The resulting transmitted signal also ranges 400-2000 mV. In order to translate the electric signal in water level values, the following relationship has been applied

$$H_0 = (U - 460) \times \frac{250}{1600} \quad (5)$$

H_0 is the water level in mm, U the measured voltage in mV, 460 represents the offset, 250 the modified nominal range in mm, 1600 the nominal range in mV.

The water level is then transformed in discharge by using the Manning-Strickler equation (Eq. 5). This formula is usually used to estimate the average velocity (and discharge) of water flowing in an open channel. It is commonly applied in sewer design containing circular pipes.

$$Q_0 = V \times S = K \times R^{\frac{2}{3}} \times i^{\frac{1}{2}} \times S \quad (6)$$

Where V is the average water velocity [m.s^{-1}], K the friction coefficient [-], S the wet surface [m^2], R the hydraulic radius [m], and i the pipe slope [m/m] which is equal to 0.0074 here. R and S are directly linked to the water level:

$$R = \frac{S}{P} \quad (7)$$

$$S = \frac{(\theta - \sin(\theta)) \times r^2}{2} \quad (8)$$

$$P = r \times \theta \quad (9)$$

$$\theta = 2 \times \arccos\left(\frac{r - H}{r}\right) \quad (10)$$

K has been chosen to 85. This value corresponds with a cast iron material.

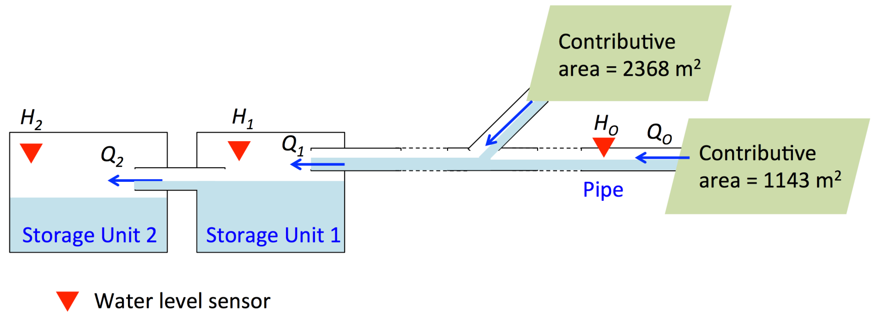

Figure 3. Location of the water level sensors in the stormwater management network

Two additional UM18 sensors have been implemented in the two consecutive storage units (see Figure 3) collecting the rainwater drained by a large contributive area of 3511 m^2, and including the previous monitored area. The first storage unit is a rainwater tank (characterized by a floor area of 32.2 m^2) devoted to irrigation. Filled most of the time, the excess water is routed by a pipe toward the second unit (floor area of 22.5 m^2). A relationship similar to Eq. 4 between the voltage measurement and the water level has been adjusted for both units:

$$H_i = (U - 0.38) \times \frac{20}{1.62} - dh \quad (11)$$

Here U the measured voltage in V, the nominal range is 20 cm and dh (equal to 1.06 cm) corresponds to an additional offset due to the elevation of the sensor

By studying both water level variations, a relationship between the water level measured in the first unit (H_1) and the outflow routing to the second unit Q_2 (and related to H_2) has been established (see

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Figure 4). Finally, the total discharge reaching the first unit and collecting the downstream rainfall can be assessed by the following equation depending only on H_1:

$$Q_1 = Q_2 + \frac{dH_1}{dt} \times A1 = f(H_1) + \frac{dH_1}{dt} \times A1 \quad (12)$$

Where Q_1 is the discharge reaching the first unit and Q_2 the second respectively, $A1$ = 33.2 m^2 is floor area of the first unit.

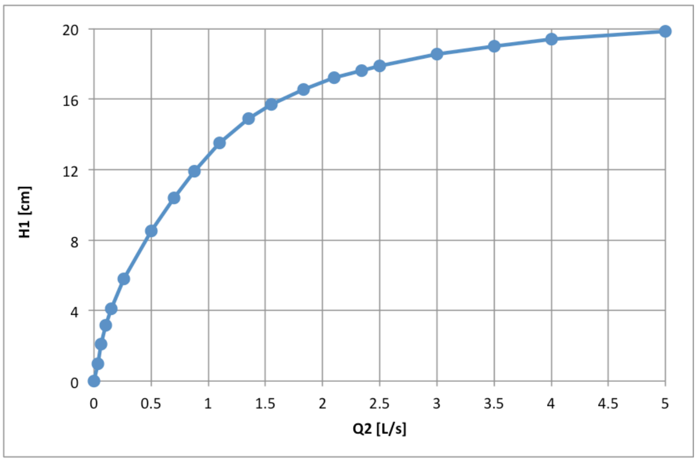

Figure 4. Relationship adjusted between the water level H_1 and the downstream discharge Q_2

Finally, discharge data was recorded with a time step of 30 seconds for the sensor implemented in the conduit, and 15 seconds for the one in the storage unit.

2.3 Available output, data processing and period of study

As already presented in details in (Gires et al., 2018), precipitation data is collected in real time and stored through daily files.. Here, these files for 30 s time step rain rate have been gathered with the help of a Python script to create a long time series covering the whole period of study. Each line contains the time step expressed as YYYY-MM-DD HH:MM:SS and the corresponding rainfall intensity (in mm/h) separated by a coma.

Water content and water level data inside the pipe are collected and stored every night on the HM&Co server in two different files. For this purpose, the Loggernet software produced by Campbell Scientific® has been used. It supports programming, communication, and data retrieval between data loggers and a PC. Concerning the water level file, each line corresponds to a time step for which the following information is recorded (in each line, these values are separated by a coma):

- Exact definition of the time step expressed as YYYY-MM-DD HH:MM:SS
- Item number
- Voltage indicator to ensure the quality of the measurement (it should be close to 12 V)
- Internal temperature of the datalogger box
- Unused data coming from a non operational sensor
- Water level measured inside the pipe (U in Eq. (4), expressed in mV)
- Unused data coming from a non operational sensor
- Unused data coming from a non operational sensor

Similar format has been chosen for volumetric water content data (note that names of the 16 VWC sensors are indicated in the header and also are reported on Figure 1):

- Exact definition of the time step expressed in YYYY-MM-DD HH:MM:SS
- Item number
- Voltage indicator to ensure the quality of the measurement (it should be close to 12 V)

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- Internal temperature of the datalogger box
- Volumetric water content (expressed as k_a) for the 16 TDR sensors
- STT_B3: Summary Transfer Time for basis, which is related to the total time required for collecting information from all the sensors that are collected to that base.

Water level data inside the storage units have been collected by using the open-source Arduino Uno microcontroller board that works in the offline regime. This Arduino system was chosen because the storage unit was instrumented few months after the conduit, and that the distance was too long to make a connection between the storage unit and the existing data logger. Data are continuously stored on the 64 MB memory card implemented on the board, and copied manually to the HM&Co server once per week. Data contain the following information (in each line, these values are separated by a space):

- Item number
- Voltage values for the first storage unit – *U1* (in mV)
- Voltage values for the second storage unit – *U2* (in mV)
- Exact definition of the time step expressed in YYYY-MM-DD HH:MM:SS

By using Equation (10) *U1* values are transformed into *H1* as a part of post-processing. Note that *U2* data have been used only for a short period of time after the implementation of UM18 sensors, until *Q2* = f(*H1*) functionality has been obtained. After that they were no longer necessary.

3 Data availability

Contrary to rainfall and discharge, which are measured continuously at the same locations, water content sensors can be moved from one location to another on the BGW. Moreover, they were rarely kept installed during the night for security reason. Nevertheless, during several months at the beginning of 2018, they were maintained on the same section of the BGW (the one showed in Figure 1). This time period corresponds to 78 days, from February 19th to May 7th 2018. After this period, the water content sensors were moved over the BGW to proceed to several evapotranspiration measurements campaigns (see Conclusion section). It has been selected to provide water balance components measurements to potential users. This data set is available for download from the following web page (Versini et al., 2019): https://doi.org/10.5281/zenodo.3687775

3.1 Presentation of the available data set

This data set presented in details in the next section contains the following files:

- A rainfall file: 2018_0219-0507_Data_rainfall.csv
- A water content file: 2018_0219-0507_VWC.csv
- A water level inside the pipe file: 2018_0219-0507_Data_discharge.csv
- A water level in the storage file: 2018_0219-0507_Data_Arduino.csv
- A python script to select the data, transform the raw data in physical measurements and carry out some initial analysis.

In details, the python script is structured as follow:

- Time period selection: this part could be changed to select a study time period by choosing an initial and final date.
- Data selection and transformation: the data corresponding to this time period is selected in the different files. Electric signals measured by the water level sensors are converted in water level (by using Eq. 4 and 10), then in discharge by using Manning-Strickler equation (Eq. 5) for the pipe and Eq. 11 for the storage unit. In order to smooth the erratic 15s-signal produced by storage unit measurements, the computed discharge data are averaged on a moving window, whose number of time steps can be modified. Dielectric constants measured by the 16 TDR sensors are converted in water content by using Topp equation (Eq. 3).
- Representation of the computed data: Several figures are plotted to illustrate the variation of the hydrological components in time. The first one represents the corresponding hydrographs for both discharges computed inside the pipe and in the storage unit. The second one synthetizes the water content measured by the 16 TDR sensors. In each figure, the precipitation is drawn on an invert y-axis.
- Computation of runoff coefficients: runoff coefficient is the ratio between the total amount of precipitation (computed by multiplying the rain depth by the corresponding contributive area) and the total volume of water flowing through the monitored pipe or the storage unit. This value ranging 0 to 100% illustrate the capacity of the green roof to retain rainwater.

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3.2 Presentation of the time series

During the available time period including half of winter and half of spring, it rained a total amount of 123.1 mm (see Figure 5). The rainfall file has no missing value, and 6 rainfall events can be defined. They correspond to periods with cumulative rainfall depths greater than 5 mm (separated by a dry period of at least 6 hours) that caused discharge in both pipe and storage unit: 7th March (9 mm), 11th March (9.7 mm), 17th March (7.5 mm), 27th and 28th March (13.9 mm), 9th April (9.6 mm), 29 and 30th April (23.5 mm). These events are obviously not representative of the full range of precipitation events in the area. Nevertheless, it has to be mentioned that since the BGW is monitored (2017), intense rainfall has never caused any flooding on the surface, nor pipe filling (the higher water level measured was about 12 cm).

Concerning the 16 VWC sensors, 5.6% of the time steps are considered as missing data. This is essentially due to 2 particular sensors that were out of service from 16th March to the end of the study time period. The 16 sensors follow the same dynamic, responding to the several rainfall events (see Figure 6). Water content measurements decrease simultaneously during two long dry periods, at the end of February and from mid-April to the beginning of May. The sensors show a significant spatial variability in terms of absolute values. These differences illustrate the heterogeneousness of the substrate profiles in terms of hydrological behaviour. This is due to the granular composition of the substrate but also to the wavy-form of the BGW. Note that the grain size distribution time evolution is difficult to assess. Only the loss of some small particles has been noticed in the conduits.

Discharge data is almost complete. Only one measurement is missing in the pipe and 0.2% of total amount of time steps for the storage unit. These missing data correspond to the short periods during which the manual collection of the data was carried out. Note that in order to avoid the loss of relevant data, this collection was done during a dry period. On this time period of 78 days, runoff coefficient computed for both pipe and storage unit are equal to 70.6% and 71.1% respectively. These close values demonstrate the relevance of the monitored set-up. The missing water corresponds to the water retained by the substrate and the vegetation. It should be returned to the atmosphere by evapotranspiration. As already mentioned, Topp equation (Eq. 3) used to convert dielectric constant in water content could be not adapted to the specific substrate implemented on the BGW. For this reason, the dielectric constant data are provided, letting free the reader to use another relationship to convert this data in water content.

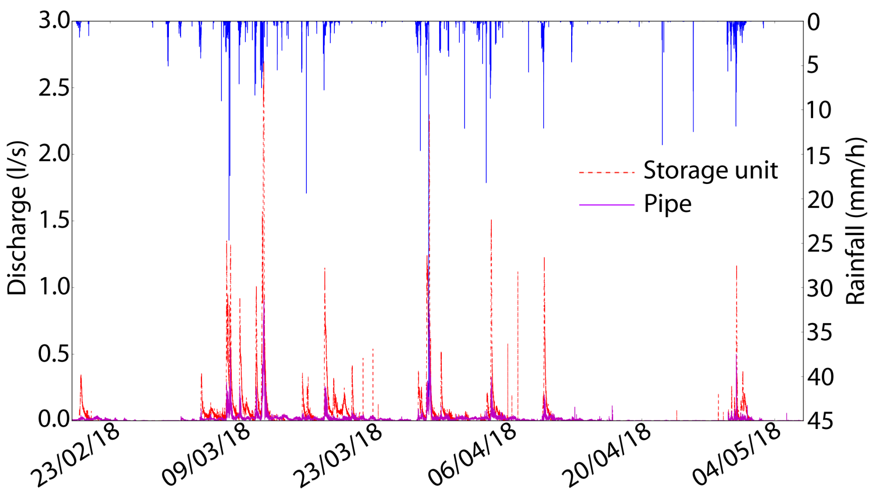

Figure 5. Rainfall and computed discharges for the whole time period

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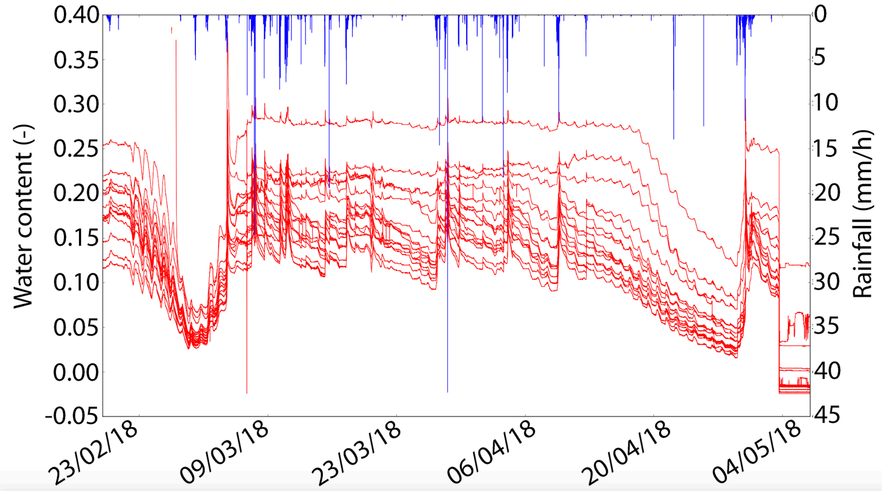

Figure 6. Rainfall and Volumetric Water Content ($m^3.m^{-3}$) for 16 TDR sensors

3.3 Illustration with a particular event

The 29 and 30th April rainfall event is presented in details in this section. It corresponds to the most intense event with a total cumulative rainfall depth of 23.5 mm. Figure 7 shows the corresponding hydrograph from which the delay between rainfall and discharge peaks can be deduced. It reaches 1h for the first contributive area (drained to the pipe) and 1.5 h for the second one (drained to the storage unit).

To assess the water stored in the substrate during this event, the water content difference was computed with Topp's equation between initial and final values. For the 16 sensors, this value ranges between 9.8% and 13.7%. This corresponds to a water depth comprised between 19.6 mm and 27.2 mm, and a storage capacity representing between 83% and higher than 100% of the rainfall (Note that a range comprised between 20.6 and 30.0 mm is obtained with the lab relationship presented in Eq. 4). It is clear the larger values are overestimated but the order of magnitude is consistent with the computed runoff coefficients: 15% for the surface drained to the pipe and 22% for the surface drained to the storage unit. This result illustrates the retention and detention properties of green roof. It has to be recalled that these impacts differ from one event to another depending on the precipitation but also on the initial conditions.

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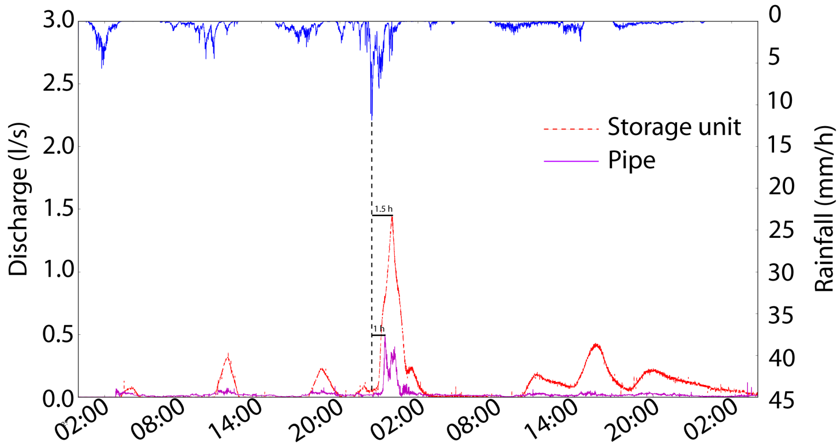

Figure 7. Rainfall and computed discharges for the 29-30th April 2018 event

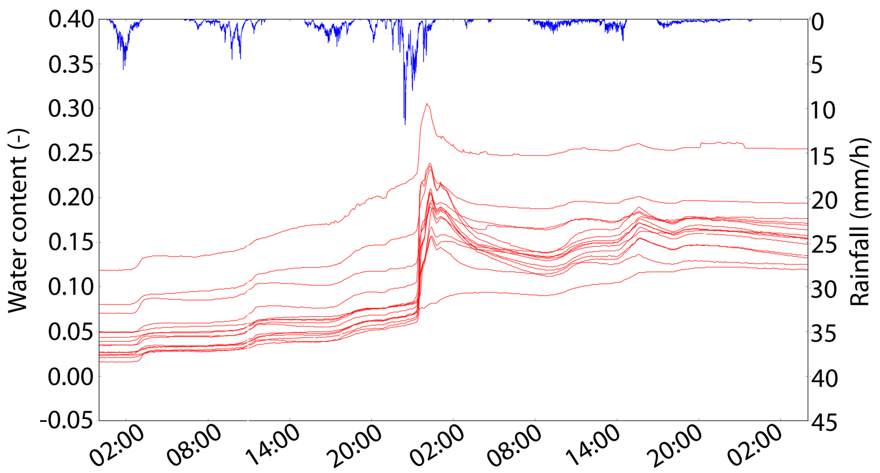

Figure 8. Rainfall and Volumetric Water Content ($m^3.m^{-3}$) for 16 TDR sensors on the 29-30th April 2018 event

4 Conclusion

This paper presents the data collected by several devices devoted to the assessment of the water balance of a particular green roof located close to Paris. The dataset made available for research purposes contain 3 types of data, representing the relevant components of the water balance during a rainfall event: rainfall, water content in the substrate and the discharge flowing out of the infrastructure. They were collected during 78 days between February and May 2018. These measurements are useful to study the capacity of such vegetated infrastructures to store rainwater and act as stormwater management tool. They could also be useful to develop and validate some appropriate modeling approaches (Stovin et al., 2013; Versini et al., 2016).

This data set is available for download free of charge from the following web page (Versini et al., 2019): https://doi.org/10.5281/zenodo.3687775

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It is provided by the Hydrology, Meteorology, and Complexity laboratory of École des Ponts ParisTech (HM&Co-ENPC). The following references should be cited for every use of the data:

Versini, P.-A., Stanic, F., Gires, A., Scherzer, D., and Tchiguirinskaia, I. (2019). Measurement of the water balance components of a large green roof in Greater Paris Area. Earth System Science Data. XXXXX

Versini, P.-A., Stanic, F., Gires, A., Schertzer, D., Tchinguirinskaia, I.: Data for "Measurement of the water balance components of a large green roof in Greater Paris Area", https://doi.org/10.5281/zenodo.3467300, 2019

Researches focused on the assessment of ecosystem services provided by Blue Green Solutions is continuing at HM&Co-ENPC, and particularly on the BGW. The monitoring set-up has been recently extended to the energy balance components measurement (radiation balance, conduction, sensitive and latent heat flux) and particularly to the evapotranspiration flux. Such data will be particularly useful to study the ability of Blue Green Solutions to mitigate urban heat islands (but also to assess its retention potential during dry periods). The French ANR EVNATURB project (https://hmco.enpc.fr/portfolio-archive/evnaturb/), that aims to develop a platform to assess some of the eco-system services (ie stormwater management, cooling effect, or biodiversity conservation) provided by BGS is now pursuing this work of monitoring (Versini et al., 2017).

Author contribution

Pierre-Antoine Versini supervised the study, reviewed, and wrote a large part of the manuscript; Filip Stanic and Auguste Gires worked on the implementation of some of the presented sensors, the collection of the data and participate to the review of the paper; Daniel Schertzer and Ioulia Tchiguirinskaia collaborate to the study supervision and the review process.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgment

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