MODELLING THE HYDROLOGICAL PERFORMANCE OF BIORETENTION CELLS FOR MONTEVIDEO (URUGUAY)

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Water Engineering

By

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Declaration Statement:

Analía Gandolfi Prior certifies that all the material contained within this document is his/her own work except where it is clearly referenced to others.

(signature)

Abstract

Bioretention cells (BRC) are used in sewerage systems to retain part of the stormwater runoff and control the flow directed to the system by delaying and reducing the hydrograph peak. In Montevideo with a small rainfall of only 3.6mm some parts of the system overflow. BRC are starting to be used there, applying international guidelines yet without analyses of performance that consider local conditions.

The first aim of this study is to develop a BRC model that represents the physical processes of retention and detention. The second aim is to use the local climatic data to assess the performance and test the sensitivity of the results for the input parameters. Then, if possible suggest design guidelines for this location.

Two models were developed for a lined and an unlined BRC with Montevideo standard characteristics (rain garden typology), 6 years of recorded rainfall with a 5 min frequency data and design storm events were used. It is concluded that for this BRC typology the parameters of evapotranspiration (ET) and the substrate media characteristics (field capacity, wilting point, and porosity) are insignificant to its performance. The hydraulic loading ratio and the outflow limitation, defined by an infiltration rate or an outlet device, are the key parameters that affect the performance.

For Montevideo's lined rain garden, the retention will only be provided by the ET process, resulting in 6% of the total water budget and no actual detention is accomplished. Therefore, the runoff will enter the sewerage system without any considerable delays and less than 1% of the drainage layer will be used for half of the events, showing this layer is over-designed. For the unlined rain garden, retention was considered as the water that is not directed to the sewerage system (infiltration and ET). For an infiltration rate of 7.2 mm/h (Greenfield criteria) 80% of the total water budget is retained, the remaining 20% overflows for 10% of the recorded events.

The mean initial moister content (θi) for the events was calculated using the model and show that for this climatic condition, the available volume for retention before an event is only 24% of its capacity.

Keywords: Sustainable Drainage Systems (SuDS), bioretention cells, (BRC), Low impact development (LID), Best management practices (BMP), modelling, retention, detention, hydrological performance, climate conditions, rain garden.

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ADWP: Antecedent Dry Whether Period

BRC: Bioretention cell

CSO: Combined Sewer Overflow

DNH: National Directorate of Hydrography

DNM: National Directorate of Meteorology

ET: Evapotranspiration

FAO: Food and Agricultural Organization of the United Nations

GSI: Green Stormwater Infrastructures

HLR: Hydraulic Loading Ration

IDF: Intensity-Duration-Frequency relationships

IETD: Inter-Event Time Definition

IHLR: Inverse Hydraulic Loading Ration

INIA: National Institute for Agricultural Research

INUMET: Uruguayan Institute of Meteorology

MIT: Minimum Inter-Event Time

PDSM: Montevideo Sanitation Master Plan

PDSDUM : Master Plan for Sewage and Urban Drainage of Montevideo

PET: Potential Evapotranspiration

SEPS: Sanitation Studies and Projects Service of the Montevideo City Hall

SuDS: Sustainable Drainage Systems

SWMM: Storm Water Management Model

UTE: National Administration of Power Plants and Electric Transmissions

WRC: Water Retention Characteristics

θ: Water Content

Ψ: Matric potential

1 Introduction

Bioretention cells capture and retain part of the stormwater runoff, so that when light, frequent rain occurs water does not enter the sewerage system. For events with higher intensity rainfall, these structures would direct the rainfall to the sewerage system with a delay, flattening the hydrograph curve, and consequently reducing the peak flow received by the system. When infiltration processes are allowed (e.g. unlined rain gardens) less water will be directed to the sewerage system.

When a light rainfall takes place in Montevideo the sewerage and drainage system overflows and spills polluted water to the rivers and the beaches. Records studied by Artelia, Halcrow, Rhama, CSI (2019b) show that for some parts of the system with only 3.6 mm rainfall spills occur.

Bioretention cells (BRC) are starting to be used in Montevideo, using international guidelines and without analyses of performance that consider local conditions. Understanding the hydrological process and the parameters involved in this process will allow the BRC designers to improve the design criteria and the applicability of these systems in this specific environmental context (i.e. climate conditions, type of soils, geology, etc.).

The few studies involving sustainable drainage systems (SuDS) in Uruguay use commercial models such as SWMM and Infoworks ICM and do not emphasise the sensitivity of the simulation results to the model parameters to assess the performance of these systems. This project attempts to evaluate the performance of using bioretention cells in Montevideo building a model and when possible suggesting design modifications.

The following research questions are going to be addressed:

- What processes need to be represented to deliver a simple model of a bioretention cell that represents the hydrological performance in this unit using Matlab?
- Which is the sensitivity of the model results of hydrological performance to the input parameters?
- What is the performance metric to use in a bioretention cell using the previously developed model?
- What do the findings imply for the design guidelines to use this SuDS typology in this particular location?

2 Aims and Objectives

This project has two aims: to produce a bioretention cell simulation model; and to use it to model the hydrological performance of bioretention cells in specific climate conditions.

The objectives for the first aim are:

- Develop a hydrological simulation model of a bioretention cell in Matlab.

The objectives for the second aim are:

- To establish the retention and detention performance of bioretention cells using the model produced and climate data (e.g. rainfall, Evapotranspiration (ET)) from Montevideo, Uruguay.
- Conduct a sensitivity analysis of model hydrological performance to the input parameters.
- With the performance results and the sensitivity analysis, if possible, suggest design recommendations for Bioretention cells in Montevideo, Uruguay.

3 Literature review

Bioretention systems such as rain gardens, green roofs, and biofilters are different typologies of SuDS, defined in Woods Ballard et al. (2015) as: “a shallow planted depression that allows runoff to pond temporarily on the surface before filtering through vegetation and underlying soils prior to collection or infiltration. In its simplest form it is often referred as a rain garden.”

The philosophy of SuDS is well described by Woods Ballard et al., (2015). Those systems use a natural approach promoting the natural water balance processes (i.e. infiltration, absorption and transpiration by plants) against the urbanization that reduces the permeability of the land with impermeable surfaces, generating an increase in surface runoff.

Nature-based solutions are actions that are inspired by, supported by, or copied from nature. They have tremendous potential to be energy and resource-efficient and resilient to change, but to be successful they must be adapted to local conditions. (Horizon 2020 - European Commission, 2015)

The hydrological performance of a bioretention cell can be thought in terms of retention or detention. Retention can be measured as the component of the rainfall that does not become runoff, this could be analysed for a particular event or for a long term time series. Detention can be measured as the decrease in the peak or the delay of runoff for any storm event. Different approaches have been made to assess the hydrological performance and model the physical phenomena undertaken by a bioretention cell, from models based on empirical calibrations to models based on more physical processes.

3.1 Retention

An approach to model the retention processes in a bioretention cell was made by Berretta et al. (2018). Figure 3-1 is an adaptation of Berretta et al. (2018) in order to explain the physical processes involved.

Storage in a bioretention cell can be categorized into two portions of the pores media, the large pores and the small pores. These are naturally mixed in the bioretention cell substrate, but in Figure 3-1 they are represented as two independent parts of the storage, to explain how they function. The storage in the large pores is where water can be detained during a storm event. This will be drained until empty during and after the event by runoff and infiltration. The storage in the small pores retains the water which will be used by the plants and return to the atmosphere as ET. This happens until the moisture reaches the wilting point, where water cannot be extracted by the plants.

In Figure 3-1 subplot (a) the initial water content conditions are represented before the start of a rainfall event. In subplot (b) it is shown there is an inflow (during rainfall event), how the initial the retention availability has been filled in a previous step and how the runoff has not started yet. In the subplot (c) the rainfall event continues and the detention storage starts to be filled while part of the water exits the system as runoff and infiltration. In the subplot (d) the storm event has stopped so there is no more inflow and the infiltration and runoff continue until the detention volume is empty. In the subplot (e) the volume of water stored in the retention storage is being consumed by plants through ET until it reaches the wilting point in the subplot (f).

Berretta et al. (2018) study long term simulations of lined and unlined biofilters considering four types of United Kingdom (UK) climatic regimens, ponding depth, the ratio between biofilter area and drainage area and infiltration rate that affect the hydrological performance. The hydrological performance in this model was measured only in terms of retention considering the contribution of runoff that becomes ET and infiltration/runoff of the water budget. The conclusions highlight the fact that local climatic differences impact significantly in the performance expected in biofilters. Also, the infiltration rate defined the suitability of the systems in those local climate conditions.

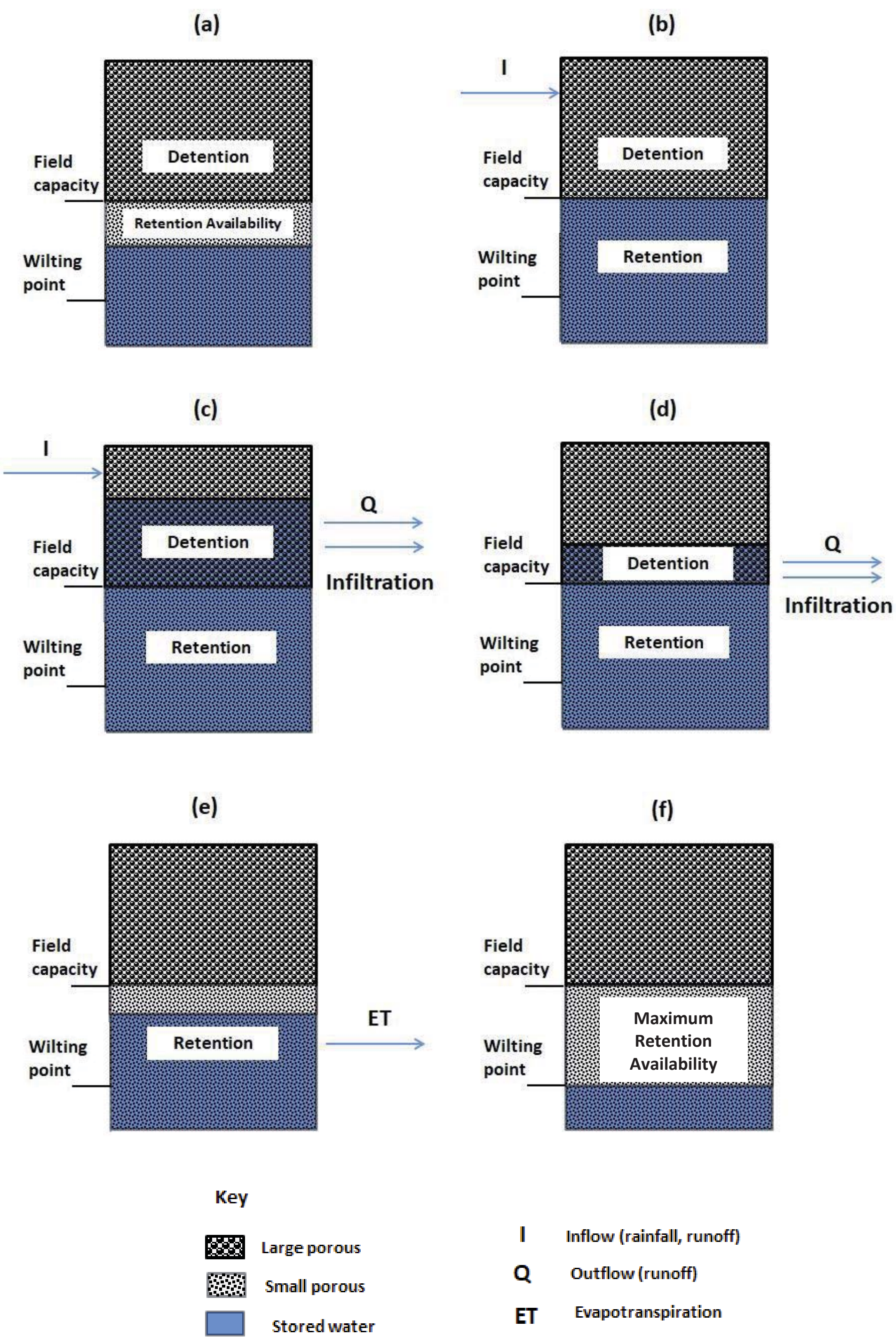


Figure 3-1: Bioretention conceptual storage model in different time steps. Subplot (a): initial condition before a storm event with some retention storage availability. Subplot (b): the storm event begins filling the retention storage until reaching the field capacity without infiltration and runoff (initial losses). Subplot (c): use of the detention storage during a storm event. Subplot (d): emptying of the detention storage after the storm event. Subplot (e): emptying of the retention storage due to the ET. Subplot (f): the retention storage stops emptying reaching the maximum retention availability.

3.2 Detention

A first approach to model detention by Vesuviano and Stovin (2013) used a rain simulation in green roofs with constant intensity, spatially uniform and measured the runoff. They then modelled the phenomenon considering a storage routing incorporating a delay parameter (Eq. 1) and a power-law relationship for the outflow (Eq.2).

$$\frac{\partial S}{\partial t} = I - Q \qquad \text{Eq.1}$$

$$Q = K * S^{n} \qquad \text{Eq.2}$$

Where,

$\partial S/\partial t$ is the variation of the storage with time in L/s

I is the rate of inflow in L/s

Q is the rate of outflow in L/s

K is a calibration parameter in L^{1-n}/s

n is a dimensionless calibration parameter

This model was built to focus only on the detention processes in green roofs. An empirical calibration was made considering the system as a black box with an outlet control structure and applying the principle of mass conservation. This was made without considering the actual physical representation of the water flow in the roof drainage layer.

3.3 Key input parameters

3.3.1 Climatological data

The study of bioretention cell under different climatic conditions has shown different hydraulic performances. The main climatic parameters used in the model are the rainfall and ET data. As previously mentioned, this is one of the most relevant conclusions of Beretta et al (2018).

A review in Evapotranspiration (ET) in Green Stormwater Infrastructures (GSI) by Ebrahimian, Wadzuk and Traver (2019), highlights the processes to incorporate ET in the GSI design depending on the objective, the location (climatic conditions), and the different methodologies to be used. In this review, the importance of the ET in the water budget for a BRC is different for a green roof than a rain garden because they have different hydraulic loading ratio (ratio between the drained area and the BRC area (HLR)) between these structures. Rain gardens have less annual retention because of the higher hydraulic loading ratio. This study concludes the importance of considering ET in GSI design and two methods to estimate it.

Some studies like Brown and Hunt (2011), consider the ET to be 3% of the annual water budget for two BRC of 0.045 inverse hydraulic loading ratio (ratio between the BRC area and the drained area (IHLR)) under the climate conditions of North Carolina. Others like Li, Sharkey, Hunt and Davis (2009) found it to be more significant, 19% of the water budget for a BRC with 0.04 IHLR under the climate conditions of North Carolina.

There are different methods to estimate the ET of a reference crop, also known as Potential Evapotranspiration (PET). Some of these methods are described in Section 5.2.1 applied to the case study data.

According to the Food and Agricultural Organization of the United Nations (Allen, 2004) the real evapotranspiration of a plant depends on several variables (e.g. plant type, development, and environmental conditions) and there are coefficients for food crops developed that estimate the actual ET of the plant. The plants used in SUDs, located in urban environments, do not have a crop coefficient, so normally the ET is measured or the PET is used to represent the ET.

This parameter could also change according to the moisture content in the soil, Stovin, Poë and Berretta (2013) defined the ET in their model of a green roof retention performance for each time step in Eq. 3. ET is as a function of potential ET for that time step (PET), the soil moisture content in the previous time step, and the maximum substrate retention capacity (Smax).

$$ET_t = PET_t \times \frac{S_{t-1}}{S_{max}} \qquad \text{Eq. 3}$$

3.3.2 Substrate and drainage media

The process of retention and detention occurs in the different parts of the porous media, as explained in Figure 3-1. Hence a characterization of the media is necessary in order to represent this phenomenon using a physical model.

Typically bioretention cells have a substrate, also called engineered soil media and an under drainage layer. Depending of the type of BRC (e.g. green roof or rain garden) these layers will vary in their composition and their depth.

In bioretention systems engineered soils can be used for the substrate layer to increase the hydraulic retention performance. Lui and Fassman-Beck (2018) studied the Water Retention Characteristics (WRC) for 7 living roof media and 7 bioretention media. They measured the water content (θ) for different matric potentials (Ψ), defining the wilting point and the field capacity and therefore the available water capacity (defined in Figure 3-1 subplot (f) as maximum retention availability).

3.3.3 Infiltration

The infiltration process for saturated flow can be represented by hydraulic conductivity as defined by Darcy's law (Eq.4) extracted from Hillel (1980).

$$q = \frac{Q}{A} = K\,\frac{\Delta H}{L} \qquad \text{Eq.4}$$

Where

Q is the specific discharge rate in cm/s

K is the hydraulic conductivity in cm/s

$\frac{\Delta H}{L}$ is the hydraulic gradient dimensionless

As stated in Hillel (1980): "when the seepage into and through a underlying soil of a water reservoir is only by gravity force, its rate would be approximately equal to the hydraulic conductivity." This would mean a constant rate of level descend in the storage while there is a saturated flow.

The infiltration process of rainfall normally is not considered to be a constant rate through time, because initially the soil is not saturated. This can be represented by Horton's equation (Eq.5), an empirical formula proposed by Horton (1941) where the infiltration rate varies with time.

$$f_t = f_c + (f_0 - f_c)e^{-kt} \qquad \text{Eq.5}$$

Where

f_t is the infiltration rate (mm/h) at time t (h)

f_0 is the initial infiltration rate or maximum infiltration rate (mm/h)

f_c is the constant infiltration rate after the soil has been saturated (mm/h)

k is the decay constant specific to the soil (1/h).

Equation 5 represents a higher initial infiltration rate when the soil is not saturated with an exponential decay until reaching an asymptote value equal to the saturated infiltration rate

Woods Ballard et al. (2015) establishes that the infiltration viability of a BRC should be considered only when rates are greater than 3.6 mm/h (10^{-6} m/s).

3.4 Performance

There are different recorded performance data for monitored BRC with different characteristics. All the different BRC configurations and locations can make it difficult to compare performance results. Some performance results could be obtained by monitoring built BRC parameters trough time or for experimental setups; while others can be obtained by modelling the processes in a BRC modifying the desire input parameters.

3.4.1 Performance measured from monitored BRC

The International Stormwater Best Management Practices (BMP) Database project website features a database of over 700 BMP studies, performance analysis results, tools for use in BMP performance studies, monitoring guidance and other study-related publications (BMP Database, 2020). Their data was studied and presented by Clar et al. (2015), they summarise for different BMP categories the volume of runoff reduction recorded, see Table 3-1. There a significant difference for undertrain (unlined) BRC and without underdrain (lined) BRC can be appreciated. Also, the authors recognize the important constraint of the limited time recorded data. It would cause that high intensity storms with low recurrence, that cause overflow, may not be represented.

Table 3-1: Volume runoff reduction for different BMP Categories recorded data from 2010 to 2011 expressed as a percentage of inflow adapted from Clar et al. (2015)

BMP Category	Number of studies	25th percentile	Median	75th percentile	Average
Bioretention (with underdrain)	14	33%	52%	73%	56%
Bioretention (without underdrain)	6	85%	99%	100%	89%

Li, Sharkey, Hunt and Davis (2009) study the performance of 6 different configurations of BRC in Maryland and North Carolina, with measured data for 6 to 15 months period (depending on the location). The designs for all the BRC had different characteristics, different HLR, media characteristics, and depth. The values for the retention performance are presented for two cells in the same location, with same characteristics except for one being lined and the other not, see Table 3-2.

Table 3-2: Retention performance of two bioretention cells adapted from Li, Sharkey, Hunt and Davis (2009)

	BRC L1(unlined)	BRC L2 (lined)
Runoff	50	70
Overflow	23	11
ET	19	19
Infiltration	8	0

The median values detention performances were also presented for all the BRC. The peak attenuation median value ranges from less than 1% to 14%. In addition, the peak discharge time span ratio of effluent to influent mean value ranges from 3 to 200 (defined as the ratio between the time form the beginning of the inflow to the inflow peak and the time form the beginning of the inflow to the outflow peak).

Stovin, Vesuviano and Kasmin (2012) monitored for 29 months a green roof (a particular type of a BRC) in the UK. Overall the cumulative annual rainfall retention was 50.2%, with a total volumetric retention of 30% for the significant events (events with at least 2 year return period). The detention performance was also studied, observing mean peak flow reduction of 60% for the significant events.

3.4.2 Performance obtained by simulated scenarios for BRC

Theoretical annual performance was studied by Jennings (2016), for identical rain gardens in 35 sites with different climatic conditions in the United States, the BRC main characteristics are presented in Table 3-3. The author found, for a 3 year hourly simulation, a range of runoff reduction from 99.8% to 51.3% for an infiltration rate of 6.35mm/h, and with no infiltration the range of runoff reduction would decrease to 37.9% to 0.5%

Table 3-3: Jennings (2016) BRC main characteristics

BRC Area (m2)	Drained area (m2)	BRC depth (mm)
9.3	93	150

As previously mentioned Berretta et al. (2018) study long term simulations of lined and unlined biofilters considering four types of UK climatic regimens, ponding depth, the ratio between biofilter area and drainage area and infiltration rate that affect the retention hydrological performance. The authors found that for an unlined BRC with an IHLR of 0.1 and a high infiltration rate (7.2 mm/h) the runoff reduction will be above 85% for all climatic locations and all ponding depths tested (100, 200, 400 mm). Whereas, if reduce the infiltration rate to 0.36mm/h the values of runoff reduction will decrease even to less than 5% for the most compromised location.

Stovin, Vesuviano and De-Ville (2015) study the detention processes and performance for 4 testes beds located in different climatic conditions in the UK. They calculated the detention parameters, Peak Attenuation and Centroid Delay for each event and analyzed them with respect to rainfall depth. They showed a negative relationship between rainfall depth and Peak Attenuation. Also found a variable behavior of centroid delay with respect to rainfall depth. The authors highlighted that the detention performance for the same roof can vary for different storm events even if the physical travel time through the system does not change with events. They concluded that detention metrics incorporate the retention effects because a green roof system will exhibit different apparent detention characteristics for different climatic inputs.

3.5 Montevideo

In Montevideo these infrastructures are starting to be used but are not yet widely accepted. In addition, there is no monitoring or measurements of their performance.

The only three references regarding studies in SuDS in Uruguay are the undergraduate dissertation thesis of Agesta, Arce and Guido (2019), the Vincent et al.(2017) article and the Master Plan for Sewage and Urban Drainage of Montevideo (Plan Director de Saneamiento y Drenaje Urbano de Montevideo – PDSDUM) finished in December 2019.

Agesta, Arce and Guido (2019) took measurements of rainfall in the Colombes basin (located in Montevideo) and the water level in the combined sewer overflow (CSO) outfall for a six month period. They then analysed the frequency of overflows and compared different solutions applying SuDS and grey infrastructure alternatives, concluding that rain gardens were the third best alternative out of 24 cases. They proceeded to design the solution for this basin using rain gardens and made suggestions to improve their design. The authors also recommend moving the location of the outlet pipe at the bottom of the rain garden drainage layer.

Agesta, Arce and Guido (2019) and Vincent et al. (2017) use SWMM to model Bioretention cells choosing input parameters without evaluating the sensitivity of the results to those input parameters. Hence, the need to develop a new model, apply it to the local conditions and assess the performance of these systems for the local conditions. In addition, a better comprehension of the physical processes involved through a sensitivity analysis to the models input parameters would allow to improve the design criteria for local conditions.

4 Methodology

The strategy is to build the most suitable mathematical model and its variables to simulate the hydrological behaviour of the bioretention cells and develop it using Matlab. The starting point will be the model developed by Berretta et al. (2018) for the representation of the retention processes and a storage routing model as used by Vesuviano and Stovin (2013) to represent the detention processes.

In order to model a bioretention cell the inputs will be explored outputs and the capacity to store water in this element. As inputs there are the direct rainfall and the runoff of other drainage areas that discharge into it. There is runoff or infiltration (in case of unlined systems), overflow, and evapotranspiration. One of the model limitations is that there is no available data of measured outflow (Runoff/Infiltration/Overflow) of any BRC in order to validate or calibrate these models.

Local climatological data will be used to assess the performance of a bioretention cell in Montevideo. The model scenarios will be based on the local guidance for rain garden constructions. If possible modifications to this guidelines design may be attempted to improve the bioretention cell performance.

Sensitivity analyses of the results will be made considering the different inputs of the model: the media characteristics, the outflow condition, the ET, and the inverse of the hydraulic loading ratio. A performance metric will be established to measure the performance of these systems in this particular location.

4.1 Bioretention cell model

The BRC to be model is based on the ones built in Montevideo by the Sanitation Projects and Studies service of the Montevideo City Hall. These rain gardens have a surfaces area of 7.84 m^2, and are divided into three layers. From the bottom to the top there is a drainage layer of 40 cm height, then a substrate 40 cm layer to support the plants and a ponding area of 15 cm height. An illustration is presented in Figure 4-1.

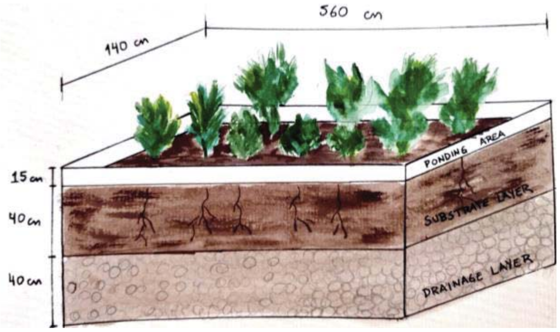


Figure 4-1: Lined and unlined rain garden basic dimensions illustration

Two types of bioretention cells will be model, a lined rain garden with an outlet pipe at bottom directed to the sewer system and an unlined rain garden designed to infiltrate the inflow. Both models are based on the Berretta et al. (2018) for the retention process. For the detention process, a storage routing with the orifice equation (Eq.5) was set for the outflow condition for the lined rain garden. For the case of the unlined rain garden, the outflow was defined by a constant infiltration rate. Both models were implemented in Matlab and are presented in Appendix A. The input parameters of the models are presented in Table 4-1 and the outputs in

Table 4-2.

The simplifications and assumptions made are explained below:

- For the unlined rain garden, the infiltration rate was considered a constant rate even though in reality this rate initially varies with time in a decreasing exponential form (Horton, 1941) until it reaches a constant value.
- For the lined rain garden, the outlet drainage pipe was changed from 160 mm presented on the blueprint "Plano Tipo Jardines de Lluvia" 2018 SEPS Montevideo City Hall to a smaller diameter to limit the runoff. The outflow runoff rate commonly adopted in the UK is the Greenfield runoff rate of 2 l/s/ha (Woods Ballard et al., 2015). For that to be accomplished for this small drained area (78.4m^2) an outlet pipe of approximately 1 cm would be required. Such a small pipe is not feasible so a 50 mm pipe was adopted for the model.
- In the case of the lined rain garden the runoff was considered a function of water height in the storage:
    - If the water height is less than 0.95m the flow can only move through the exit pipe, working as an orifice expressed in Eq.6:

      $$Q = Cd * S * \sqrt{2 * g * h} \qquad \text{Eq. 6}$$

      Cd is 0.60
      S is the area of the pipe in m^2
      g is 9.81 m/s^2
      h is the water depth in m
    - After the maximum height is reached, the maximum volume that can be drained by the exit pipe in every time step is 1.53m^3. If the rainfall continues the overflow starts. The maximum capacity of the exit pipe of 50 mm working as an orifice with a water level of 0.95 m is 5.1 l/s, which can be translated to a runoff rate of 65.0 L/s/has.

- Both models were initially built with a time step of 5 minutes. For the lined rain garden this time step was reduced to 1 minute due to the dependence of the Eq. 6 on the water height in the BRC. Smaller time intervals result in better approximation for this equation.
- The Vesuviano and Stovin (2013) model uses a storage routing with calibrated coefficients and a time delay parameter. Calibration for this model is not made due to the lack of monitored outflow data. The time delay is represented in the model by the time step chosen. The model will start to allocate water into infiltration or runoff in the next time step after some water gets into the detention storage.
- For both models the ET was estimated as a function of PET, moister content in the previous time step and the maximum substrate retention capacity (Eq.3)

Auxiliary functions were used to:

- Identify the events according to a set value of minimum dry period time inter events (MIT/IETD).
- Transform daily ET values per month in a time series to obtain a vector with ET values every 5 minutes (to match the rainfall data resolution).
- Load design events with a 5 min resolution rainfall depth.

Table 4-1: Model Inputs

Symbol	Parameter	Adopted value	Design and considerations
I	Rainfall time series in mm	-	The rainfall time series has 6 years of data with a resolution of 5 min. The design storm events are defined with PDSDUM 2019 (Artelia, Halcrow, Rhama, CSI, 2019)
tini	When the rainfall time series starts (date)	7:00 January 1st 2014	Value for the whole time series
tend	When the rainfall time series ends (date)	6:55 January 1st 2020	Value for the whole time series
MIT/IDTE	Minimum time inter events in min	-	This value is adopted after using the model to determine after which amount of time to events are independent.
Ad	Area to be drained in m2	78.4	The rain garden area is 10% of the total area to be drained.
W	Width of the rain garden in m	1.4	Defined by the standard Montevideo Rain Garden blueprints
L	Length of the rain garden in m	5.60	Defined by the standard Montevideo Rain Garden blueprints
hs	Depth of the substrate layer in m	0.40	Defined by the standard Montevideo Rain Garden blueprints
hd	Depth of the drainage layer in m	0.40	Defined by the standard Montevideo Rain Garden blueprints
hmax	Maximum ponding depth in m	0.15	Defined by the standard Montevideo Rain Garden blueprints

Symbol	Parameter	Adopted value	Design and considerations
Fc	Field capacity in vol/vol.	0.30 and 0.20	Two scenarios are going to be analysed one with engineered soil (0.30) and the other with substrate characteristic similar to the actually used at Montevideo rain gardens (0.20)
Wp	Permanent wilting point in vol/vol	0.05 and 0.10	Two scenarios are going to be analysed one with engineered soil (0.05) and the other with substrate characteristic similar to the actually used at Montevideo rain gardens (0.10)
ns	Porosity of the substrate layer	0.60 and 0.30	Two scenarios are going to be analysed one with engineered soil (0.60) and the other with substrate characteristic similar to the actually used at Montevideo rain gardens (0.30)
nd	Porosity of the drainage layer	0.40	This value was selected considering it can vary from 0.2-0.5 and the drainage layer should have a high porosity.
ET	Evapotranspiration in mm/day	-	This is the potential ET for Montevideo, extracted from Las Brujas INIA station using the Penman–Monteith method. It is a vector with monthly values.
Ir	Infiltration rate in mm/h	-	Two possible values where analysed, high infiltration rate (100mm/h) , medium infiltration rate (40mm/h).
M	Initial moisture content	-	This value is the proportion of the voids volume in the substrate that initially is filled with water. It can vary from the Wp to Fc. This parameter will be statistically determined analysing the long time series data with the model
D	Diameter of the exit pipe in m	0.050	Minimum size of pipe adopted. The dimension of the drainage pipe was 160mm, and it changed to 50mm to increase the detention performance of the rain garden.

Table 4-2: Model Outputs

Symbol	Parameter	Type
Inflow	Inflow time series in m^3	Vector the size of the rainfall data time series
EvT	Evapotranspiration time series in m^3	Vector the size of the rainfall data time series
Inf	Infiltration time series in m^3	Vector the size of the rainfall data time series
Runoff	Runoff time series in m^3	Vector the size of the rainfall data time series
Overflow	Overflow time series in m^3	Vector the size of the rainfall data time series
VD	Volume stored in detention time series in m^3	Vector the size of the rainfall data time series
VR	Volume stored in retention time series in m^3	Vector the size of the rainfall data time series

4.2 Data analysis

Stormwater management requirements are such that the BRC response to both routine and extreme events is of interest. According to Woods Ballard et al. (2015) the design criteria of the drainage system should consider that runoff from the site does not occur for the majority of small events, and that for extreme event the runoff is controlled. For that reason, the data will be analysed in terms of cumulative performance for the time series of 6 years and also for significant storm events. No minimum rainfall depth was specified, so the storm event data set contains events with as little as 0.25 mm rainfall, which is the minimum depth recordable by the rain gauge.

First, the rainfall data will be classified by events, considering different events if there is no rain for a minimum period of defined hours between events. In the literature this dry period is defined as the minimum inter-event time (MIT) Dunkerley (2008), or inter-event time definition (IETD) Joo et al. (2013).

The importance of independence between 2 different events relays on the end of the runoff before the next event starts, thus the detention storage is empty to receive water from the next event. Analogously for an infiltration system, this will be the end of the infiltration. The IETD depends on the rainfall characteristics and the basin characteristics (Joo et al., 2013).

According to Dunkerley (2008), the majority of papers that present rain event data adopt a fixed value of MIT of 6–8 hours. Many authors defined the IETD or MIT for bioretention cells as green roofs as 6 hours, Stovin, Vesuviano and Kasmin (2012), Wong and Jim (2014), Voyde, Fassman and Simcock (2010). These structures are similar to rain gardens, the main differences are that they only receive the rainfall of their own area and are normally shallow (20cm). That could lead to smaller MIT than in rain gardens. For a rain garden in Montreal studied by Géhéniau et al. (2015) the MIT was estimated as 8 hours in warm weather conditions. To define the actual IETD/MIT of the rain garden the model will be used to estimate the time when the runoff /infiltration stops after a significant design event.

4.3 Initial conditions

For both models, the initial conditions set for the storage are that there is no volume stored in the detention storage and there is an initial moisture content (θi) that indicates what proportion of the retention storage is used. The retention capacity is the same for the unlined and lined rain garden, and it only depends on the media characteristics (porosity, field capacity, and wilting point).

The model will be run for the 6 year data period for different values of θi. The mean water content before each storm event will be used as the initial condition for future runs of the model, for the time series data and the design events. There should not be a dependency between the initial condition of water moisture and the statistical mean value obtained.

4.4 Event characterization

In order to define the hydrological performance, the events will be characterized using a Matlab script with the inputs and outputs of the previous models, see Table 4-3.

Table 4-3: Event characterization outputs

Symbol	Parameter	Type
DEF event	Vector defining the events	Each vector entry will have the value 0 if there is not an event happening at that time, or the number of the event. The vector size is equal to rainfall data time series
Quantity_events	Number of total events identified	Number
number_event	Number of the event	Vector with entries from 1 to quantity of events
duration_event	Total rainfall duration of the event in minutes	The vector size is equal to Quantity_events
tot_depth	Total rainfall depth for the event in mm	The vector size is equal to Quantity_events
mean_intensity_event	Mean storm intensity of the event in mm/h	The vector size is equal to Quantity_events
start_index	Index that identify the start of the event in the long time series	The vector size is equal to Quantity_events
end_index	Index that identify the end of the event in the long time series	The vector size is equal to Quantity_events
peak	Value of depth at the peak (mm/5min)	The vector size is equal to Quantity_events
peak_index	Index that identify the peak d of the event in the long time series	The vector size is equal to Quantity_events
peak_intensity	Peak intensity in (mm/h)	The vector size is equal to Quantity_events

4.1 Performance metrics and scenarios

4.1.1 Retention

The retention capacity of the rain garden lined or unlined will not depend on the infiltration rate only of the media characteristics (storage retention capacity) and the available volume before the rain starts (initial moisture content θi). Therefore, the outlet flow determined by the infiltration rate (unlined rain garden) or the size of the outlet pipe (lined rain garden) should not influence the retention capacity as long the rainfall events are independent. This implies the detention volume is zero before the next event starts.

The retention metric can be observed as the percentage of water evapotranspirated after the time series events or the water retained in the retention storage after a single event. For the unlined BRC from a drainage management point of view, the infiltration can also be added as water retained. Although the water infiltrated is not actually retained on the BRC, it returns to the natural hydrological cycle and does not enter to the drainage system.

4.1.2 Detention

To measure detention (how the hydrograph changes) due to the water passing through a BRC previous to being directed to the sewerage system the parameters considered are identified in Figure 4-2 and explained below:

- Peak attenuation: the difference between the maximum inflow rate and the maximum outflow rate (Runoff and Overflow)
- Peak delay: the difference between the time the peak occurs in the inflow and the peak occurs in the outflow (Runoff and Overflow)
- Runoff starts (Runoff delay): when the outflow (Runoff and Overflow) starts after the beginning of the rainfall event
- Runoff duration: is the duration of the outflow (Runoff and Overflow).

The only outflows that will be considered of importance are the ones directed to a drainage system, runoff in the case of the lined BRC or overflow for both BRC.

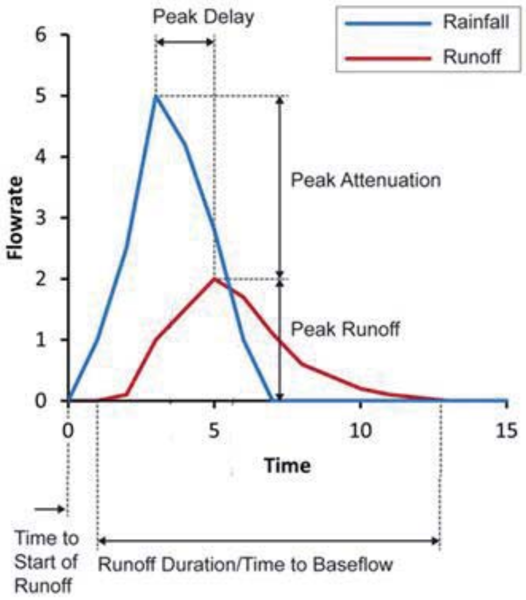


Figure 4-2: Detention performance metrics adapted from Stovin, Vesuviano and De-Ville (2015)

4.1.3 Scenarios

In order to analyse the sensitivity of different input parameters with respect to the performance metric several scenarios will be studied. If one variable is not significant, it will not be analysed for further scenarios.

Firstly, for different outflow conditions (different infiltration rates for the unlined BRC and an outlet of 50 mm for the lined BRC) the time series data of two types of media will be analysed.

Secondly, the significant and design events will be examined for the different outflow conditions, and the sensitivity of the models outputs for the design events will be tested for the initial moisture conditions.

Thirdly, sensitivity analysis of the model results will be made for:

- a new outflow condition of greenfield runoff rate
- different loading ratios, maintaining the fixed greenfield outflow condition
- another set of PET data from the same climatic station but estimated with a different method

5 Case study

5.1 Climatic data

Uruguay is located in the Southern hemisphere temperate zone and it stands between 30º and 35°S and 53° and 58°W. Although between the different parts of the country it is possible to observe differences between the climatic variables, these are not of sufficient magnitude to distinguish different types of climate. According to the Koppen climate classification, Uruguay is classified as "Cfa" or humid subtropical climate (Clasificación climática | Inumet, 2020).

Different organisations study climatic variables in Uruguay. In Appendix B the information of these institutions and their data is presented extensively:

- National Institute for Agricultural Research (Instituto Nacional de Investigación Agropecuaria-INIA)
- National Directorate of Meteorology (Direccion Nacional de Meterología- DNM) and Uruguayan Institute of Meteorology (Instituto Uruguayo de Meterología-INUMET)
- Montevideo City Hall, Sanitation Studies and Projects Service (SEPS)
- The National Directorate of Hydrography (Dirección Nacional de Hidrografía-DNH)
- The National Administration of Power Plants and Electric Transmissions (Administración Nacional de Usinas y Trasmisiones Eléctricas- UTE)

For the rainfall parameter in the Montevideo department and its surrounding areas, there is long term historical data from INUMET and INIA with a daily measurement frequency. There is also short term historical data since 2013 to date from rain gauges installed by the Montevideo City Hall Sanitation Studies and Projects Service, with rainfall measurements every 5 minutes.

For the PET parameter there is long term historical data from INUMET and INIA, and measurements of evaporation are used to estimate it with different formulations. The DNH and UTE have analysed the available climatic data to estimate PET as well.

5.2 Climatic data analysis

5.2.1 Potential Evapotranspiration

With the available climatic data, the PET is calculated with different methods described below and then compared to select its use in the bioretention cell model.

Class «A» Pan

The method to estimate the PET for the recorded data in the Class «A» Pan is extracted from Anido (2012).

$$ETP = k * EVAP \qquad \text{Eq.7}$$

Where,
ETP is the potential evapotranspiration of the reference crop (PET)
K is a calibrated coefficient for each month of the year.
The k coefficients were calibrated for the south area of Uruguay by Puppo and García Petillo (2009), these are presented in Table 5-1.

Table 5-1: Estimated class «A» pan coefficients to calculate the reference crop evapotranspiration in the south of Uruguay extracted from Puppo and García Petillo (2009) .

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
k	0.71	0.72	0.71	0.73	0.65	0.62	0.58	0.63	0.65	0.68	0.72	0.71

Thornthwaite

The Thornthwaite method is used to calculate the PET per month of the crop of reference. The following equations and tables are extracted from Anido (2012).

$$ETP\left({}^{mm}/_{month}\right) = K * ETP_{12,30} \qquad \text{Eq.8}$$

$$ETP_{12,30} = 16 * \left(\frac{10t}{I}\right)^{a} \qquad \text{Eq.9}$$

$$a = 675 * 10^{-9} * I^{3} - 771 * 10^{-7} * I^{2} + 1792 * 10^{-5} * I + 0.492329 \qquad \text{Eq.10}$$

$$k = \frac{N}{12} * \frac{d}{30} \qquad \text{Eq.11}$$

$$i = \left(\frac{t}{5}\right)^{1.514} \qquad \text{Eq.12}$$

$$I = \sum_{1}^{12} i \qquad \text{Eq.13}$$

ETP is Potential evapotranspiration of the crop of reference in (mm/month) (PET)
N is the maximum number of sunlight hours according to latitude (Table 5-2)
d is the number of days of the month
t is the average temperature of the month (oC)
i is the monthly heat index
I is the annual heat index

Table 5-2: Maximum number of sunlight hours of latitude 34º for each month. Values of the 15 day of each month. Source: Smithsonian Meteorological (1951) extracted from Anido (2012).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
N	14.20	13.30	12.30	11.30	10.30	9.80	10.10	10.90	11.90	12.90	13.90	14.40

Penman-Monteith

The Penman–Monteith method developed by the Food and Agricultural Organization of the United Nations (FAO) to obtain Potential Evapotranspiration (Allen, 2004) was adapted for Uruguay by INIA.

Comparison and Conclusions of Potential Evapotranspiration and its use in the bioretention cell model

All of PET data from the different institutions and estimation methods are presented in Table 5-3 and Figure 5-1.

Figure 5-1 provides a visual comparison of the PET estimated with different methods and data. The first thing to observe is that during spring and summer (October to March) there is a bigger spread in the values while in autumn and winter (April to September) the curves get closer together. The minimum difference is of 0.23 mm for June and the maximum difference is 1.99 mm for December.

It can be observed that PET estimated using Thornthwaite has practically the same curve for the 3 different climatic stations. This is because the main parameter is temperature and it does not vary significantly between the 3 climatic stations. It is shown that the lower values of PET are estimated by Thornthwaite, and the highest by Penman-Monteith.

The PET estimations using Penman-Monteith are the highest values, 10% to 20% higher than the mean values considering all methods.

The PET estimated using The Class «A» Pan is in between the other two methods, but closer to fit the Penman-Monteith curve. The reason for it is that the coefficients used in the Class «A» Pan method were calibrated against the estimated PET with Penman-Monteith.

According to the FAO studies, the best estimation for PET is obtained the Penman-Monteith method (Allen, 2004). The PET is a value for the ET of a referential crop; to obtain the real ET, the value has to be adjusted by a crop coefficient. This coefficient depends on the crop type and development stage, as well as parameters such as the crop height, roughness, reflection, ground cover, and crop rooting characteristics.

In conclusion, INIA values of PET at the Las Brujas station are going to be used for the bioretention cell modelling in Montevideo. The importance of the accuracy of this parameter will be assessed by a sensitivity analysis.

Table 5-3: Comparison of Potential Evapotranspiration (mm/day) for Montevideo, Uruguay

METHOD	INSTITUTION AND STATION	DATA PERIOD	J	F	M	A	M	J	J	A	S	O	N	D
Thornthwaite	INUMET- CARRASCO	1981-1990	4.09	3.72	2.98	2.04	1.29	0.83	0.82	0.99	1.37	1.99	2.78	3.66
Thornthwaite	INUMET-PRADO	1981-1990	4.17	3.76	2.99	2.02	1.29	0.83	0.83	1.01	1.38	2.03	2.84	3.70
Thornthwaite	UTE-PRADO	Published 1980	4.06	3.79	3.00	2.03	1.29	0.83	0.81	1.06	1.33	1.97	2.83	3.65
Class «A» Pan	DNH-PRADO	Published 1988	5.04	4.32	3.05	2.34	1.56	0.93	0.99	1.32	2.08	3.06	3.96	4.83
Class «A» Pan	DNM-PRADO	1988-1999	4.63	4.12	3.08	2.16	1.30	0.94	0.86	1.33	1.97	2.83	3.86	4.41
Thornthwaite	INIA-LAS BRUJAS	1972-2020	4.14	3.66	2.93	1.99	1.24	0.79	0.74	0.99	1.35	2.05	2.83	3.71
Pennman-Monteith	INIA- LAS BRUJAS	1972-2020	5.81	4.77	3.55	2.14	1.19	0.82	0.93	1.54	2.48	3.54	4.75	5.64
Class «A» Pan	INIA-LAS BRUJAS	1972-2020	5.46	4.56	3.56	2.48	1.41	1.02	1.06	1.51	2.20	3.15	4.38	5.30

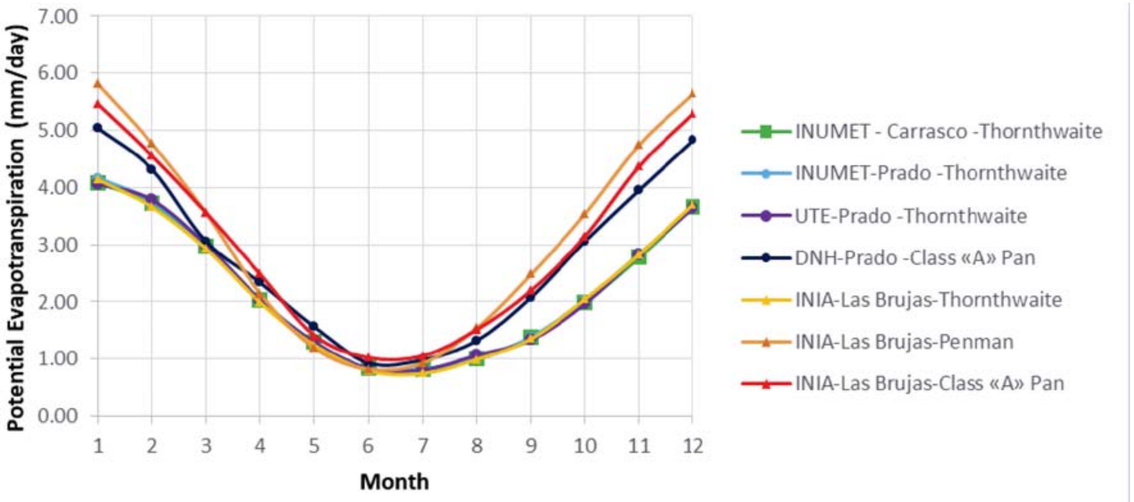


Figure 5-1: Comparison of Potential Evapotranspiration (mm/day) for Montevideo, Uruguay

5.2.2 Rainfall data

Analysis of rainfall data to be used in the bioretention cell model

A comparison with the monthly average for the INUMET Prado and Carrasco and INIA las Brujas is presented in Figure 5-2 and Table 5-4.

Table 5-4: Comparison of accumulated precipitation per month, monthly average (mm) for Montevideo, Uruguay

INSTITUTION AND STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
INUMET-CARRASCO	92	92	106	87	90	79	89	92	93	107	94	78
INUMET-PRADO	87	101	105	86	89	83	86	88	94	109	89	84
INIA – Las Brujas	102.9	107.5	108.5	100.8	93.9	75.6	86.5	89	87	106.3	98.7	87.4

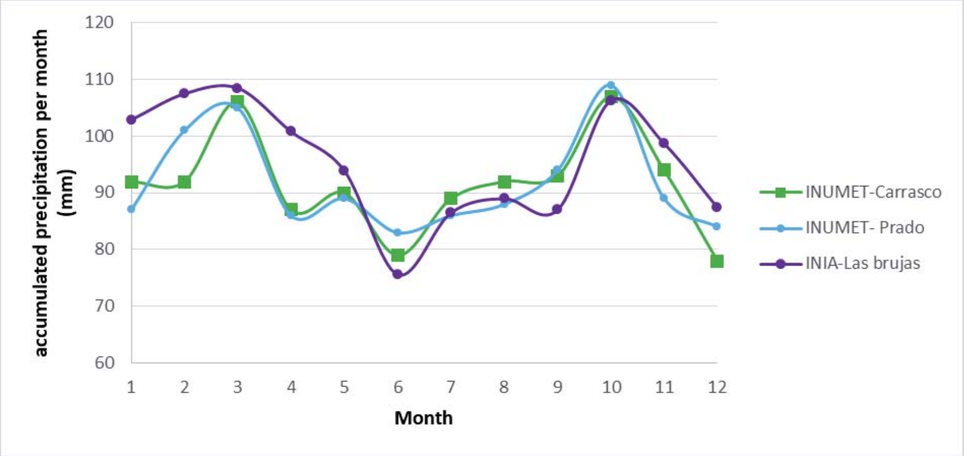


Figure 5-2: Comparison of accumulated precipitation per month, monthly average (mm) for Montevideo, Uruguay

All of the stations have very similar values of monthly average precipitation, with less than a 10% difference between each other, except for INIA- Las Brujas in January February and April, where there is a higher rainfall monthly depth.

For the bioretention cell model the data with the highest resolution (every 5 minutes) will be used from the SEPS hydrometeorological network. Only the 8 stations with less than 10% days of missing data will be considered for the analysis, and one of them selected to use as model input. The criteria to select this station will also take into consideration the correlation of the measured data with the INUMET Prado station and their geographic location.

The station CZ 9 has the highest correlation index, also one of the lowest missing data percentages, and it is located in an urban environment. For these reasons the station CZ9 was selected to use their daily data as an input for the bioretention cell model, see the analysis in Figure 5-3.

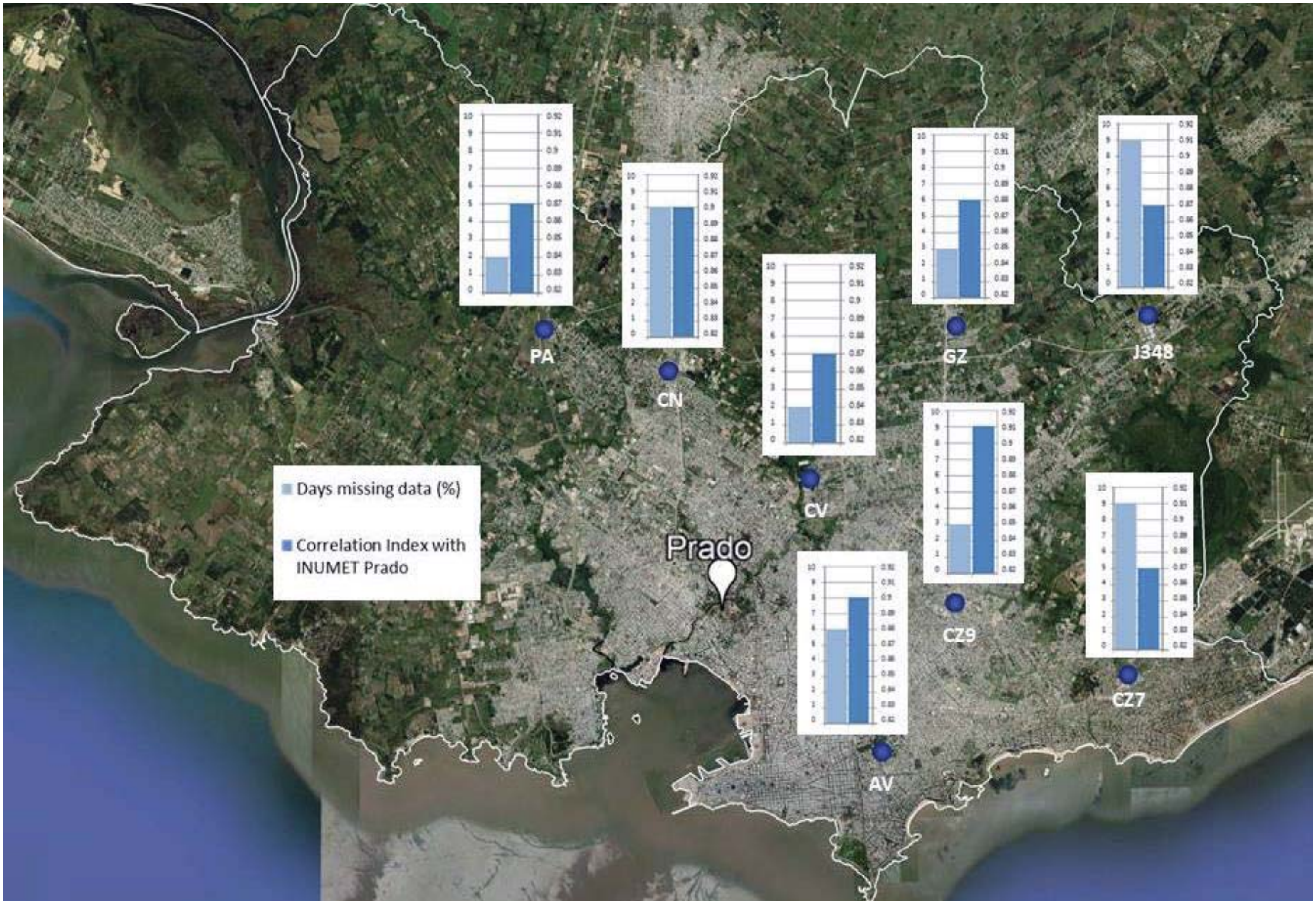


Figure 5-3: Criteria to select SEPS stations

5.2.3 Intensity-Duration-Frequency relationships (IDF)

The statistical analysis of the rainfall to obtain the Intensity- Duration-Frequency relationships have been done first for the whole country extension, and then derivations to the specific area of Montevideo.

The methods used here to determine the rainfall IDF relationships are statistical methods comparable to the ones used in the United Kingdom for the Flood Studies Report in 1975 (Flood studies report, 1975) and their actualization, The Flood Estimation Handbook in 1999 (Bayliss et al., 1999) .

<u>IDF for URUGUAY 1980-1998</u>

The national curves of Intensity-Duration-Frequency were developed by Rodríguez Fontal (1980) using the rainfall data available from 1906 to 1974. The equations developed by Rodriguez Fontal were updated by Genta et al. (1998), who developed an isohyet map (Figure 5-4) for an event of 3 hours duration and 10 years return period. A set of equations were developed to calculate the intensity for a different return period and/or event duration.

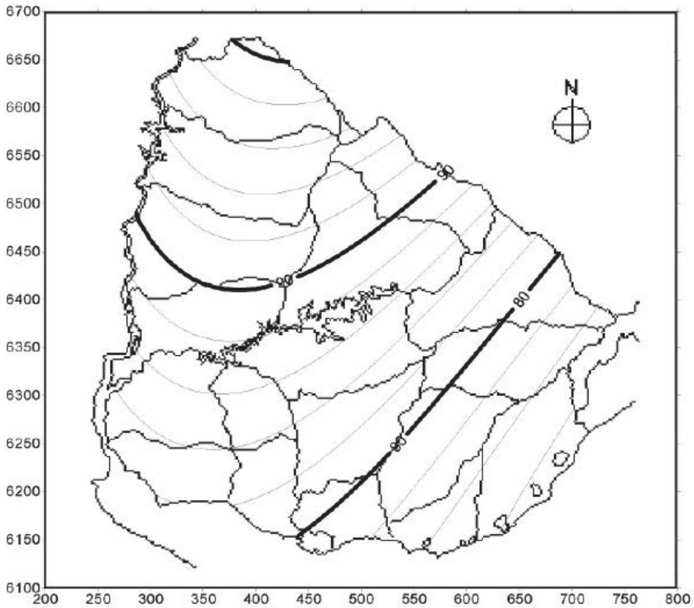


Figure 5-4: Isohyet Map for rainfall depth events of 10 year return period, 3 hour duration in Uruguay (Genta et al., 1998). Where the rainfall depth is represented in mm.

Genta et al. (1998) set of equations:

$$P(d, Tr, p) = P(3,10, p) * CT(Tr) * CD(d) * CA(Ac, d) \qquad \text{Eq. 14}$$

Where,

Tr is the return period in years
d is the duration in hours

Ac is the catchment area in km^2
P(3,10,p) is the total rainfall depth in mm on the point p for an event of 3 hours duration and 10 year return period. It is obtained of the map in Figure 5-4

$$CT(Tr) = 0.5786 - 0.4312 * Log\left[Ln\left(\frac{Tr}{Tr-1}\right)\right] \qquad \text{Eq. 15}$$

For durations less than 3 hours:

$$CD(d) = \frac{0.6208*d}{(d+0.0137)^{0.5639}} \qquad \text{Eq. 16}$$

For durations higher than 3 hours:

$$CD(d) = \frac{1.0287*d}{(d+1.0293)^{0.8083}} \qquad \text{Eq. 17}$$

$$CA(Ac,d) = 1.0 - (0.3549 * d^{-0.4272}) * (1.0 - e^{-0.00572*Ac}) \quad \text{Eq.18}$$

IDF for Montevideo Sanitation Master Plan 1994 (Plan Director de Saneamiento de Montevideo 1994-PDSM 1994)

The PDSM 1994 studied the rainfall time series of the INUMET climatic station Prado from 1912 to 1990 and adjusted the parameters of the empirical formulation Montana Law (Eq. 19) to obtain the intensity of the rainfall event (Intendencia Municipal de Montevideo (Montevideo City Hall), 1994):

$$I = at^b \qquad \text{Eq. 19}$$

Where:
I is the intensity in mm/min
t is the duration in minutes
a and b are statistics coefficients, presented in Table 5-5.

Table 5-5: Rainfall statics for Montana Law (Intendencia Municipal de Montevideo (Montevideo City Hall), 1994)

Return period (years)	Duration less than an hour		Duration more than an hour	
	a	b	a	b
2	4.76	-0.52	9.52	-0.68
5	6.62	-0.52	13.23	-0.68
10	7.84	-0.52	15.69	-0.68
20	9.02	-0.52	18.05	-0.68

Derivation of IDF for Montevideo by Silveira et al., 2014

The study of the Intensity-Duration-Frequency curves for Montevideo was updated with the last 30 year data by Silveira et al. (2014). The results vary less than 5% compared to the study done by Rodriguez Fontal (1980). The following equations are slightly different from the ones presented in the paper by Silveira et al. (2014). These were extracted from the notes for the course Advanced Hydrology II Alonso (2019), one of the co-authors of the Silveira et al. (2014) paper:

For events of less than 1 hour duration:

$$I(Tr,d) = \frac{30.129-9.757*Ln\left[Ln\left(\frac{Tr}{Tr-1}\right)\right]}{(d+0.0399)^{0.5872}} \qquad \text{Eq.20}$$

For events of more than 1 hour duration:

$$I(Tr,d) = \frac{44.648-14.036*Ln\left[Ln\left(\frac{Tr}{Tr-1}\right)\right]}{(d+0.7612)^{0.795}} \qquad \text{Eq.21}$$

Where
Tr is the return period in years
d is the duration of the event in hours
I is the intensity in mm per hour

Montevideo Urban Sanitation and Drainage Master Plan (Plan Director de Saneamiento y Drenaje Urbano de Montevideo 2019 - PDSDUM 2019)

The PDSDUM 2019 studied the Hydrometeorological characterization for Montevideo and proposes a relationship for Precipitation-Duration-Frequency (Table 5-6) based on a frequency analysis all of the available rainfall data derived from partial duration series.

Table 5-6: Relation for Precipitation-Duration-Frequency for Montevideo (Artelia, Halcrow, Rhama, CSI, 2019)

Rainfall Depth (mm)										
Return period (years)	Duration of the rainfall event									
	24h	12h	6h	3h	2h	1h	30min	15min	10min	5min
2	109	93	75	58	49	38	29	21	17.6	11.7
5	133	113	92	70	60	46	35	26	21.4	14.3
10	151	128	104	80	68	53	40	30	24.3	16.2
25	176	150	122	93	79	62	47	35	28.4	19
50	198	168	137	105	89	69	53	39	31.9	21.3
100	222	189	153	118	100	78	59	44	35.8	23.9

5.2.4 Design storms

There are different methods to model a design storm. Some are commonly used worldwide like the Constant intensity, or the Alternating Block Method. The ones presented in this document were proposed to use in the design of Montevideo's sewerage and drainage system at the different Montevideo Sanitation Master plans in 1994 and 2019.

The methods used to determine design storms are the Alternating block methods comparable to the ones used in the UK in Flood studies report (1975) and their actualization by Bayliss et al. (1999).

“Nested Storm” PDSM 1994

The PDSM 1994 defines the “Nested Storm” as a 6 hour duration event. It is an alternate block-type storm with a step of 5 minutes, and a peak at the first hour. To calculate the rainfall depth, the Alternate Block Method described by Chow, Maidment and Mays, (1994) is used with the difference that the intensity is calculated through the Montana Law and the blocks are symmetrical. The “nested storms” for different return periods are presented in Figure 5-5. Artelia, Halcrow, Rhama, CSI (2019a) analysed this storm and concluded there is not a basis behind selecting 6 h duration and the peak in the first hour.

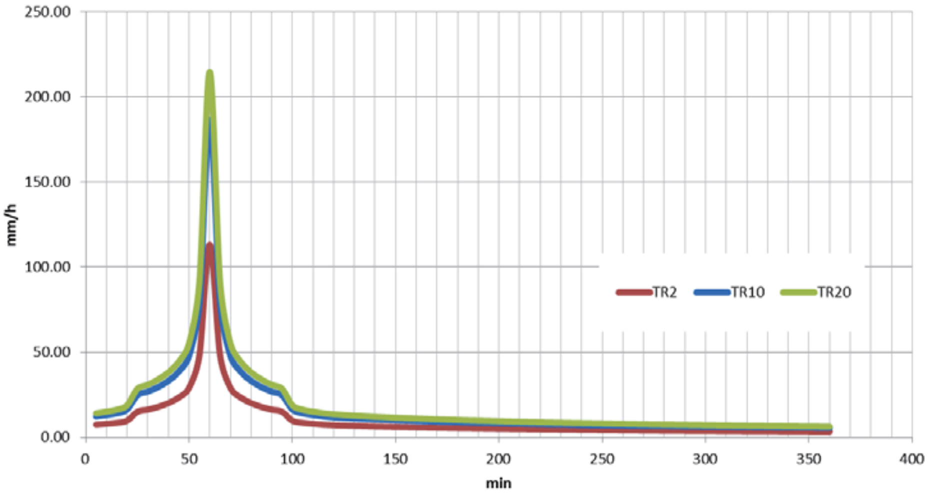


Figure 5-5: “Nested storms” for 2, 10 and 20 year return period

Design storms for PDSDUM 2019

The PDSDUM 2019 (Artelia, Halcrow, Rhama, CSI, 2019a) suggests the use of the following storm distribution based on a statistical analysis of significant rainfall events. There are some other considerations such as moving the peak of the storm from the beginning, as it is observed in the data analysis, to a quarter of the event duration. Artelia, Halcrow, Rhama, CSI (2019a) argue that for design proposes the peak should not occur at the beginning when the system has more availability to store water.

The recommended design storm profile is presented in Table 5-7 and Figure 5-6.

Table 5-7: Recommended storm profile as a percentage of the total rainfall (Artelia, Halcrow, Rhama, CSI, 2019)

Percentage of storm duration	8	17	25	33	42	50	58	67	75	83	82	100
Percentage of total rainfall	11	11	25	9	8	7	6	6	6	4	4	3

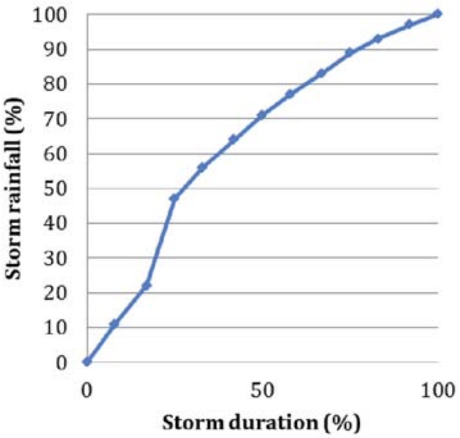


Figure 5-6: Recommended storm profile presented as accumulated rainfall through the storm duration, using the data from Table 5-7 (Artelia, Halcrow, Rhama, CSI, 2019)

5.2.5 IDF and design storms analysis and conclusions

The latest IDF relationships and the design storms presented at PDSDUM (Artelia, Halcrow, Rhama, CSI, 2019) will be used as the inputs for the design events in the BRC model.

Climate change factors could be considered, by increasing the rainfall intensity. For Montevideo, an increment of 10% of the rainfall is recommended for the 2050 horizon by the PDSDUM (Artelia, Halcrow, Rhama, CSI, 2019a). The approach of increasing the rainfall by a coefficient or a percentage is also suggested for the United Kingdom, where the Met Office UKCP18 project simulates a range of climate outcomes for five emission scenarios and obtains the percentage of increase or decrease in annual (or seasonal) rainfall (Land Projection Maps: Probabilistic Projections, 2020).

5.3 Montevideo's BRC characteristics

The BRC used in Montevideo by Sanitation Studies and Projects (SEPS) at the Montevideo City Hall are rain gardens with a standard size and components, see Table 5-8 and Figure 5-7. These structures allow infiltration, but there is not a study of the infiltration rate of the sites where they are located. They also have a drainage pipe outlet located at the top of the drainage layer. As observed by Agesta, Arce and Guido (2019) this pipe should be located at the bottom of the drainage layer; this configuration will be set into the model design.

Table 5-8: Rain Garden main characteristics

Width (m)	1.40
Length (m)	5.60
Area (m2)	7.84
Average Soil layer depth(m)	0.40
Drainage layer depth(m)	0.40
Average ponding depth (m)	0.15
Drainage pipe (m)	0.160

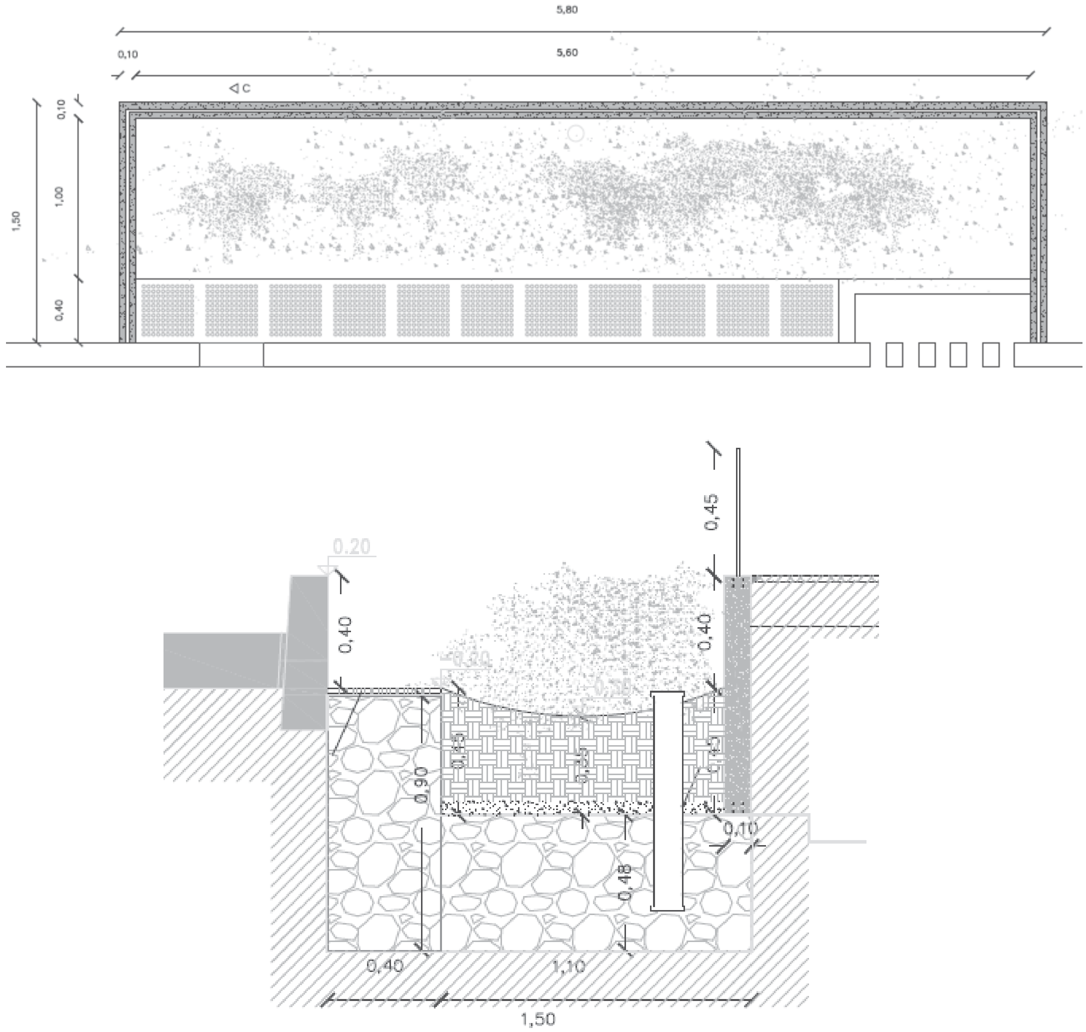


Figure 5-7: Rain Garden dimension extracted from blueprint "Plano Tipo Jardines de Lluvia" 2018 SEPS Montevideo City Hall.

5.4 Substrate media analysis

In the case of the rain gardens built in Montevideo, the substrate layer is not designed with engineered soil. Based on field observation, it is assumed to be mainly topsoil with a high percentage of organic matter. It could be considered similar to loam or silty loam texture according to FAO (2020). No tests or any physical characterization has been made on this substrate.

Montevideo's media

Since the substrate used for the Montevideo rain gardens is more similar to common soils the typical values of the water retention characteristics (adopted by the FAO for different soils according to the USDA texture classification) are presented in Table 5-9. The values selected for Montevideo's substrate media are a field capacity of 0.20 m^3/ m^3, a wilting point of 0.10 m^3/ m^3, and a porosity of 0.30.

Table 5-9: Typical soil characteristics for different soil types adapted from FAO 56(Allen, Pereira, Dirk and Smith, 1998)

Soil Type (USA Soil texture classification)	Soil water content at field capacity (m^3/m^3) θ_{FC}		Soil water content at wilting point (m^3/m^3) θ_{WP}		Maxima Retention Availability (m^3/m^3) θ_{FC} - θ_{WP}	
	Min	Max	Min	Max	Min	Max
Sand	0.07	0.17	0.02	0.07	0.05	0.11
Loamy Sand	0.11	0.19	0.03	0.10	0.06	0.012
Sandy Loam	0.18	0.28	0.06	0.16	0.11	0.15
Loam	0.20	0.30	0.07	0.17	0.13	0.18
Silt Loam	0.22	0.36	0.09	0.21	0.13	0.19
Silt	0.28	0.36	0.12	0.22	0.16	0.20
Silt Clay Loam	0.30	0.37	0.17	0.24	0.13	0.18
Silty Clay	0.30	0.42	0.17	0.29	0.13	0.19
Clay	0.32	0.40	0.20	0.24	0.12	0.20

Engineered media

To assess the incidence of the media a scenario with engineered media will be analysed for the model of BRC. Lui and Fassman-Beck (2018) studied the Water Retention Characteristics (WRC) for 7 living roof media and 7 bioretention media. The composition of the soils and the WRC for the bioretention media are presented in Table 5-10 and Figure 5-8. Then, the values selected for the model engineered media are a field capacity of 0.30 m^3/ m^3, a wilting point of 0.05 m^3/ m^3 and a porosity of 0.30.

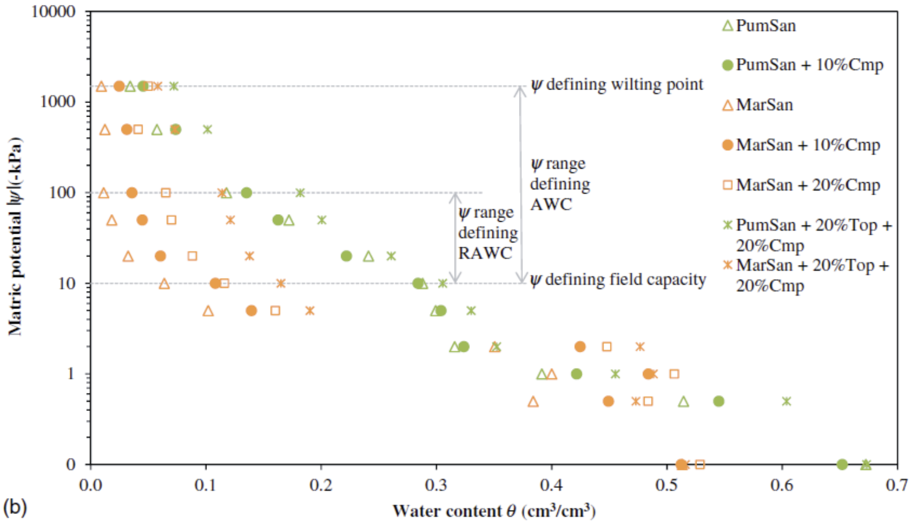


Figure 5-8: WRC for living roofs and bioretention media extracted from Lui and Fassman-Beck (2018)

Table 5-10: Engineered soil composition for living roofs and bioretention media extracted from Lui and Fassman-Beck (2018)

	Media label	Volumetric % of aggregate and compost	Dry Bulk density (gr/cm3)	Porosity	Saturated hydraulic conductivity (cm/s)	Textural classification according to USCS
Bioretention media	PumSan	100% pumice sand	0.79	0.67	0.076	SP
	PumSan +10% Cmp	90% pumice sand +10% Compost	0.81	0.65	0.083	SP
	MarSan	100% Marine Sand	1.31	0.51	0.022	SP
	MarSan +10%Cmp	90% Marine Sand +10% Compost	1.30	0.51	0.024	SP
	MarSan +20%Cmp	80% Marine Sand +20% Compost	1.23	0.53	0.018	SP
	PumSan+ 20%Top +20%Cmp	60% Pumice sand +20% top soil + 20% compost	0.76	0.67	0.019	SP
	MarSan+ 20%Top +20%Cmp	60% Marine sand +20% top soil + 20% compost	1.23	0.52	0.013	SP

[A] SP= poorly graded sand; SPg=poorly graded sand with gravel [ASTM D2487-11 (ASTM 2011)]

5.4.1 Infiltration rate

Woods Ballard et al. (2015) established that the infiltration viability of a BRC should be considered only when rates are greater than 3.6 mm/h (10^{-6} m/s). Table 5-11 adapted from Woods Ballard et al. (2015) presents typical values of infiltration rate ranges for different soil textures. Based on these values, to scenarios of infiltration rate will be model for 40 mm/h and 100 mm/h.

Table 5-11: Typical infiltration rates based on soil texture for good infiltration media adapted from Woods Ballard et al. (2015)

Texture	Typical infiltration rate (mm/h)	
Gravel	1080	108000
Sand	36	180
Loamy Sand	108	360
Sandy Loam	0.36	36

6 Results

6.1 Model sensibility to representing physical processes

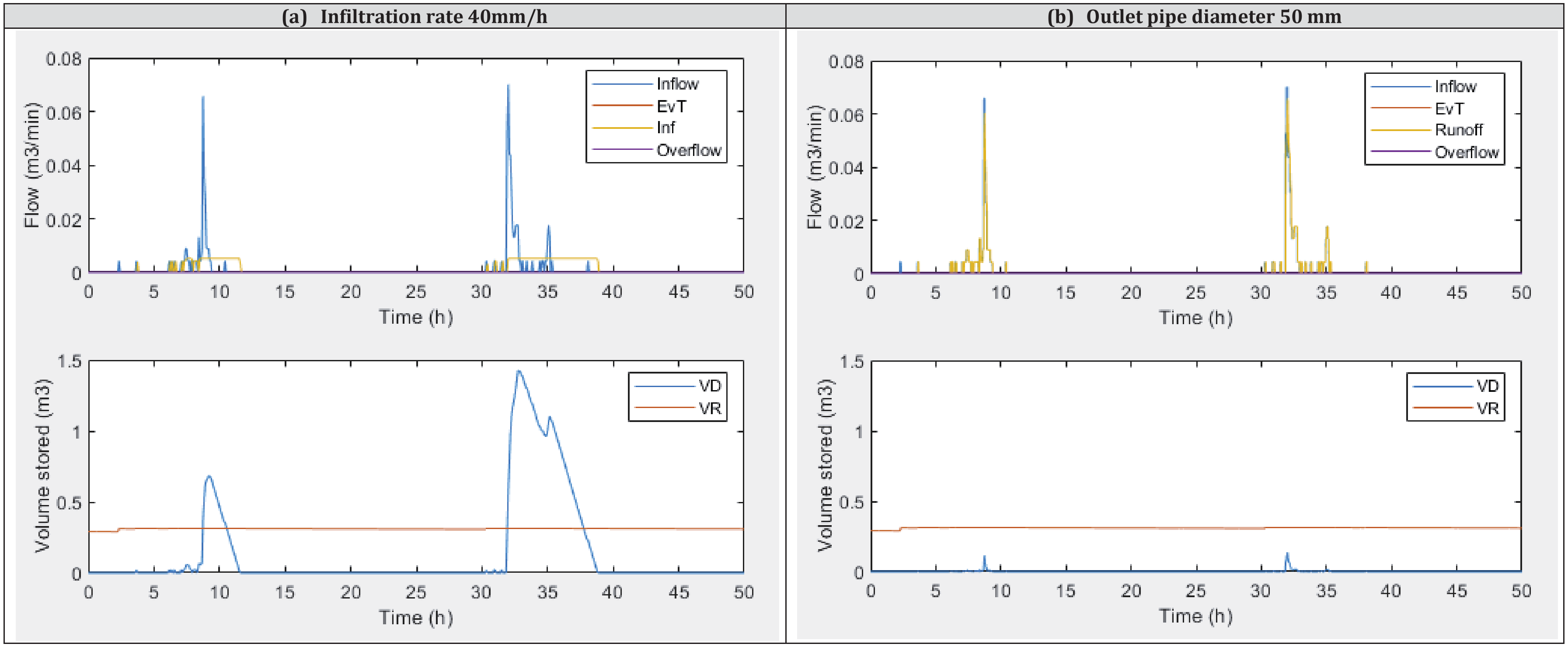
To assess the sensibility of the models to represent the physical processes in a BRC, two periods of time were selected to show the inflow and outflow hydrographs and the stored volume through time. The models were set for a BRC with Montevideo's media, for two outflow conditions. The lined model the outflow is defined by an outlet pipe of 50 mm diameter, while for the unlined it is defined by an infiltration rate is 40 mm/h.

In Figure 6-1 two independent and consecutive winter storm events are shown for the period between 9:35 h of 11 June 2014 to 11:35 of 13 June 2014. In Figure 6-2 one summer storm event is displayed for the period between 9:55h of 13 January 2018 to 11:55 h of 15 January 2018. This event is identified as a significant event with a return period between 5 to 10 years (see section 6.2.2, Table 6-3).

In both figures, it is shown how the volume stored in retention during the dry periods slightly decreases over time until is quickly filled to capacity when the rainfall events start. There is more available retention volume previous to the summer storm than for the winter. The available retention volume previous to a storm event depends on two factors the ADWP and the ET rate. Even though the summer storm has a lower ADWP (2.5 days) than for the first winter event (3.75 days), the ET rates are almost 7 times higher for January (5.8 mm/day) than for June (0.8 mm/day).

In both figures, it is shown how there is almost no detention for the lined BRC, where the detention volume is barley filled (maximum of 9.5%). This happens because the outflow limitation imposed by the outlet pipe is a high value, for 10 cm of water height in the BRC the pipe will evacuate 1.65 L/s (99×10^{-3} m^3/min). While for the unlined BRC there is clear detention by limiting the outflow to 5.2×10^{-3} m^3/min (0.087 L/s). Also, it is shown how the detention storage is more occupied, and even fully used for the summer event when overflow occurs.

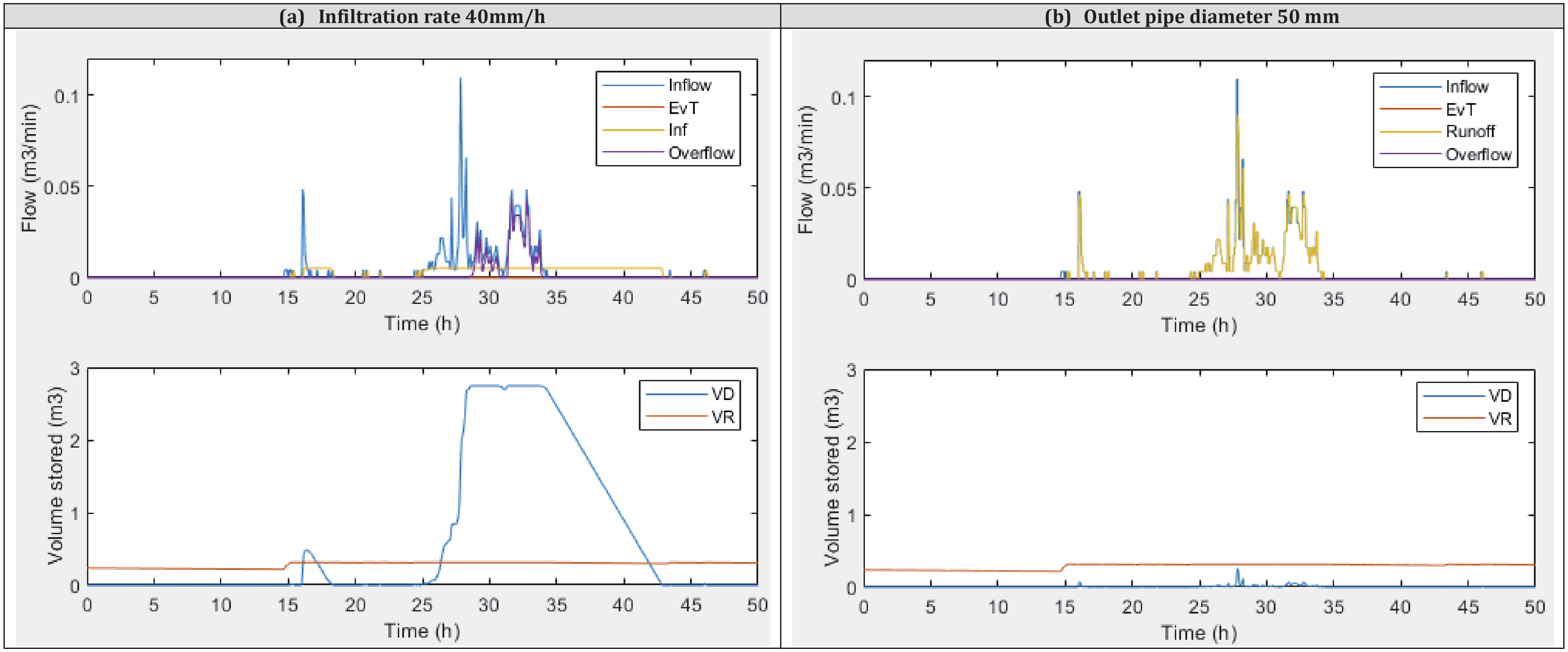
Figure 6-1: Hydrographs and storage volume trough time from 11 June 2014 9:35 h to 13 June 2014 11:35



(a) Infiltration rate 40mm/h

(b) Outlet pipe diameter 50 mm

Figure 6-2: Hydrographs and storage volume trough time for the period of 13-Jan-2018 09:55:00 to 15-Jan-2018 11:55:00



(a) Infiltration rate 40mm/h

(b) Outlet pipe diameter 50 mm

6.2 Definition of events, antecedent dry weather period and initial moisture content analysis

6.2.1 Definition of events using MIT/IETD

In order to separate the independent rainfall events of a 6 year time series rainfall record, with 5 min time step, for rain gauge located in Montevideo, the model was used to determine an appropriate value for the MIT/IETD. The sensitivity for different design rainfall events was tested for the unlined rain garden model with Montevideo's media (see Table 6-1).

The most restrictive outflow condition was selected (infiltration rate of 40 mm/h) because it would take more time for the detention storage to be empty. For the lined rain garden or the unlined with a higher infiltration rate, smaller times will be obtained. To check the variability with the outflow condition, the model with a high infiltration rate was also analysed.

Initially, the selection of the media was arbitrary, later on, it was discovered that for engineered media larger times than the MIT/IETD selected were necessary to ensure independent events, see section 6.3.2.. The engineered media has more retention capacity; consequently, the infiltration starts later than for Montevideo's media. These properties in addition to a constant infiltration rate result in a longer the process of infiltration compared to Montevideo's media.

Table 6-1: Unlined rain garden MIT

Return period (years)	Duration (h)	Total depth (mm)	Infiltration rate (mm/h)	Time when detention storage is empty (min)	MIT (h)
2	6	75	40 100	890 495	8.83 2.25
2	12	75	40 100	1235 725	8.58 0.083
100	6	153	40 100	890 575	8.83 3.58
100	12	153	40 100	1250 890	8.83 2.83

Another thing that changes with the MIT/IETD is the number of events identified and their return period. When the MIT/IETD increases, the number of events decreases and so does the return period for some events. This happens because for greater MIT/IETD values the events have longer durations and even if they have a slight increase in the total depth; it is not enough to maintain the event in the same return period curve (Figure 6-3).

In Table 6-2 the results for different MIT/IETD are presented. In Figure 6-3 the curves of depth vs duration for design events and the identified events for the 8 h MIT are presented.

Table 6-2: MIT/IETD relation with events

MIT/IETD (h)	Number of Events	Number of significant events
3 hours	773	5
6 hours	597	4
8 hours	548	4
12 hours	489	3

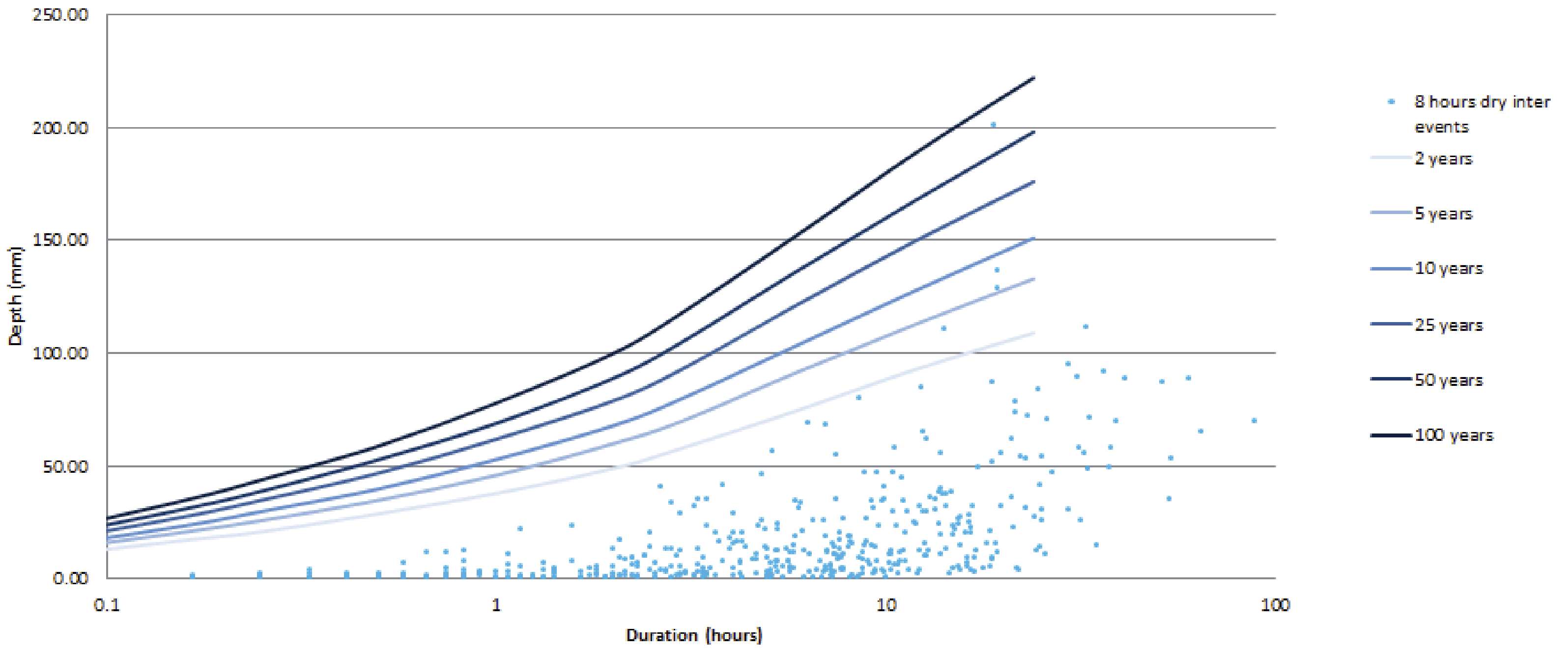


Figure 6-3: Depth vs Duration for design storms curves and recorded storms events with 8 h MIT/IETD in logarithmic scale

Based on the data obtained by the model (Table 6-1) and the observations in the literature review, a MIT/IETD between 6 and 8 hours is a reasonable value to use in this BRC. Between these times the significant events do not change their characteristics, and the difference between the amounts of events is approximately 10% (Table 6-2).

The MIT value of 8 hours is selected considering that in the time after a rainfall event most of the detention storage will be emptied for the majority of the events (non-significant events) with a return period of less than 2 years.

6.2.2 Rainfall events characteristics

There are 548 events defined using the IMT/IETD criteria of 8 hours, 50% of the events last less than 4.1 h and have a total rainfall depth smaller than 4.2 mm. The statistical analysis of depth and duration is presented in Figure 6-4 and Figure 6-5. Only 4 of those events are considered significant, with a return period over 2 years, their characteristics are presented in Table 6-3.

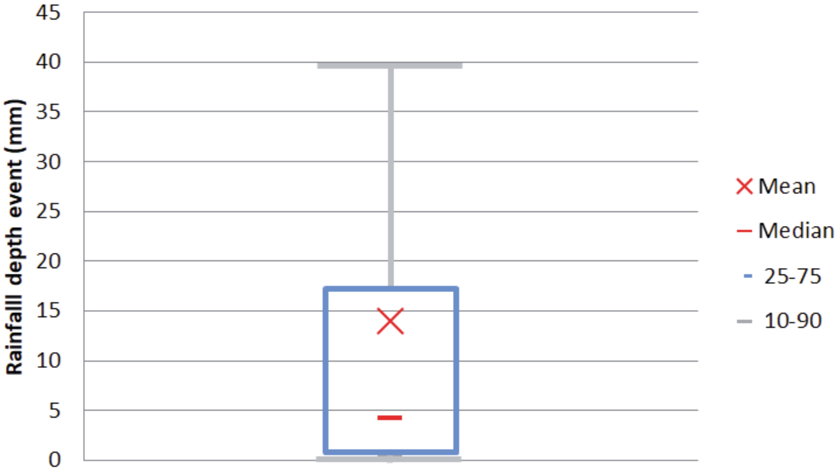


Figure 6-4: Rainfall events depth statistics

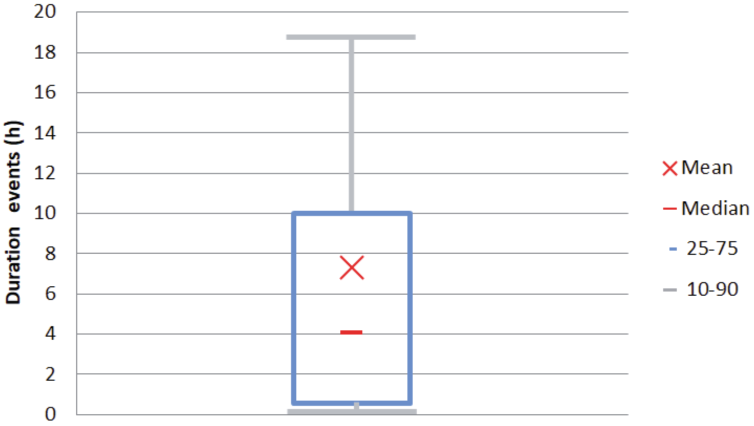


Figure 6-5: Rainfall events duration statistics

Table 6-3: Significant events characteristics

Event Nº	Start	End	Duration (h)	Depth(mm)	Intensity (mm/h)	Return Period (years)
15	'07-Feb-2014 03:15:00'	'07-Feb-2014 17:25:00'	14.25	110.4	7.75	2-5
364	'14-Jan-2018 00:40:00'	'14-Jan-2018 20:10:00'	19.58	128.2	6.54	5-10
449	'13-Dec-2018 13:10:00'	'14-Dec-2018 08:35:00'	19.50	135.9	6.97	5-10
376	'17-Mar-2018 22:35:00'	'18-Mar-2018 17:35:00'	19.08	200.76	10.52	50-100

6.2.3 Antecedent Dry Weather Period (ADWP)

After defining the events, the antecedent dry weather period (ADWP) can be obtained for each event and a statistical analysis is made. On average there is a 3.7 days ADWP but the standard deviation is 4.6 days. The ADWP of the data series has a high standard deviation; therefore a seasonal analysis is made and presented in Table 6-4. This high variability of the occurrence of rainfall event is consistent with the extreme inter-annual irregularity and variability of the rainfall in Uruguay (El clima y su variabilidad en Uruguay, 2020).

Table 6-4: ADWP seasonal analysis

	Mean	Standard deviation
ADWP summer (days)	3.4	3.3
ADWP winter (days)	4.2	6.7
ADWP autumn (days)	3.3	4.1
ADWP spring (days)	3.9	3.7

6.2.4 Initial moisture content (θ_i)

To obtain a mean θi the unlined rain garden model is used, under the assumption that there is not a high variability between the retention process for the lined and unlined rain garden. However, the sensitivity to the media was analysed later on (see section 6.3).

At first, the θi for the model initial conditions was selected as the mid value between the wilting point and the field capacity. The θi for each storm event was obtained from the model, and the statistics calculated (see Table 6-5). There is not a significant difference with the mean and standard deviation values obtained changing the initial condition from the wilting point to the field capacity (less than 0.2%). Hence the initial conditions are irrelevant for a long time-series model, once that the BRC retention storage is full for an event, initial conditions are no longer relevant.

Initial conditions will be critical for a design storm analysis. The mean θi for each media is going to be used as the initial condition for the time series events and the design event analysis.

Table 6-5: initial Moisture Content obtained from the BRC model for the time series data

	Wilting Point (minimum moisture content) (vol/vol)	Field Capacity (maximum moisture content) (vol/vol)	Mean Initial Moisture Content θ_i (vol/vol)	Standard deviation Initial Moisture Content θi (vol/vol)
Montevideo's Media	0.10	0.20	0.176	0.022
Engineered Media	0.05	0.30	0.270	0.034

These results show that the mean volume available for storage retention is only 0.024 or 0.030 m^3/m^3, for Montevideo's and Engineered media respectively. These are very small values comparing them to the capacity, only 24% for Montevideo's media, and 12% for the Engineered media.

The moisture content in the soil is related to the ADWP, more days without rainfall more water will be consumed by ET and more retention storage will be available for the next storm event. To empty the substrate when the retention storage is at capacity would take more than the mean ADWP of 3-4 days. Depending on the actual value of ET this could take approximately 10 to 25 days in summer and 40 to 100 days in winter for the Montevideo's and Engineered media respectively.

This phenomenon has been observed by Stovin, Poë, De-Ville and Berretta (2015) for the case study of different green roof beds substrate and vegetation configurations in Sheffield. Where they conclude that in practice for temperate climates, the actual substrate moisture retention capacity was closer to zero than to its maximum value.

6.3 Retention performance

6.3.1 Overall retention

The water budget for the 6 year data for the unlined rain garden is presented in Figure 6-6. For the unlined rain garden, the infiltration can be considered as part of the retention since this water does not enter the drainage system. The water budget is presented in Figure 6-7.

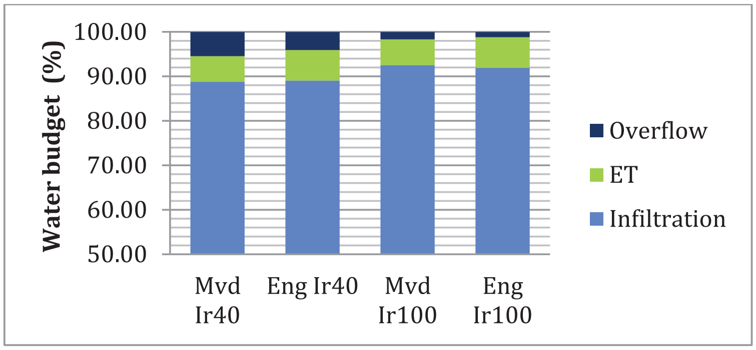


Figure 6-6: Overall water budget for the unlined garden for different media where Mvd represents the Montevideo's media, Eng the engineered media, Ir40 is an infiltration rate of 40mm/h and Ir100 is an infiltration rate of 100mm/h.

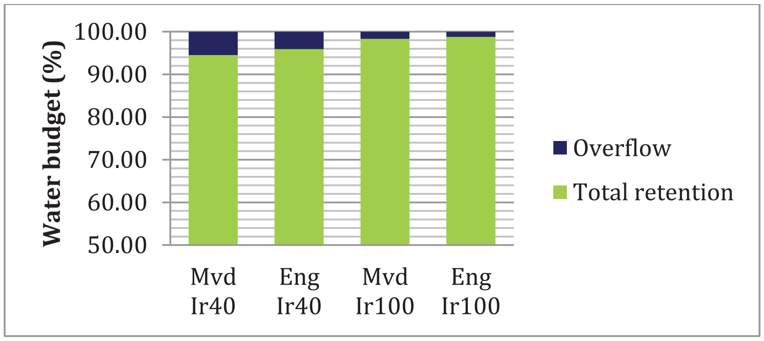


Figure 6-7: Overall water budget for the unlined garden considering Infiltration as part of the retention for different media where Mvd represents the Montevideo's media, Eng the engineered media, Ir40 is an infiltration rate of 40mm/h and Ir100 is an infiltration rate of 100mm/h.

For the lined rain garden the retention is only given by the ET, in Figure 6-8 the water budget for the 6 year data is presented.

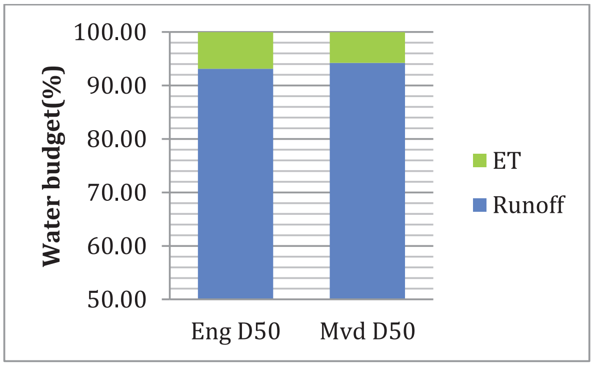


Figure 6-8: Overall water budget for the unlined garden for different medias where Mvd represents the Montevideo's media, Eng the engineered media and D50 represents the outlet pipe of 50mm.

A system designed to infiltrate water will have retention values closer to 100%, because there will be outflow to the drainage system only due to overflow.

Evapotranspiration is the same for the lined and unlined BRC with the same media, 6.86% for the engineered media and 5.76% for the Montevideo's media. For the lined garden there is no overflow for any of the 548 events.

Comparing the results with the BRC studied by Berretta (2018), this BRC also has an IHLR 0.1, when tested for low (0.36 mm/h) and high infiltration (7.6 mm/h) rates for 4 climatic conditions. The results for annual ET resemble Cornwall, where the annual climatic data is similar to Montevideo. Cornwall has an average annual rainfall of 1365 mm, while Montevideo has 1275 mm; the seasonal PET has also similar values.

6.3.2 Per-event retention

The retention storage of the BRC is fully used for a significant amount of events. For Montevideo's media, there are 91 events, all fewer than 2.51 mm of depth, which left some retention capacity available. Whereas, for the engineered media these happens for 101 events with a maximum depth of 4.57 mm.

For the unlined BRC, if infiltration is considered as part of the retention volume for its performance the retention will be 100% for all the events that do not have overflow. When there is no overflow, all of the inflow is stored in the retention volume to be consumed as evapotranspiration or stored in the detention volume to leave the rain garden as infiltration. Thus the first quartile value is 100% (red line) and the outliers are the events where there is overflow (red crosses), see Figure 6-9.

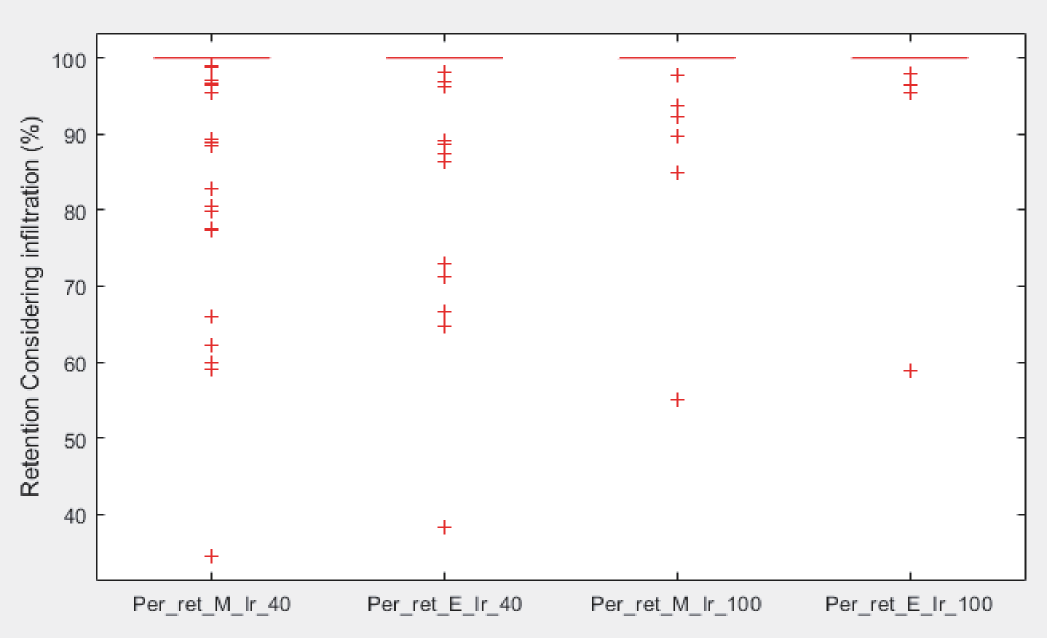


Figure 6-9: Retention statistics for unlined rain garden considering infiltration. Where Mvd represents the Montevideo's media, Eng the engineered media, Ir40 is an infiltration rate of 40mm/h and Ir100 is an infiltration rate of 100mm/h.

If we consider the strict concept of retention given only for the storage retention volume to be consumed by evapotranspiration, we can compare the retention statistics for the lined and unlined rain garden for different media, see Figure 6-10.

There is no difference in the retention per event between different outflow conditions as expected. The mean values are almost the same for all the scenarios. The 10% difference between the third quartile values happens because the retention storage volume capacity is larger for engineered media. However, as seen in the overall water budget, this only represents 1% of the inflow in the 6 year period.

It should be noted that for all of the scenarios, there is a huge variability of the retention performance from a minimum value of 0 to a maximum of 100%.

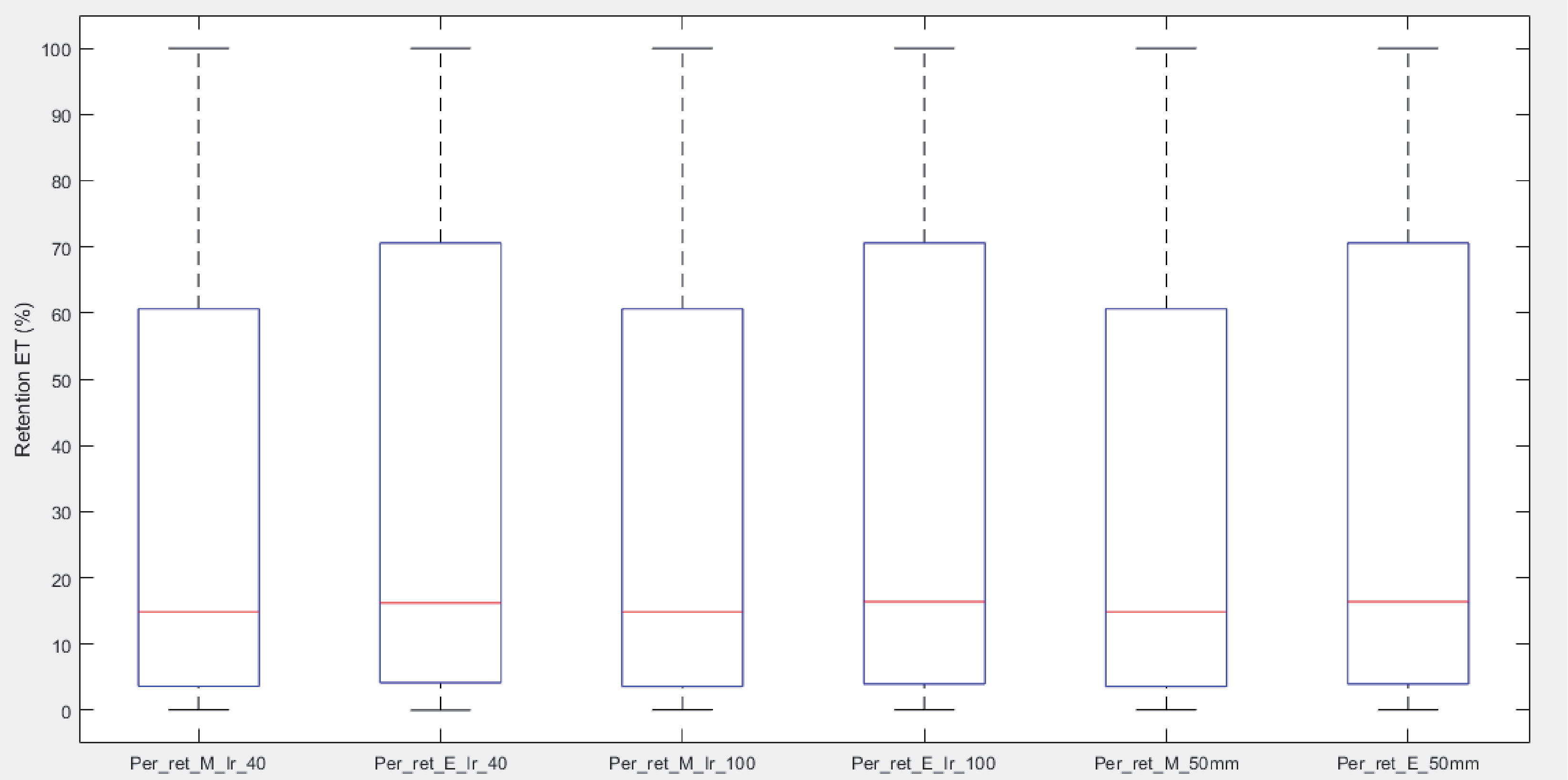


Figure 6-10: Retention Statistics for lined and unlined rain garden for different media, only considering ET. Where Mvd represents the Montevideo's media, Eng the engineered media, Ir40 is an infiltration rate of 40mm/h and Ir100 is an infiltration rate of 100mm/h and D50 represents the outlet pipe of 50mm.

*The outliers have not been plotted for any of the scenarios. The most significant ones are two negative values for Per_ret_E_Ir_40. The anomaly of these values is discussed below.

When not considering infiltration as part of the retained volume, negative values of retention occur for the BRC with Engineered media and infiltration rate of 40 mm/h for 2 events. This happens because the previous event is not independent of the next one. As a result, infiltration from the previous event continues when the second event starts, resulting in more infiltrated water than inflow for the second event. This is related to the MIT/IETD time, the infiltration rate, and the media characteristics. For engineered media there is more retention storage available, then the infiltration process starts later than for Montevideo's media and since the infiltration rate is constant, the infiltration process has the same duration but is out of phase in time consequently, overlaps with the next event. With a higher MIT/IETD of approximately 9 h, the definitions of the events would have changed and there would not be any negative retention values.

Since the outflow condition is not significant for the retention performance, it is analysed distinguishing between the total depth of the event only for the unlined rain garden with an infiltration rate of 40 mm/h, for both media (see Figure 6-11 and Figure 6-12). There is almost no difference between the retention statistics for the different media with respect to the rainfall depth. A small improvement in retention performance is made for engineered media, only a 5% of improvement in the mean retention for events of 0-2 mm depth.

Due to the fact that the media parameter has an insignificant impact on the retention for most of the events, the following analysis will only consider Montevideo's media.

It should be noted that there is an inverse and strong relationship between event depth and retention performance. This supports the statement that the mean value of retention for all the events does not express the actual event performance. This was also observed by Stovin, Vesuviano and De-Ville, (2015) for Green roofs located in Sheffield.

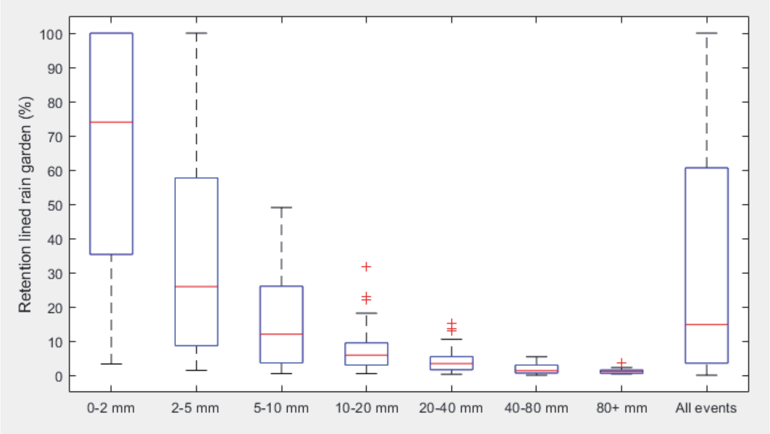


Figure 6-11: Retention performance for the lined rain garden for Montevideo’s media with respect to rainfall depth.

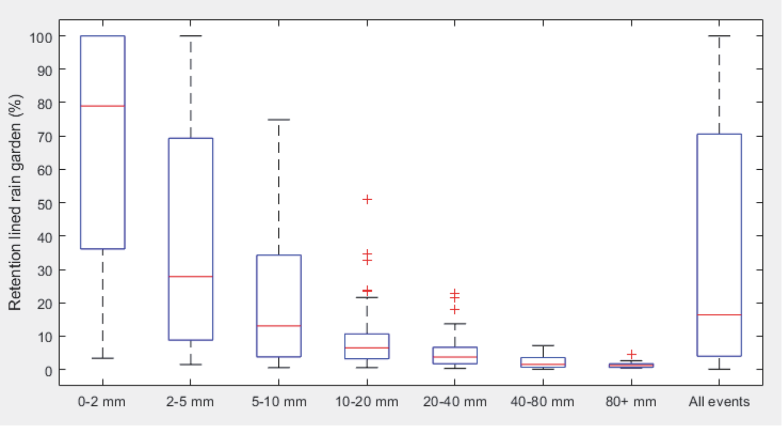


Figure 6-12: Retention performance for the lined rain garden for Engineered media with respect to rainfall depth.

6.4 Per-event detention performance

As established previously, the detention performance is only going to be analysed for the Montevideo's media.

6.4.1 Lined rain garden

For all of the events in the record there is no overflow, therefore the only parameter to measured detention is the runoff. Also, this means that the storage detention volume in never fully used. From the 2.74 m^3 available for storage detention a maximum of 40.4% is used for the Montevideo's media rain garden.

In Figure 6-13 the boxplot graph with the maximum percentage storage detention is presented with respect to rainfall depth and for all of the events. More than half of the events are in the range of 10mm total depth, have a maximum use of 8% of the detention storage volume and the mean is lower than 1%. Considering all of the events the mean value is 0.3%. This is the first indication that the drainage layer could be smaller, and the minimum constructive size could be used. Another observation is that since all the available detention volume is not used for this outflow restriction (50 mm drainage pipe), for a different media with more available storage volume the detention results would be the same.

Of 548 events, 91 have 100% retention, so they do not produce runoff. As a result, these events are not considered for the measure of runoff starts, runoff duration, peak runoff, peak attenuation and peak delay, even though they can be considered to have 100% peak attenuation and 0 m^3/min peak runoff..

In Figure 6-14 the runoff peak boxplot graph is presented with respect to rainfall depth and for all of the events. The greenfield runoff is a small value of $9.x10^{-4}$ m^3/min, and is always exceeded.

In Figure 6-15 the Peak attenuation statistics are presented with respect to rainfall depth and for all of the events, the values of 100% corresponding to events with no runoff are not included in all of the events. There is almost no attenuation for the peak for small depth rainfall events, contrary to what expected the percentage of attenuation increases with depth rainfall. In the study of detention performance for green roofs made by Stovin, Vesuviano and De-Ville (2015) there is a clear difference for peak attenuation with respect to rainfall depth, decreasing the attenuation for higher rainfall depth events. This difference between the modelled scenario and the one reported in literature shows how for the modelled scenario the outlet does not restrict the flow for most of the events. Only for events with greater depths, which are the ones with higher peaks are slightly attenuated.

The Runoff duration was calculated, but statistics were not plotted. There is almost no difference between the duration of the rainfall event and the runoff duration, the average difference is less than 1min (1 time step).

The runoff starts statistics with respect to rainfall depth and for all of the events are plotted in Figure 6-16. The plot shows there is not a significant variation for this parameter with respect to the depth of the storm event. This is because in the model, the runoff will start at a time step after the retention storage is filled. This is 1 minute, due to the discretization of the model time steps from 5 min to 1 min. The mean for al depth events is 1min, and the retention volume is mostly filled in the first 2 time steps. The cases where it takes more time for the runoff to start are mostly events with a pulse hydrograph. The beginnings of these events have small intensity rainfall pulses with dry periods, taking more time for the retention storage to be filled.

The peak delay box plot with respect to rainfall depth and for all of the events is presented in Figure 6-17. Lots of outliers with extremely high values were identified, so a further study of the runoff hydrographs was made. There are two types of rainfall hydrograph identified in the data, a continuous curve with one or more peaks or a series of pulses. For these last ones, there is a difficulty in measuring the peak delay and they are associated with the observed outlier values.

In Figure 6-18 two types of events are shown, event No 115 (continuous hydrograph) and event No 13 (pulse hydrograph). For the event No 115, the peak delay identified using a Matlab script is 10 min, whereas for the event No 13, the peak delay is 273 min. It is clear that for the pulse event the actual peak delay is 4 min, a much smaller value than the one recognized by the program. Even if the pulses look exactly the same on the graph, on the tenth decimal point there is a difference, consequently, the programmed script identifies the peak much later than when it actually happens. Clearly the values obtained using this metric are not useful, because a significant part of the events are pulses of rain that do not generate a single peak.

After looking at the detention metrics, it seems that for a lined rain garden with this outlet condition (outlet pipe of 50 mm) there is almost no detention process represented. This BRC does not work as a structure with the outlet controlling the outflow. There is almost no delay and no peak attenuation. The Runoff starts , which represents the delay, is given by the time that the retention is filled and the travel time through the BRC. In this case, these values are low because the retention volume fills quickly and the travel time is defined by the model time step (only 1 min). Regarding the peak attenuation, it could be argued that is mostly given by the retention since the duration of the runoff is the same as the event.

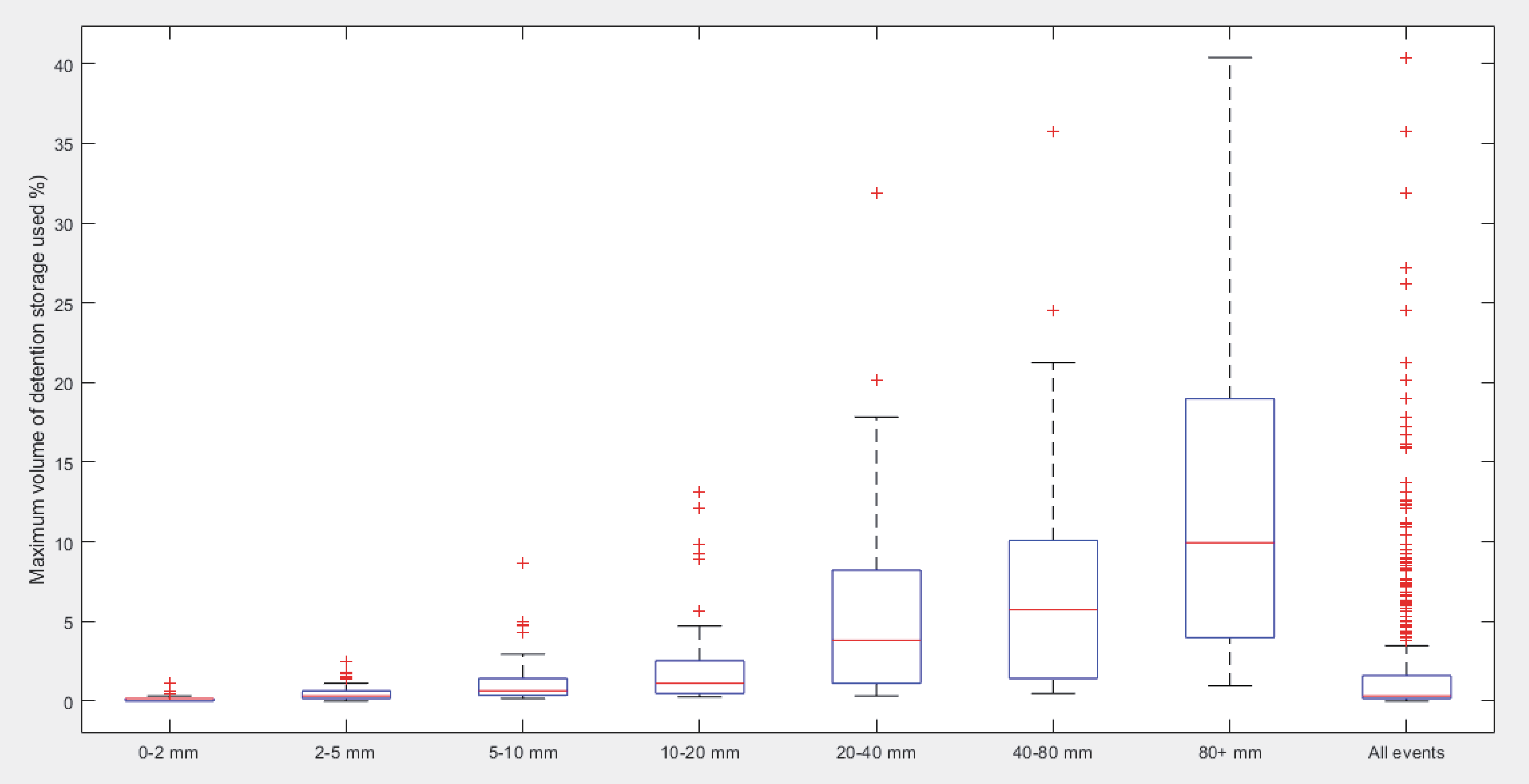


Figure 6-13: Maximum percentage of detention storage used with respect to rainfall depth and for all of the events

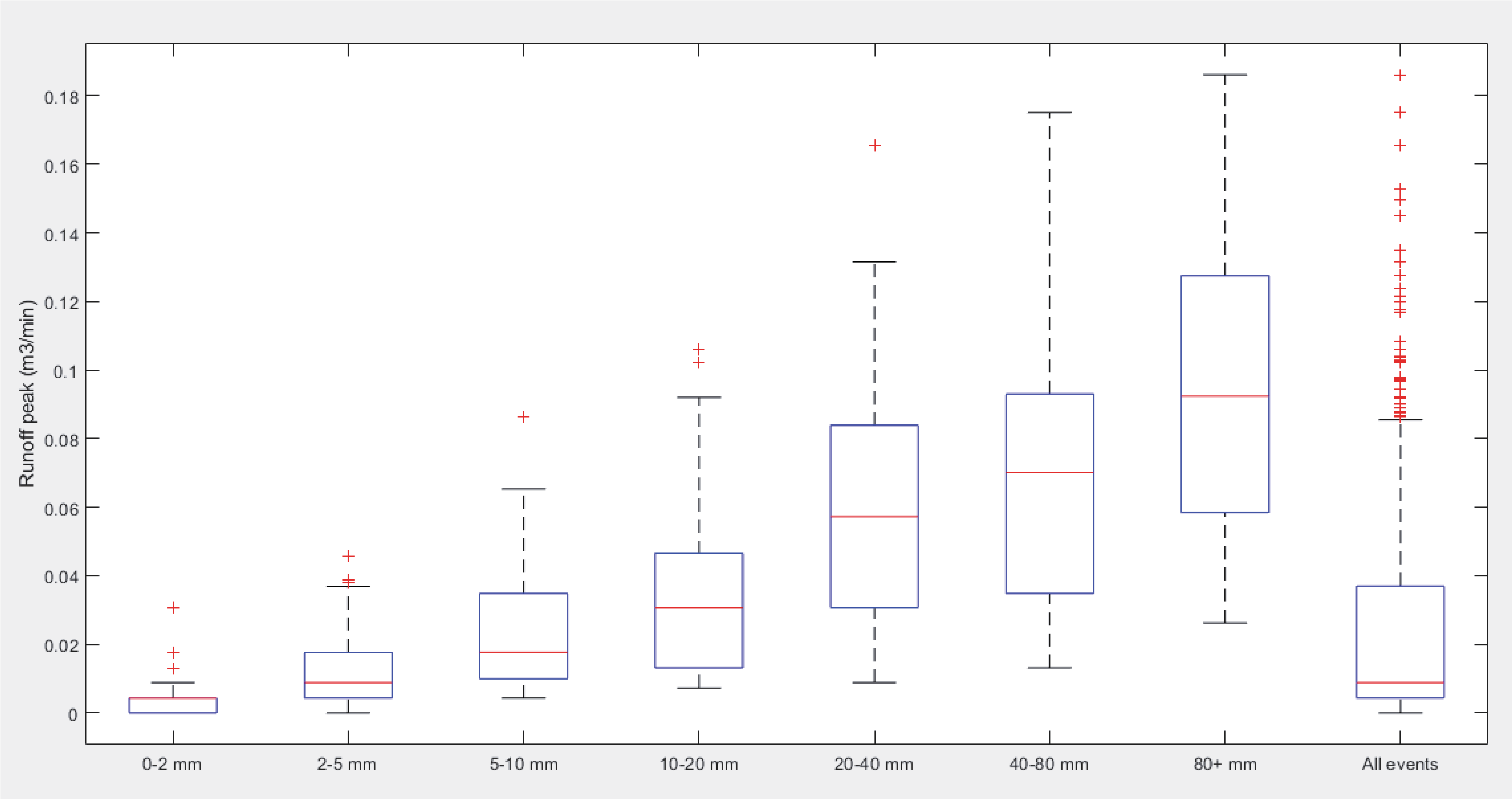


Figure 6-14: Runoff peak with respect to rainfall depth and for all of the events

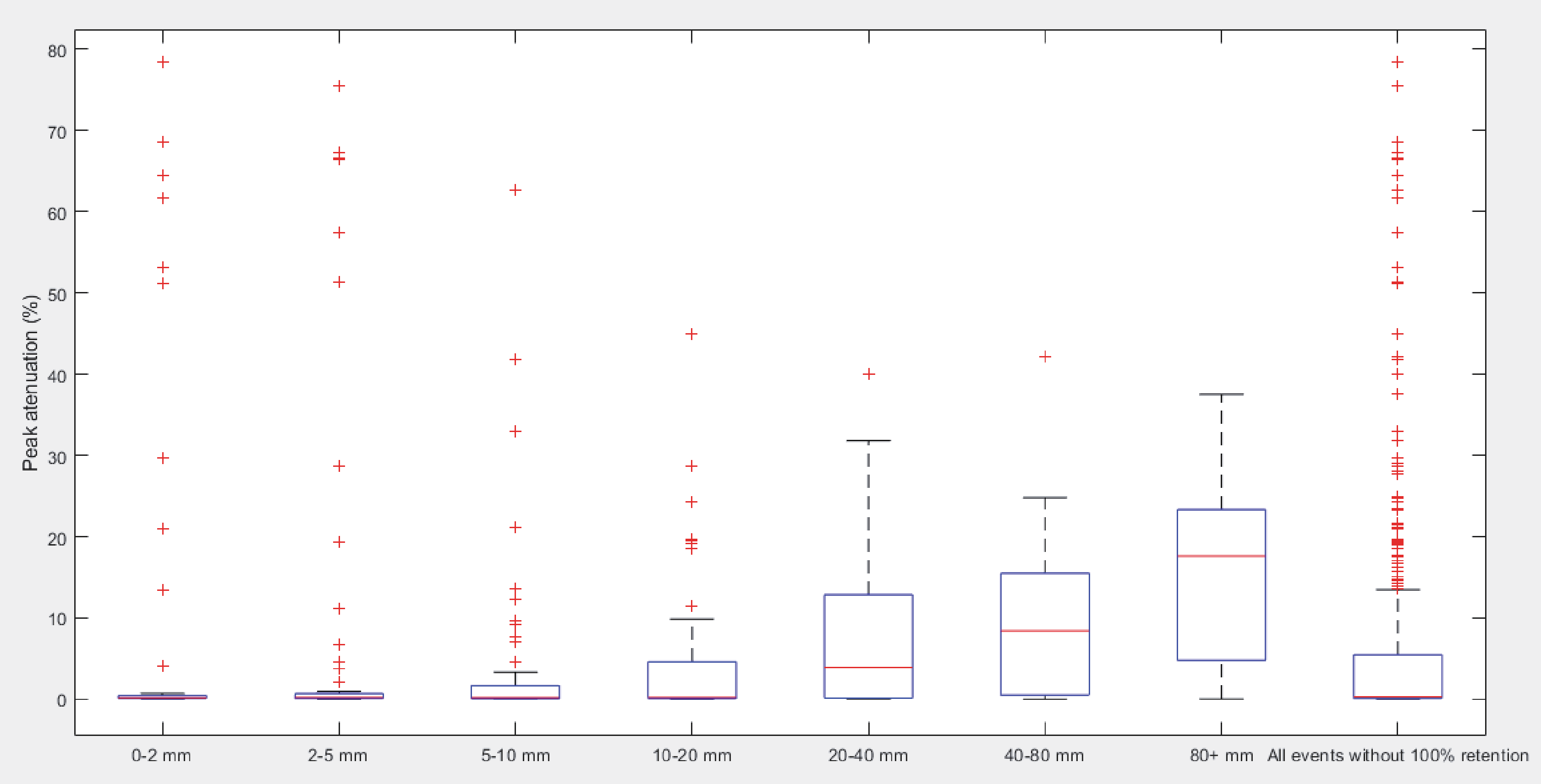


Figure 6-15 : Peak attenuation percentage with respect to rainfall depth and for all of the events

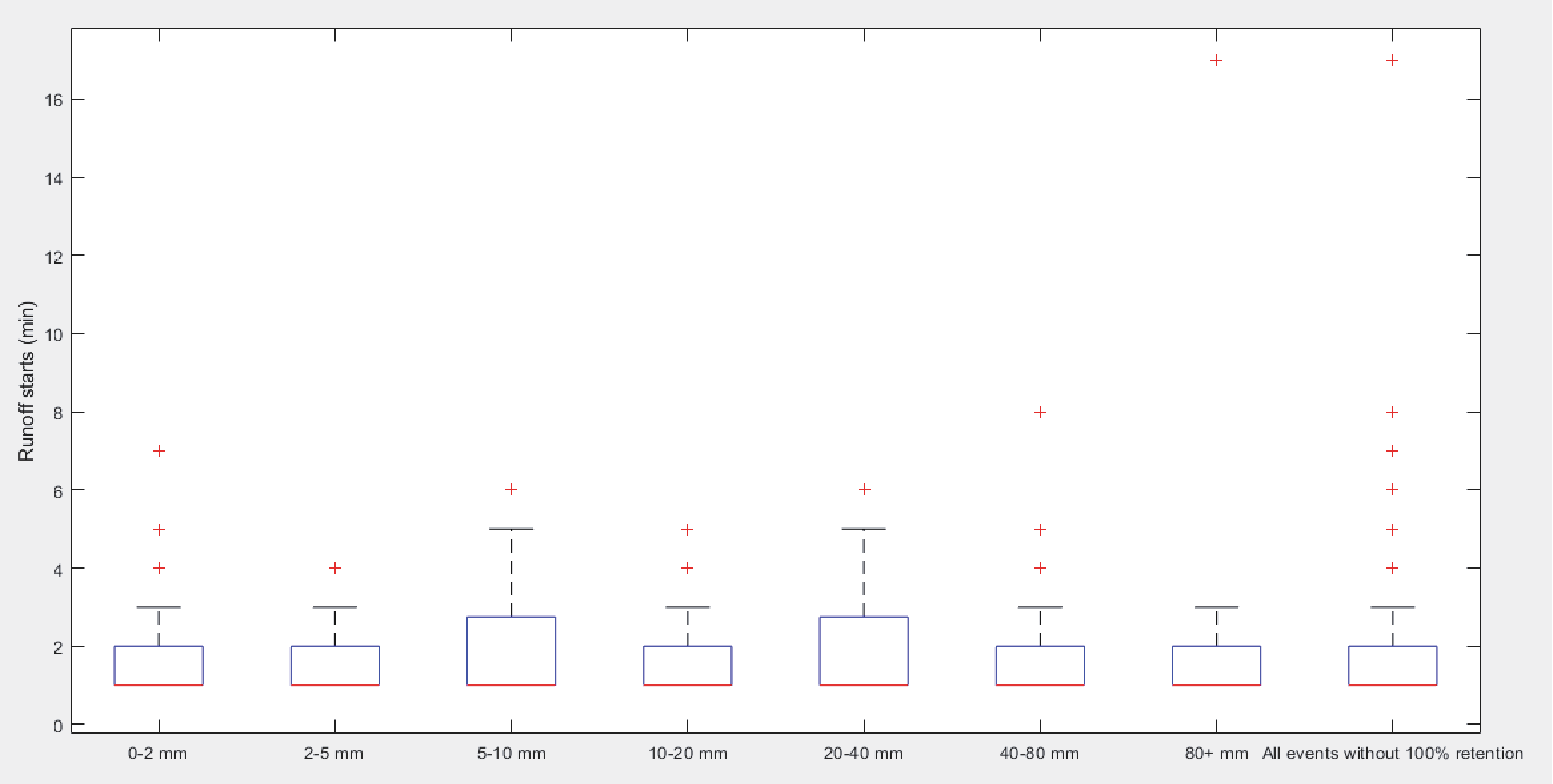


Figure 6-16: Runoff starts with respect to rainfall depth and for all of the events

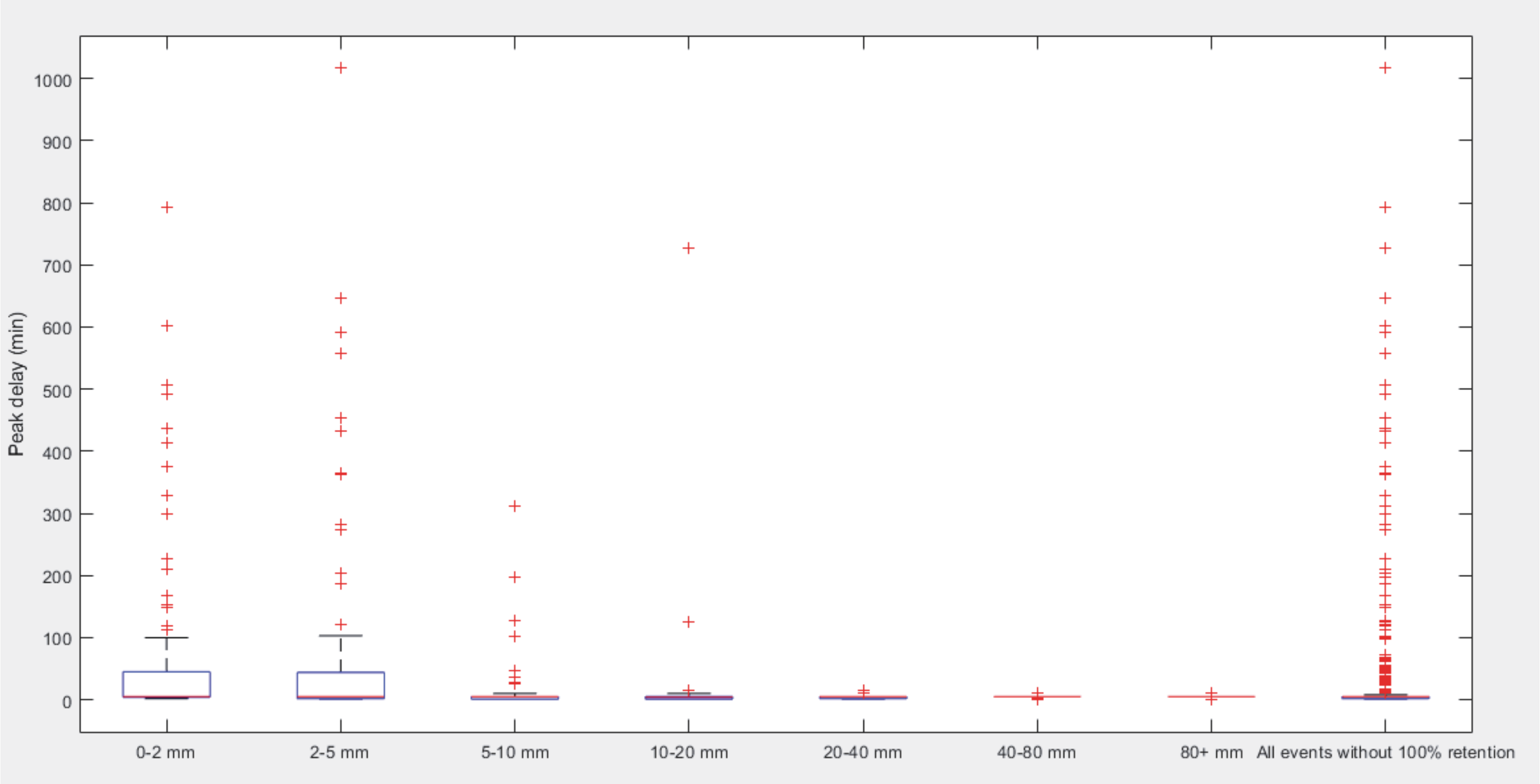
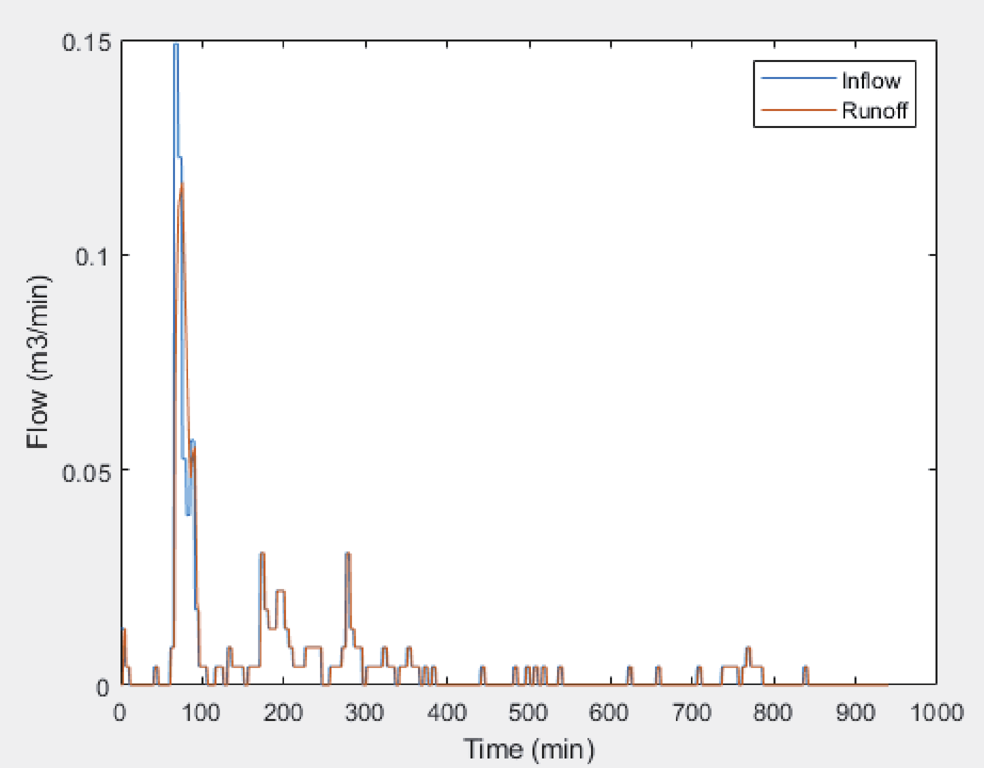


Figure 6-17: Peak delay with respect to rainfall depth and for all of the events

Continuous rainfall event Nº115



Pulse rainfall event Nº13

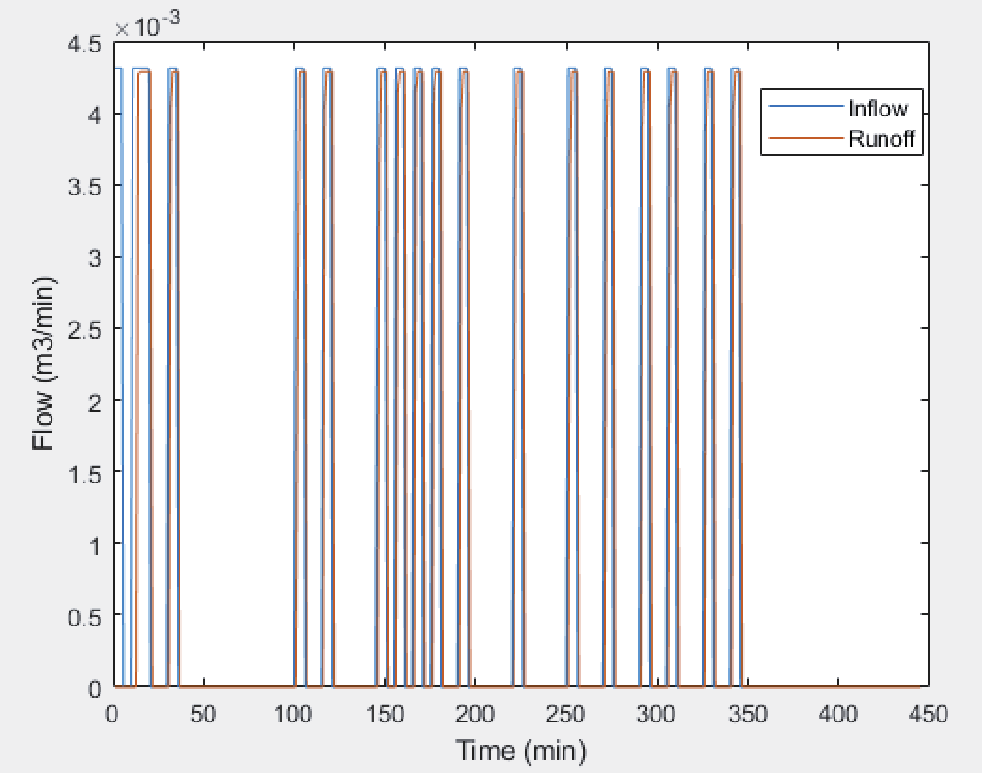


Figure 6-18: Example of two different inflow and outflow hydrograph for two events

6.4.2 Unlined rain garden

Only when there is overflow, there is an interest of measuring detention parameters. The scenario that is going to be analysed is the one with more overflow events. This is the one with an infiltration rate of 40 mm/h and Montevideo's media, resulting in 20 overflow events. The events that do not produce overflow are not considered for the measure of runoff starts, runoff duration, peak runoff, peak attenuation and peak delay, even though they can be considered to have 100% peak attenuation and 0 m3/min peak runoff. All of these events have a total depth greater than 40mm.

The four significant events previously identified are within the events that cause overflow, and can be recognized as the four with more rainfall depth also indicated at Figures 6-19 to 6-21.

In Figure 6-19 the water budget of these events is presented. It is worth to notice there is a trend where for more rainfall depth the more percentage corresponds to overflow, but for some events that is not necessarily true; this will also depend on the rainfall distribution in time. If the intensity is lower than the infiltration rate the BRC will manage to infiltrate more water and have less water overflowed.

Looking at the detention parameters, Figures 6-20 to 6-21, for this outflow condition there is significant detention, as expected since the outflow (overflow) would only start when all the available storage volume and the ponding reaches its capacity. Also, the majority of the water will not become outflow since it would be retained (evapotranspirated and infiltrated). Hence, the outflow hydrograph, only given by overflow, has a smaller base (runoff duration) and a smaller peak.

The model for the unlined BRC was built for a time step of 5 min so the time parameters shown in the figures below are multiples of 5.

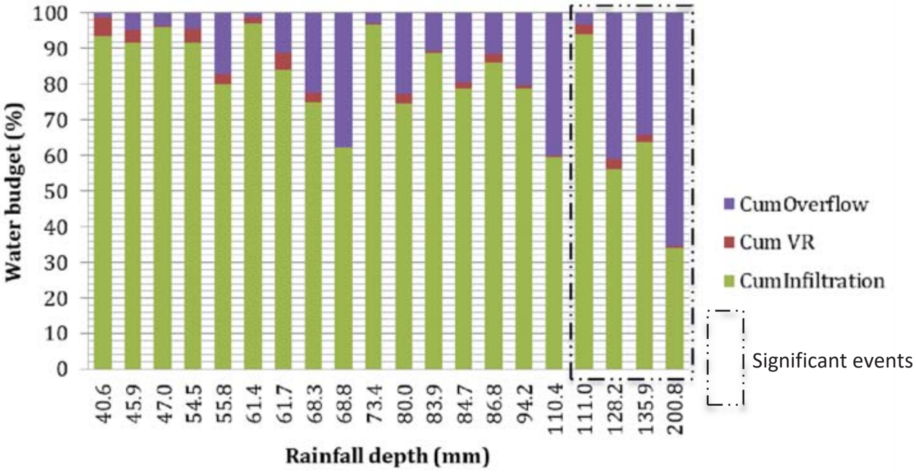


Figure 6-19: Water budget of the 20 overflow events for the unlined BRC, with Ir=40mm/h and Montevideo's media with respect to rainfall depth. Were CumOverflow is the accumulative overflow volume, Cum VR is the accumulated volume in the retention storage (ET), Cum Infiltration is the accumulated infiltration volume

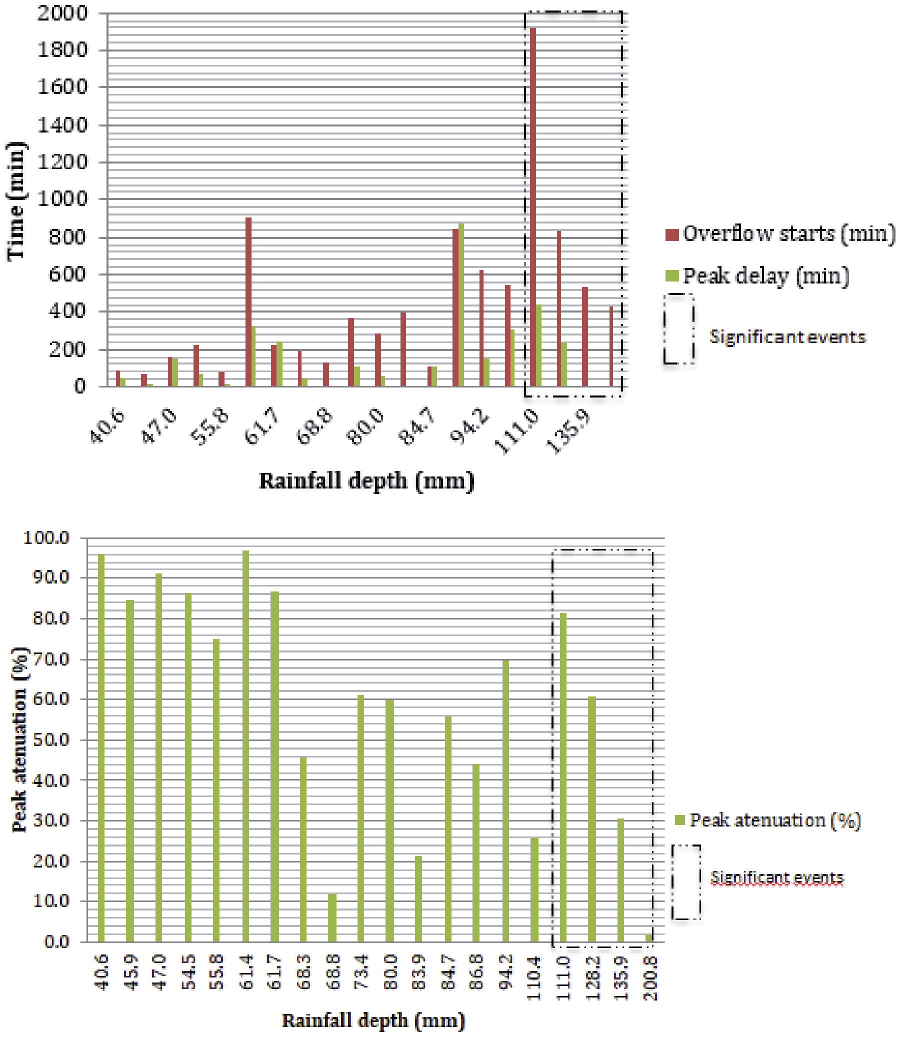


Figure 6-20: Overflow starts, Peak delay and Peak attenuation of the 20 overflow events for the unlined BRC, with Ir=40mm/h and Montevideo's media with respect to rainfall depth

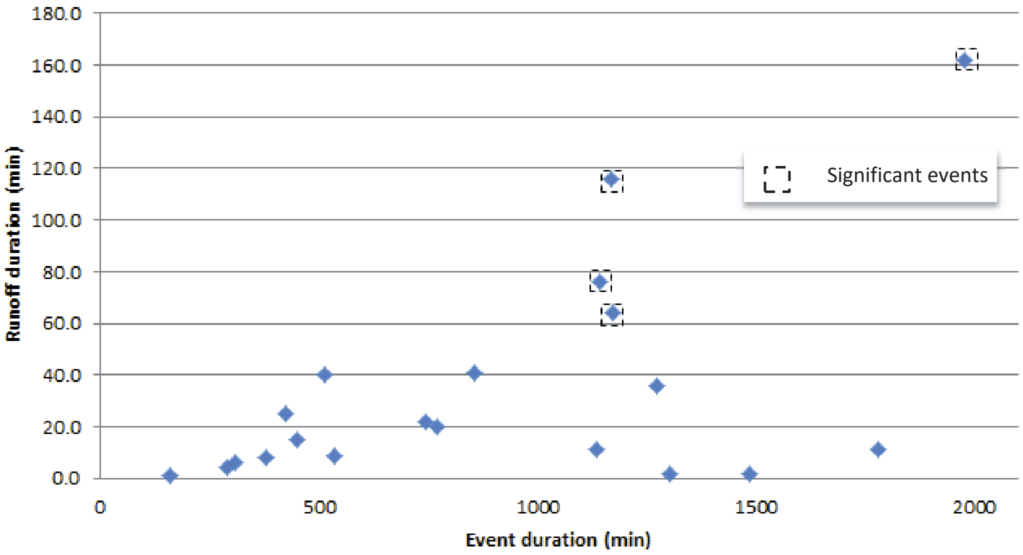


Figure 6-21: Runoff duration of the 20 overflow events for the unlined BRC, with Ir=40mm/h and Montevideo's media with respect to rainfall duration.

6.5 Significant and design event analysis

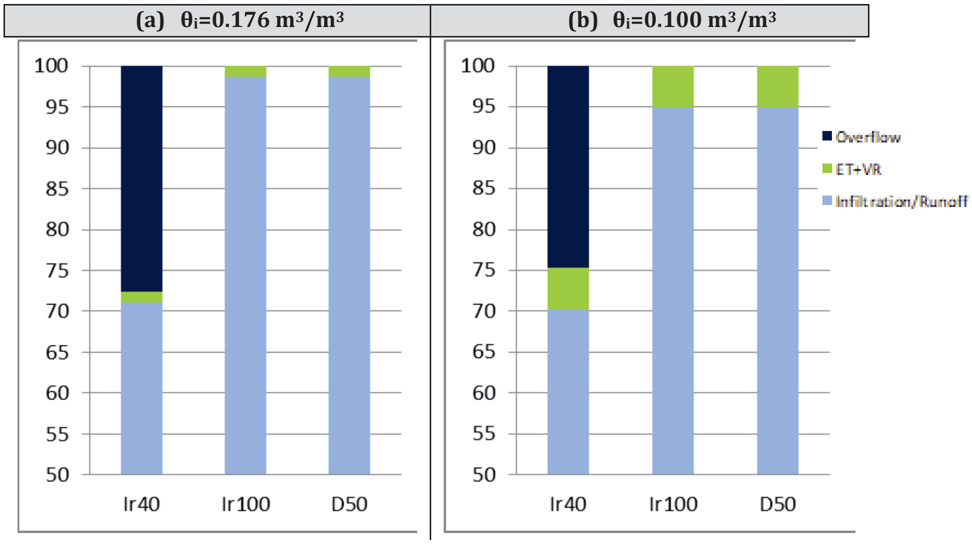
The significant events identified in Table 6-3, were particularly studied for the unlined BRC with Montevideo's media within the overflow events (see section 6.3.2). For the lined BRC these events do not cause any overflow, and the retention and detention parameters can be seen for events with more than 80 mm in the Figure 6-10 and Figure 6-13 to Figure 6-17.

The design event selected is a storm with 2 year return period and 6 hour duration, the characteristics are taken from the proposed design storms for Montevideo by Artelia, Halcrow, Rhama, CSI (2019a), a summary of its characteristics is presented in Table 6-6. For this event, the three outflow condition were studied and two θi scenarios. Firstly when the retention storage is initially empty (θi=0.100 m^3/m^3) and then when the storage is filled with the mean θi value extracted for the time series events analysis (previously done in section 6.2.4 (θi=0.176 m^3/m^3).

Table 6-6: design event characteristics

Return period	Duration (h)	Depth(mm)	Mean intensity (mm/h)	Peak (mm/5min)	Peak time (min)
2	6	75	12.5	3.26	70

The water budget for the 3 outlet conditions is presented in Figure 6-22. With an initial condition of empty retention storage, the retention increases 4%. An infiltration rate of 40 mm/h causes an overflow of 25 to 28% the inflow and the remaining water is infiltrated or drained out of the BRC. For less restrictive outlet conditions there is no overflow.


(a) θ_i=0.176 m^3/m^3

(b) θ_i=0.100 m^3/m^3

Figure 6-22: Water budget for the design event of different outflow conditions for Montevideo's media for different θ_i. Where the overflow is blue (Overflow), the volume retained is green (ET+VR), and the infiltration or runoff is light blue (Infiltration/Runoff)

The inflow generated by the design storm has a peak at 70 min of 0.281 m^3/5min (0.936 L/s). The first part of the inflow is retained; this volume is filled in 4 to 5 min for the mean θi and in 15 min for the initial condition of empty retention storage.

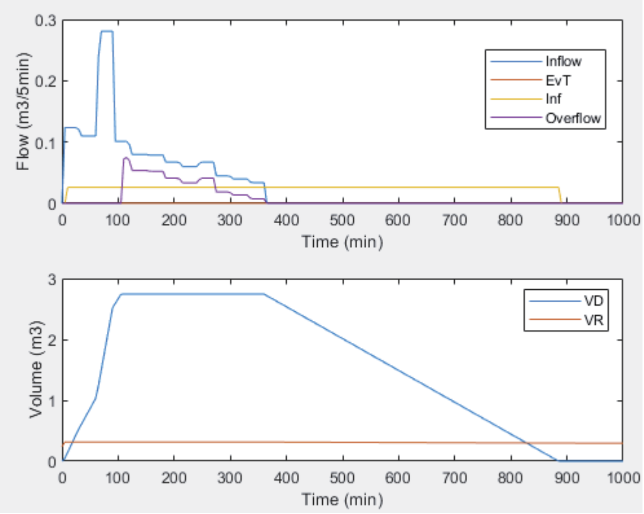
Figure 6-23 (a) shows the detention process when there is overflow. When the peak attenuation is 81% with an overflow peak of 0.054 m^3/5min (0.179 L/s), the overflow starts after 115 min and the duration is 245 min.

For the detention parameters to be of interest, it can be assumed that the infiltration rate of 100 mm/h acts as a fixed outlet restriction directing the water to the sewerage system. Figure 6-23 (b) shows the detention processes, the attenuation of the peak by 78%, by restricting the outflow to 0.218 L/s for 480 min. During this, the detention storage is not fully used, only 78 % of its capacity is reached.

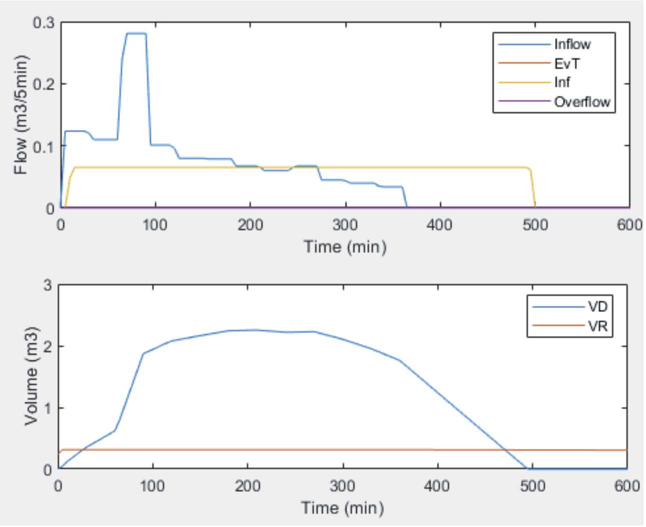
From the Figure 6-23 (c) it is clear how for the lined BRC there is not a significant detention process, and the structure does not function controlled by the outlet pipe; the same phenomenon was observed for the time series events. Only a 4% of the detention volume is used.

In order to avoid overflow generated by this design storm, the outflow conditions should be set at an infiltration rate of 85 mm/h. Alternatively, an equivalent device that limits the outflow to 0.185 L/s could be used.

(a) Infiltration rate 40mm/h



(b) Infiltration rate 100mm/h



(c) Outlet pipe diameter 50 mm

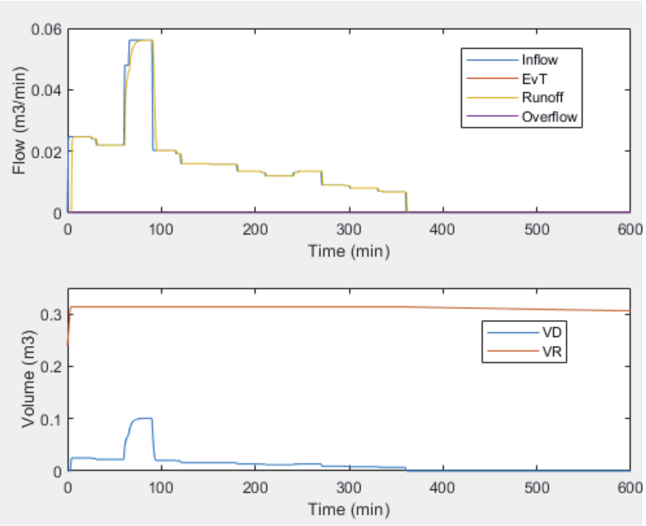


Figure 6-23: Flow and stored volume in the BRC for the design event for all the outflow conditions initial moisture content 0.176. Where EvT is the evapotranspiration, Inf is the infiltration, VD is the volume stored in the detention storage and VR is the volume stored in the retention storage

6.6 Sensitivity analysis

During the previous analysis, the sensitivity for the two types of BRC models outputs were tested for different media characteristics and θi.

6.6.1 Outlet condition (Greenfield)

The outflow criteria used in UK by the CIRIA manual establishes that the outflow should be limited to a greenfield flow of 2 L/s/has (Woods Ballard et al., 2015) In the previous section of the document, it was mentioned that imposing such a restrictive condition for a total drained area of 78.4 m^2 is not feasible because there is not an outlet device that could impose that flow restriction. This restriction imposes a maximum outflow of 0.016 L/s, which is a much smaller value compared to the infiltrations rates scenarios (0.087 L/s for an infiltration rate of 40 mm/h and 0.218 L/s for one of 100 mm/h).

Now assuming that the Greenfield outflow condition could be met, this could be translated to a constant infiltration rate of 7.2 mm/h. A lower outflow condition increases the events where there is overflow. There are 57 events with overflow, these represent 19.2% of the overall water budget. In Figure 6-24 the water budget over time is presented.

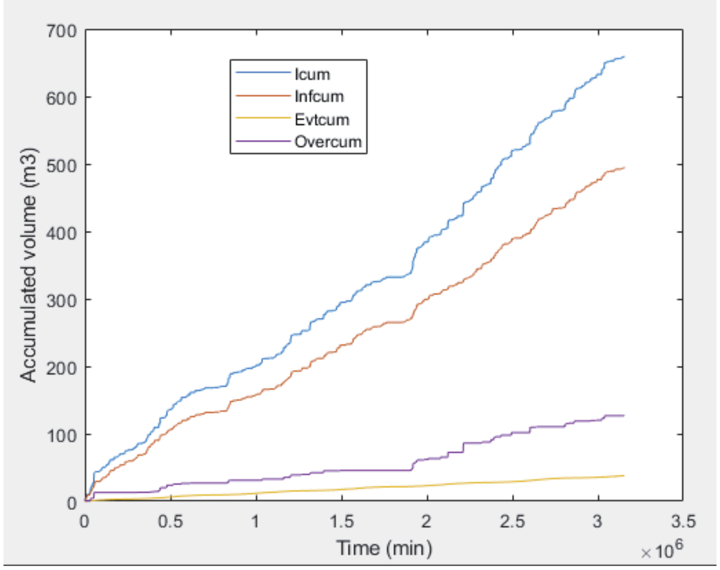


Figure 6-24: Greenfield outflow condition water budget over time (where Icum is the accumulated inflow, Infcum is the accumulated infiltration, Evtcum is the accumulated evapotranspiration, and Overcum is the accumulated overflow)

Maintaining the IHLR of 0.1, these results would be equivalent for a bigger BRC with bigger drained areas. As a consequence of having more drained area the inflow would increase making feasible an outlet structure that would limit the outflow to a Greenfield condition. The Greenfield criteria for the climatic conditions tested imply a failure of the structure (overflow) for 10% of the recorded events. Failure happens for recorded events of 39 mm depth or higher.

6.6.2 Inverse hydraulic loading ratio (IHLR)

To study the sensitivity of the model results to the IHLR parameter, the outflow condition was fixed to meet the Greenfield runoff rate. The parameters that were changed to accomplish this are the IHLR, the drained area and the infiltration rate, see Table 6-7.

Table 6-7: IHLR inputs

IHLR	BRC area (m^2)	Drained area (m^2)	Greenfield (l/s/ha)	Infiltration rate (mm/h)
0.2	7.84	39.2	2.0	3.6
0.1		78.4		7.2
0.05		156.8		14.4
0.03		261.3		24.0

The Water budget results obtained for all modelled IHLR and their overflow characteristics are presented in Table 6-8 and Table 6-9 respectively.

Table 6-8: Water budget for different IHLR

IHLR	ET (%)	Infiltration/Runoff (%)	Overflow (%)
0.2	10.2	81.9	7.8
0.1	5.8	75.0	19.2
0.05	3.1	62.9	34.0
0.03	1.9	53.4	44.7

Table 6-9: Overflow characteristics for different IHLR

IHLR	Overflow events	Overflow events (%)	Minimum depth that causes overflow (mm)
0.2	25	4.6	70.2
0.1	57	10.4	35.0
0.05	114	20.8	25.0
0.03	161	29.4	15.2

An increase in the IHLR will cause an increase in the ET because less inflow is entering a water planter with the same retention characteristics. Increase in the IHLR will decrease the number of events that have overflow and therefore its water budget component. This happens even if the outflow condition is the same (Greenfield), because the inflow increases but not the capacity of the detention storage.

Woods Ballard et al. (2015) in the SuDS manual presents two criteria for the IHLR of a BRC. If the BRC is designed for interception the IHLR should be at least 0.20, whereas if they are designed with infiltration capacity the IHLR could be reduced to 0.05 or even 0.03.

If the BRC is lined a IHLR of 0.1 can be permitted knowing that the structure will fail to accomplish with the greenfield outflow for a 10% of the events, which represents 20% of the water budget. While if the BRC is designed for infiltration (unlined), allowing lower values of IHLR (0.03-0.05) will increase the water that is not directed to the drainage system but it also would fail to comply with the greenfield runoff between 20-30% of the time allowing an overflow between 34 to 45% of the total inflow. This means that to obtain similar overflow events than for the lined garden, with a 0.10 IHLR, the infiltration rate would have to be higher, 45 mm/h for 0.05 IHLR and 120 mm/h for 0.03 IHLR.

6.6.3 ET

The percentage of the water budget that transforms into ET is 5.8%, for Montevideo's media, using as input the data from INIA Las Brujas station calculated with Penman-Monteith. This data set of PET was selected in section 5.2.1 and as mentioned before these has also the highest values of PET estimated. Then the model was tested with the lowest values of estimated PET, for the same station, estimated by Thornthwaite and resulting in a 4.5% ET for the total water budget. The difference is only 1.3%, such a low value that could be considered insignificant for the whole water budget. This was expected because the ET component itself is not significant for a BRC with this IHLR (0.10) located in a template climatic region.

For a higher IHLR value of 0.20, the ET will be 8.1% for the Thornewaite data set and 10.2% for the Penman-Monteith. Concluding that sensitivity to the PET data is not significant for this BRC typology.

7 Conclusions

7.1 Definition of events

To use the models to study the performance for different events, the first step is to separate the rainfall record into events. An MIT/IETD of 8 h was selected for these BRC configuration and rainfall distribution. It was shown that failing to identify independent events would lead to incorrect results in the retention performance metrics. Also, the definition MIT/IETD would change the return period of the events. Greater times would have fewer events with greater durations and some events would be classified with a lower return period. Hence the definition of MIT/IETD could change the statistic results of the analysis, if not selected carefully. Further studies could be made using the method proposed by Joo et al. (2013) to calculate the IETD, to use this method the runoff data time series is needed.

7.2 BRC model and metrics

The models were elaborated to represent the physical processes in a BRC for different outlet restrictions. Later, they were used to study the performance of a BRC with fixed characteristics for specific climatic conditions. It is important to mention that there was no available data of measured outflow (Runoff/Infiltration/Overflow) in order to validate or calibrate these models.

Even without validation, it is considered that the retention processes are well represented comparing the performance of the BRC to a similar study case. Sensitivity analyses of model results were made considering two media with different characteristics and two PET data sets estimated by different methods. In conclusion, the sensitivity to these inputs is not significant for this BRC typology. Other key parameters that do affect the retention performance are the IHLR and θi. Clearly, the proportion of the vegetated area and the availability of retention storage previous to an event will affect the amount of water that can be retained for an event. Results were found for this specific climatic condition.

Representing the detention processes without a calibrated model is more difficult to assess because the travel time of the water within the different layers of the BRC depends on the configuration, materials, and vegetated surface of the BRC. For the model this time was defined as the length of a time step, 5 minutes for the unlined BRC and 1 minute for the unlined one.

For the lined BRC the detention performance was studied, showing two important things. Firstly, that the peaks of rainfall and runoff are difficult to identify for pulses hydrographs, and therefore the use of peak metrics is not useful. Secondly, for detention to happen, the outlet restriction has to be smaller than feasible outlet structures for a BRC with a small drained area.

Whereas for the unlined BRC, considering of interest only overflow as outflow for management drainage systems proposes, the detention performance showed that the metrics for the 20 overflow events were measurable and represented an attenuation of the peak and a decrease in the outflow. There were not any difficulties identifying the peaks, because the events that produce overflow do not have a rainfall pulses hydrograph.

7.3 BRC performance under Montevideo's climatic conditions

The mean θi was calculated using the model. For this climatic condition, the actual available volume to retained water before a rainfall event is less than 30% of the capacity depending on the media. The sensitivity to this parameter was tested for a design event, where having an empty storage could increase the retention component from 1% to 4%. Unfortunately, unrealistic antecedent dry weather periods are required to empty the retention storage.

For a BRC that promotes infiltration process, the infiltration can be considered as part of the retained volume since it does not direct water to the drainage system unless there is overflow. For Montevideo's rain gardens this would mean an actual retention of 95% of the water budget for an infiltration rate of 40 mm/h or 80% if the infiltration rate is decreased to 7.20 mm/h.

If the BRC does not allow infiltration these structures as constructed today will only provide 6% retention of the total water budget and no actual detention, so the runoff will enter the system without any considerable delays and less than 1% of the drainage layer will be used for half of the events. It is important to note that the hydraulic retention time of this structure has not been studied, only defined as 1 minute. And the drainage layer of 0.40 m height is over designed.

If for lined BRC the outflow could be limited to an equivalent infiltration rate of 100 mm/h (0.218 L/s), for a design event there would be significant detention with a peak attenuation of 78% and also 78% of the drainage layer will be used.

For a BRC with an IHLR of 0.10 under these climatic conditions, the Greenfield runoff rate was imposed (7.2 mm/h or outflow limit of 0.016 L/s). It was concluded that these criteria would be reasonable to apply, allowing overflow to occur for events with a higher depth than 39mm, which represent 10% of the events and almost 20% of the water budget. For a design storm of 2 years and 6 hour duration, to ensure that the structure does not fail (overflow) the outflow condition should be set at an infiltration rate of 85 mm/h or an equivalent device that limits the outflow to 0.185L/s.

For this climatic conditions different IHLR were tested, maintaining an outflow restriction of Greenfield runoff rate. The CIRIA manual presents two criteria for the IHLR of a BRC. If the BRC is designed for interception the IHLR should be at least 0.20, whereas if the BRC is design with infiltration capacity the IHLR could be reduced to 0.05 or even 0.03. Results show that for an interception BRC a 0.20 IHRL is acceptable, and could even be restricted to 0.10, as long as the runoff is controlled by the Greenfield criteria. Whereas for the BRC designed with infiltration capacity, decreasing the area will require a minimum infiltration rate of 45 mm/h for a 0.05 IHLR and 120 mm/h for 0.03 IHLR.

7.4 Design recommendations

If infiltration is possible, systems that promote this process would be better to use because a significant part of the water does not enter the sewerage system. It is seen that even with low infiltration rates acceptable performances can be obtained depending on the BRC size and IHLR.

If infiltration cannot be used, then improvements on the drainage layer and the outlet design should be applied. This implies reducing the size of the drainage layer and constructing bigger BRC with a minimum IHLR of 0.1, and the minimum feasible outlet pipe.

Having understood the physical processes that occur in a BRC through modelling, and done sensitivity analysis, the most important parameters are the outlet restrictions defined by the infiltration rate or pipe outlet, and the hydraulic loading ratio. These conclusions should be transferable to a commercial model. Therefore, could be of interest for design purposes compare the model with a commercial one (e.g. SWMM) and look for similarities or differences.

7.5 Further research

For further research having a monitored BRC is key, measuring the runoff, infiltration, and overflow. Firstly, it would allow validating the model and verifying that the processes are well represented. Secondly, the time that the water takes to travel through the media could be measured and a routing equation (Eq.2) to represent the detention process could be calibrated for this BRC configuration. Thirdly, the MIT/IETD time to separate the events could also be calculated.

For this typology of bioretention cell exploring better approximations of ET or characterizations of the substrate media would not be recommended, since they are insignificant parameters. What would be worthy is exploring the outflow control, either the outlet devices to control the runoff, or characterizing the infiltration processes of the surrounding soil where BRC were to be installed.

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9 Appendices List

Appendix A: Matlab scripts

Appendix B: Climatic data and institutions

Appendix A: Model Scripts

The two main scripts with the two models for lined and unlined BRC are presented, and some auxiliary scripts, see Table A-1.

Table A-1: Main scripts

Script	File name	Functionality
Unlined BRC model	raingarden_Inf_rainfall_data.m	Model the processes in a unlined BRC
Lined BRC model	raingarden_D_50mm_1min_v4.m	Model the processes in a lined BRC
Potential ET from INIA Las Brujas Pennman Monteith	monthlyPET_PM_INIA.m	Transform daily ET values per month in a time series to obtain a vector with ET values every 5 minutes (to match the rainfall data resolution).
Define events script	define_events_CZ9_rainfall.m	Separate the rainfall data in events according to a value of minimum dry period time inter-events (MIT/IETD).
Design events script	design_event.m	Load design events with a 5 min resolution rainfall depth.

Unlined BRC model script (raingarden_Inf_rainfall_data.m):

```
function
[Inflow,EvT,Inf,Overflow,VD,VR]=raingarden_Inf_rainfall_data

%this function is to design a rain garden with infiltration

%hypothesis: in the initial condition there is not ponding and water
%stored in the detention volume, this implies no infiltration. There
%can be water stored in the retention, given by the initial moisture
content.

%inputs:
%I is the rainfall it must be expressed in 5 min intervals in a
column
%vector the unit is mm
%Ad is the area that is drained to the rain garden in m2
%W is the width of the rain garden must be a number in m
%L is the length of the rain garden must be a number in m
%hs is the depth of the substrate must be a number in m
%hmax is the maximum depth it is allowed to pond in the surface,
must be a number in m
%Fc is the field capacity of the substrate must be a number in vol
water/vol substrate
%Wp is the wilting point of the substrate must be a number in vol
water/vol substrate
%M is the initial water content of the substrate, must be equal or
higher than the wilting point(Wp),
%must be smaller or equal to the field capacity. Expressed in vol
water/vol substrate
%ET is the evapotranspiration in mm per day. It is assumed constant
%ns is the porosity of the substrate
%nd is the porosity of the drainage layer
%Ir is the infiltration rate in mm/h. It is assumed constant

%inputs Montevideo
%Ir=100;
Ir=40;
Ad=0;
W=1.4;
L=5.6;
hs=0.40;
hd=0.40;
hmax=0.15;
Fc=0.2;
Wp=0.1;
ns=0.3;
nd=0.4;
M=0.176;

%engineered media
%Ir=100;
%Ir=40;
%Ad=78.4;
%W=1.4;
%L=5.6;
%hs=0.40;
%hd=0.40;
%hmax=0.15;
%Fc=0.3;
%Wp=0.05;
```

```
%ns=0.6;
%nd=0.4;
%M=0.270;

%load I from file
fid1=fopen ('CZ9.txt','r');
temp=fscanf(fid1,'%f');
I=temp(:,1);

dt=5;% time interval of 5 minutes
[f,c]=size(I);
Tf=dt*(f-1);
T=0:dt:Tf; %vector time
T=T.'; %change to column

%initializes the variables


A=W*L; % area in m2
Inflow=I*(Ad+A)/1000; %transform rainfall in volume m3
PET=monthlyPET_PM_INIA; %function that creates a vector with the
potential ET according to the date in mm/dt, where dt is the time
interval chosen
PET=PET/1000*A; %vector with volume in m3 of PET in each time step

%variables of volume
Infi=Ir/1000/60*dt*A;%volume m3 of Infi in each time step if there
is detention
Vsus=A*hs; %total volume of substrate in m3
Vd=A*hd; % total volume of the drainage layer
Vsus_v=Vsus*ns; %total volume of voids in m3 for the substrate in m3
VRmax=(Fc-Wp)*Vsus; %max volume that can be retained in the
substrate layer
VDmax_s=(ns-Fc)*Vsus; %max volume that can be detained in the
substrat layer in m3
VDmax_d=Vd*nd; %max volume that can be detained in the drainage in
m3
VDmax_h=hmax*A; %max volume that can be detained by ponding in m3
VDmax=VDmax_s+VDmax_h+VDmax_d; %max volume that can be detained in
total (substrate, drainage layer and ponding) in m3

%variables of retention in depth
Smax=VRmax/A; %max capacity of retention in the substrate in m
Si=zeros(f,1); % is the depth of retention in the substrate in time
step i VR/A

%variables of detention in depth
hdmax=VDmax_s/A; %max capacity of detention in the substrate in m
hdi=zeros(f,1);% is the depth of detention in the substrate and
drainage layer in time step i VD/A

%initialize vectors
VR=zeros(f,1);% volume of water stored in the retention in m3
VD=zeros(f,1); %volume of water stored in the detention in m3
Inf=zeros(f,1);% volume of water infiltrated in m3
EvT=zeros(f,1); %volume of water evapotranspirated in m3
Overflow=zeros(f,1); %volume that cannot be retained, detained or
infiltrated

%initial conditions
```

```
VR(1)=(M-Wp)*Vsus;  %the initial volume of water stored in the substrate that can be consumed by ET
Si(1)=VR(1)/A; %initial depth (in m) of water stored in the substrate as retention (that can be consumed by ET)

%iteration
for i=2:f
   if Inflow(i)>0 % when there is rainfall
       ETi=PET(i)*Si(i-1)/Smax;
       aux=[VRmax,VR(i-1)+Inflow(i)-ETi];
       VR(i)=min(aux);
       Si(i)=VR(i)/A;
       EvT(i)=ETi;
       if VD(i-1)==0
           Inf(i)=0;
       else
           if VD(i-1)<Infi
               Inf(i)= VD(i-1);
           else
               Inf(i)=Infi;
           end
       end
       aux=[0,VD(i-1)+Inflow(i)+VR(i-1)-VR(i)-EvT(i)-Inf(i)];
       aux2=max(aux);
       aux3=[aux2,VDmax];
       VD(i)=min(aux3);
       aux4=[aux2-VDmax,0];
       Overflow(i)=max(aux4);
   else %when there is not rainfall
       %retention
       ETi=PET(i)*Si(i-1)/Smax;
       aux=[0,VR(i-1)-ETi];
       VR(i)=max(aux);
       Si(i)=VR(i)/A;
       if VR(i)==0
           EvT(i)=VR(i-1);
       else
           EvT(i)=ETi;
       end
       %detention
       if VD(i-1)==0
           Inf(i)=0;
       else
           if VD(i-1)<Infi
               Inf(i)= VD(i-1);
           else
               Inf(i)=Infi;
           end
       end
       aux=[0,VD(i-1)-Inf(i)];
       VD(i)=max(aux);
   end
end

%store the variables in files
writematrix(EvT);
writematrix(Inflow);
writematrix(Overflow);
writematrix(Inf);
writematrix(VD);
writematrix(VR);
```

Lined BRC model script (raingarden_D_50mm_1min_v4.m):

```
function
[T,date,Inflow,EvT,Runoff,Overflow,VD,VR]=raingarden_D_50mm_1min_v4
%this function is to design a rain garden with a pipe outlet to an
approved destination

%hypothesis: in the initial condition there is not ponding or water
%stored in the detention volume this implies no runoff. There can be
%water storage in the retention, given by the initial moisture
content.

%inputs:

%I is the rainfall it must be expressed in 5 min intervals in a
%column vector, its unit is mm
%Ad is the area that is drained to the rain garden in m2
%D is the diameter of the outlet pipe in m
%W is the width of the rain garden must be a number in m
%L is the length of the rain garden must be a number in m
%hs is the depth of the substrate must be a number in m
%hd is the depth of the drainage layer must be a number in m
%hmax is the maximum depth it is allowed to pond in the surface,
must be a number in m
%Fc is the field capacity of the substrate must be a number in vol
water/vol substrate
%Wp is the wilting point of the substrate must be a number in vol
water/vol substrate
%M is the initial water content of the substrate, must be equal or
higher than the wilting point(Wp),
%must be smaller or equal to the field capacity. Expressed in vol
water/vol substrate
%ET is the evapotranspiration in mm per day. It is assumed constant
%ns is the porosity of the substrate
%nd is the porosity of the drainage layer

%date
tini=datetime(2014,01,01,7,0,0); %set initial time%
year,month,day,hour,mitue,second
deltat=duration(0,1,0);%time step
tend=datetime(2020,01,01,6,55,0);%set final time%
year,month,day,hour,mitue,second
date=tini:deltat:tend;
date=date';



%inputs Montevideo
Ad=78.4;
W=1.4;
L=5.6;
hs=0.40;
hd=0.40;
hmax=0.15;
Fc=0.2;
Wp=0.1;
ns=0.3;
nd=0.4;
M=0.176;
```

```
%Engineered media
%Ad=78.4;
%W=1.4;
%L=5.6;
%hs=0.40;
%hd=0.40;
%hmax=0.15;
%Fc=0.3;
%Wp=0.05;
%ns=0.6;
%nd=0.4;
%M=0.270;

%pipe outflow
g=9.81;
D=0.05;
Cd=0.60;
Ap=pi*(D/2)^2;

%load I from file
fid1=fopen ('CZ9.txt','r');
temp=fscanf(fid1,'%f');
I=temp(:,1);

dt=5;% time interval of 5 minutes
[f,c]=size(I);
Tf=dt*(f-1);
T=0:dt:Tf; %vector time
T=T.'; %change to column

%change time
dt=1; %1 minute discretization
T=0:dt:Tf;
T=T.'; %change to column

%discretize I in 1 min intervals
In=[];
In(1)=I(1);
for i=2:f
    In=[In;I(i)/5;I(i)/5;I(i)/5;I(i)/5;I(i)/5];
end


%initialize the variables

A=W*L; % area in m2
Inflow=In*(Ad+A)/1000; %transform rainfall in volume m3
PET=monthlyPET_PM_INIA_1min; %function that creates a vector with
the potential ET according to the date in mm/dt, where dt is the
time interval chosen
PET=PET/1000*A; %vector with volume in m3 of PET in each time step
f=length(Inflow); %change size of f for defining variables

%variables of volume
Vd=A*hd; % total volume of the drainage layer in m3
Vsus=A*hs; %total volume of substrate in m3
Vsus_v=Vsus*ns; %total volume of voids in m3 for the substrate in m3
```

```
VRmax=(Fc-Wp)*Vsus; %max volume that can be retained (in the
substrat layer)
VDmax_s=(ns-Fc)*Vsus; %max volume that can be detained in the
substrat layer in m3
VDmax_d=Vd*nd; %max volume that can be detained in the drainage in
m3
VDmax_h=hmax*A; %max volume that can be detained by ponding in m3
VDmax=VDmax_s+VDmax_h+VDmax_d; %max volume that can be detained in
total (substrate, drainage layer and ponding)in m3

%variables of retention in depth
Smax=VRmax/A; %max capacity of retention in the substrate in m
Si=zeros(f,1); % is the depth of retention in the substrate in time
step i VR/A

%variables of detention in depth
hdmax=VDmax_s/A; %max capacity of detention in the substrate in m
hdi=zeros(f,1);% is the depth of detention in the substrate and
drainage layer in time step i VD/A

Runoff=zeros(f,1);% volume of water that exits through the pipe in
m3
VR=zeros(f,1);% volume of water stored by the retention in m3
VD=zeros(f,1); %volume of all stored water in m3
EvT=zeros(f,1); %volume Evapotranspirated
Overflow=zeros(f,1); %volume that cant be retained or detained

%initial conditions
VR(1)=(M-Wp)*Vsus;  %the initial volume of water stored in the
substrate that can be consumed by ET
Si(1)=VR(1)/A; %initial depth (in m) of water stored in the
substrate as retention (that can be consumed by ET)
%iteration

for i=2:length(Inflow)
   if Inflow(i)>0 % when there is rainfall
       ETi=PET(i)*Si(i-1)/Smax;
       aux=[VRmax,VR(i-1)+Inflow(i)-ETi];
       VR(i)=min(aux);
       Si(i)=VR(i)/A;
       EvT(i)=ETi;
       if VD(i-1)==0
           Runoff(i)=0;
       else
           if VD(i-1)<=VDmax_d %drainage layer
               hdi(i-1)=VD(i-1)/(A*nd);
               Runoff(i)=Cd*Ap*(2*g*hdi(i-1))^0.5*dt*60;
               aux=[VD(i-1),Runoff(i)];
               Runoff(i)=min(aux);
           elseif VD(i-1)>VDmax_d && VD(i-1)<VDmax_d+VDmax_s
%substrate layer
               hdi(i-1)=hd+(VD(i-1)-VDmax_d)/(A*ns);
               Runoff(i)=Cd*Ap*(2*g*hdi(i-1))^0.5*dt*60;
               aux=[VD(i-1),Runoff(i)];
               Runoff(i)=min(aux);
           elseif VD(i-1)<VDmax %ponding
               hdi(i-1)=hd+hs+(VD(i-1)-VDmax_s-VDmax_d)/A;
               Runoff(i)=Cd*Ap*(2*g*hdi(i-1))^0.5*dt*60;
               aux=[VD(i-1),Runoff(i)];
               Runoff(i)=min(aux);
```

```
            else %overflow
                hdi(i-1)=hs+hs+hmax;
                Runoff(i)=Cd*Ap*(2*g*hdi(i-1))^0.5*dt*60;
                aux=[VD(i-1),Runoff(i)];
                Runoff(i)=min(aux);
            end
        end
        aux=[0,VD(i-1)+Inflow(i)+VR(i-1)-VR(i)-EvT(i)-Runoff(i)];
        aux2=max(aux);
        aux3=[aux2,VDmax];
        VD(i)=min(aux3);
        aux4=[aux2-VDmax,0];
        Overflow(i)=max(aux4);
   else %when there is not rainfall
        %retention
        ETi=PET(i)*Si(i-1)/Smax;
        aux=[0,VR(i-1)-ETi];
        VR(i)=max(aux);
        Si(i)=VR(i)/A;
        if VR(i)==0
            EvT(i)=VR(i-1);
        else
            EvT(i)=ETi;
        end
        %detention
        if VD(i-1)==0
            Runoff(i)=0;
        elseif VD(i-1)<=VDmax_d %drainage layer
            hdi(i-1)=VD(i-1)/(A*nd);
            Runoff(i)=Cd*Ap*(2*g*hdi(i-1))^0.5*dt*60;
            aux=[VD(i-1),Runoff(i)];
            Runoff(i)=min(aux);
        elseif VD(i-1)>VDmax_d && VD(i-1)<VDmax_d+VDmax_s %substrate
layer
                hdi(i-1)=hd+(VD(i-1)-VDmax_d)/(A*ns);
                Runoff(i)=Cd*Ap*(2*g*hdi(i-1))^0.5*dt*60;
                aux=[VD(i-1),Runoff(i)];
                Runoff(i)=min(aux);
        else %VD(i-1)<VDmax %ponding
                hdi(i-1)=hd+hs+(VD(i-1)-VDmax_s-VDmax_d)/A;
                Runoff(i)=Cd*Ap*(2*g*hdi(i-1))^0.5*dt*60;
                aux=[VD(i-1),Runoff(i)];
                Runoff(i)=min(aux);
        end
        VD(i)=VD(i-1)-Runoff(i);
   end
end

%store the variables in files
writematrix(EvT);
writematrix(Inflow);
writematrix(Overflow);
writematrix(Runoff);
writematrix(VD);
writematrix(VR);
```

Potential ET from INIA Las Brujas Pennman Monteith (monthlyPET_PM_INIA.m):

```
function PET=monthlyPET_PM_INIA
%This transforms monthly PET data into PET each 5 min starting set
date to a final set date
% the year is not important since the data is statistical from INIA
Las
% brujas 1972-2020 using Pennman-Monteith (FAO 56)
t=datetime(2014,01,01,7,0,0); %set initial time%
year,month,day,hour,mitue,second
dt=duration(0,5,0);%time step
DT=5; %time step in minutes
tfin=datetime(2020,01,01,6,55,0);%set final time%
year,month,day,hour,mitue,second

ET=[5.81,4.77,3.55,2.14,1.19,0.82,0.93,1.54,2.48,3.54,4.75,5.64];%ve
ctor of ET in mm/day for month

%initial step
PET=[];

while t<=tfin
T=month(t);
ET_DT=ET(T)*DT/(24*60);
PET=[PET,ET_DT];
t=t+dt;
end
```

Define events script (define_events_CZ9_rainfall.m):

```
function
[Quantity_events,date,depth,def_event,number_event,duration_event,to
t_depth_event,mean_intensity_event,start_index,end_index,peak,peak_i
ndex,peak_intensity]=define_events_CZ9_rainfall
% this function is to separate the rainfall data recorded into
events separated with
% a certain amount of time (MIT) to ensure independent events
responses and
% to define the characteristics of the event (total depth, event
duration,
% mean intensity, peak depth, time when the peak occurs, peak
intensity)

%inputs
%d is the minimum separation between events in hours (MIT)
%depth is the rainfall it must be expressed in 5 min intervals in a
column
%vector the unit is mm
%date is the date when the depth was recorded, in 5 min intervals in
a
%column vector

%outputs
% def_event defines at which event the time series depth is
assigned, if the
% value is 0 there is not an event at that time (column vector)

% number_event this vector defines only the events numbers from 1 to
the
% quantity of events, without zeros (index to know to which event
% correspond the next variables)

% duration_event: the duration of the event in minutes

% tot_depth_event: total depth of the event in mm

%mean_intensity_event: mean intensity of the event in mm/h

%start_index: index that defines in which moment the event starts in
the
%date vector

%end_index:index that defines in which moment the event ends in the
%date vector

%peak: peak depth of the event in mm/5min

% peak_index: index that defines in which moment the peak occurs in
the
%date vector

%peak_intensity: intensity of the event peak in mm/h


%initialize variables
%define initial and final time
```

```
tini=datetime(2014,01,01,7,0,0); %set initial time%
year,month,day,hour,mitue,second
dt=duration(0,5,0);%time step
tend=datetime(2020,01,01,6,55,0);%set final time%
year,month,day,hour,mitue,second
date=tini:dt:tend;
date=date';

d=8;%MIT
D=d*60/5; %number of intervals

%load depth from file
fid1=fopen ('CZ9.txt','r');
temp=fscanf(fid1,'%f');
depth=temp(:,1);

start_index=[];
def_event=[];
i=1;
n=1;
m=1;
length_timeseries=length(depth);

%define def_event

while i<length_timeseries
    while depth(i)==0   %there is no event yet
    def_event=[def_event;0];
    i=i+1;
    if i==length_timeseries
        break
    end
    end
    %the first event has started
    while depth(i)~=0
        if depth(i-1)==0
        start_index=[start_index;i];
        end
    def_event=[def_event;n];
    i=i+1;
    if i==length_timeseries
        break
    end
    end
    aux=min(D,length_timeseries-i);
    a=depth(i:i+aux);
    b=zeros(aux+1,1);
    %the first event stoped or zeros started apearing
    if isequal(a,b)==1 && i<=length_timeseries %the event has stoped
at i-1
    aux2=min(D,length_timeseries-i);
    def_event=[def_event;zeros(aux2+1,1)];
    i=i+aux2+1;
    else %the event has not stopped
         while isequal(a,b)==0 && length(a)==length(b)&&
i<=length_timeseries
            def_event=[def_event;n];
            i=i+1;
            aux3=min(D,length_timeseries-i);
            a=depth(i:i+aux3);
```

```
            b=zeros(aux3+1,1);
         end
    end
    n=n+1;
end

%mean event characteristics
Quantity_events=max(def_event);
number_event=[];
duration_event=[];
tot_depth_event=[];

for p=1:Quantity_events
    count=0;
    sum=0;
    for i=1:length_timeseries
        if def_event(i)==p
            count=count+1;
            sum=sum+depth(i);
        end
    end
    number_event=[number_event;p];
    duration_event=[duration_event;count*5];
    tot_depth_event=[tot_depth_event;sum];
end

aux4=ones(length(number_event),1);
end_index=start_index+duration_event/5-aux4;

mean_intensity_event= tot_depth_event./duration_event*60; %expresed
in mm/h

%peak event characteristics
peak=[];%peak depth in mm/5min
peak_index=[];%when in the time series the peak occurs
for i=1:length(number_event)
data=depth(start_index(i):end_index(i));
[p,loc]=max(data);
peak=[peak;p];
aux5=loc+start_index(i)-1;
peak_index=[peak_index;aux5];
time_peak=(loc-1)*5;%time in minutes after the event started when
the peak occurs
end
peak_intensity=peak./5*60;% in mm/h

% save the variables in files
writematrix(date);
writematrix(depth);
writematrix(def_event);
writematrix(number_event);
writematrix(duration_event);
writematrix(tot_depth_event);
writematrix(mean_intensity_event)
writematrix(start_index);
writematrix(end_index)
writematrix(peak)
writematrix(peak_index);
writematrix(peak_intensity)
```

Design events script (design_event.m):

```
function [xi,depth]=design_event
%funtion to transform design events from PDSDUM 2019 into 5 min data
using linear
%interpolation
%to use in the BRC model
%just remove or add % to select which event is representing

%TR2 duration 3 h
%t=[0   14.4    30.6    45  59.4    75.6    90  104.4   120.6   135
149.4   165.6   180]';
%ac=[0  6.38    12.76   27.26   32.48   37.12   41.18   44.66
48.14   51.62   53.94   56.26   58]';%accumulated depth
%d=180; %duration of the event
%dt=5; %duration of interval
%xi = (0:dt:d)'; %to transform into column
%yi = interp1q(t,ac,xi); %accumulated depth every 5 min

%TR2 duration 6 h
t=[0    28.8    61.2    90  118.8   151.2   180 208.8   241.2   270
298.8   331.2   360]';
ac=[0   8.25    16.5    35.25   42  48  53.25   57.75   62.25
66.75   69.75   72.75   75]';%accumulated depth
d=360; %duration of the event
dt=5; %duration of interval
xi = (0:dt:d)'; %to transform into column
yi = interp1q(t,ac,xi); %accumulated depth every 5 min

%TR2 duration 12 h
%t=[0   57.6    122.4   180 237.6   302.4   360 417.6   482.4   540
597.6   662.4   720]';
%ac=[0  10.23   20.46   43.71   52.08   59.52   66.03   71.61
77.19   82.77   86.49   90.21   93]';%accumulated depth
%d=720; %duration of the event
%dt=5; %duration of interval
%xi = (0:dt:d)'; %to transform into column
%yi = interp1q(t,ac,xi); %accumulated depth every 5 min

%TR100 duration 3 h
%t=[0   14.4    30.6    45  59.4    75.6    90  104.4   120.6   135
149.4   165.6   180]';
%ac=[0  12.98   25.96   55.46   66.08   75.52   83.78   90.86
97.94   105.02  109.74  114.46  118]';%accumulated depth
%d=180; %duration of the event
%dt=5; %duration of interval
%xi = (0:dt:d)'; %to tranform into column
%yi = interp1q(t,ac,xi); %accumulated depth every 5 min

%TR100 duration 6 h
%t=[0   28.8    61.2    90  118.8   151.2   180 208.8   241.2   270
298.8   331.2   360]';
%ac=[0  16.83   33.66   71.91   85.68   97.92   108.63  117.81
126.99  136.17  142.29  148.41  153]';%accumulated depth
%d=360; %duration of the event
%dt=5; %duration of interval
%xi = (0:dt:d)'; %to transform into column
%yi = interp1q(t,ac,xi); %accumulated depth every 5 min

%TR100 duration 12 h
```

```
%t=[0   57.6    122.4   180 237.6   302.4   360 417.6   482.4   540
597.6   662.4   720]';
%ac=[0  20.79   41.58   88.83   105.84  120.96  134.19  145.53
156.87  168.21  175.77  183.33  189]';%accumulated depth
%d=720; %duration of the event
%dt=5; %duration of interval
%xi = (0:dt:d)'; %to transform into column
%yi = interp1q(t,ac,xi); %accumulated depth every 5 min
```

Appendix B: Climatic data and institutions

National Institute for Agricultural Research (Instituto Nacional de Investigación Agropecuaria-INIA)

The INIA was created by law N° 16.065 on 6 October 1989. Their mission is: “Generating and adapting knowledge and technologies to contribute to the sustainable development of the agricultural sector and the country, considering state policies, social inclusion and market and consumer demands” (Portal INIA GRAS, 2020).

This institute has 5 experimental stations in different parts of the country and in each one they have a climatic station. The closest to Montevideo is INIA Las Brujas Experimental Station "Wilson Ferreira Aldunate”. It is located in the department of Canelones (Route 48, Km. 10), less than 4 km from Montevideo.

The Agroclimate and Information Systems Unit (Unidad de Agro-clima y Sistemas de información- GRAS) is in charge of the agroclimate bank which is free and available for any user at their website. In this agroclimatic bank you can access for each station daily data and historical statistics for the climatic variable and time period of your selection. There is also access to on-line weather station network in real time. (Portal INIA GRAS, 2020).

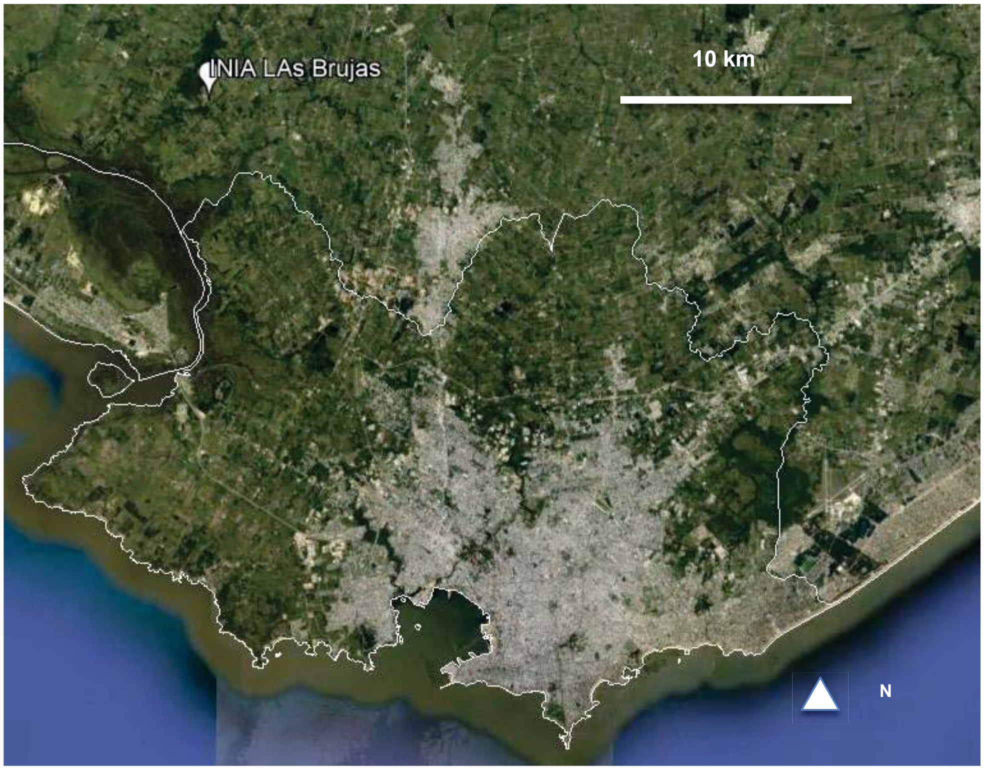

Figure B-1: Location of the INIA las Brujas climatic station

Table B-2: Statistical data of the INIA climatic station Las Brujas from 1972 to 2020 (Portal INIA GRAS, 2020).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
T_MED	22.96	22.19	20.34	16.99	13.56	10.69	10.12	11.48	13.10	15.97	18.55	21.33
T_MAX	29.07	28.00	26.04	22.49	18.73	15.66	15.00	16.82	18.50	21.42	24.34	27.44
T_MIN	17.01	16.90	15.31	12.16	9.02	6.32	5.79	6.73	8.12	10.70	12.80	15.23
HR_MED	70.26	74.33	76.68	79.19	82.17	82.56	82.47	79.51	76.72	75.45	71.94	69.20
PRECIP	102.9	107.5	108.5	100.8	93.9	75.6	86.5	89.0	87.0	106.3	98.7	87.4
EVAPO	238.39	177.24	155.31	102.00	67.27	49.50	56.42	74.40	101.40	143.53	182.40	231.26
ETP Penn	180.11	133.56	110.05	64.20	36.89	24.60	28.83	47.74	74.40	109.74	142.50	174.84
VIENTO	190.19	177.39	166.99	153.21	151.90	163.83	174.65	182.82	201.73	196.01	194.72	188.86
HELIOF	10.10	8.82	7.86	6.59	5.62	4.86	4.91	5.80	6.55	7.53	9.11	9.97

KEY	
T_MED	Average Air Temperature in degrees Celcius (ºC)
T_MAX	Maximum Air Temperature in degrees Celcius (ºC)
T_MIN	Minimum Air Temperature in degrees Celcius (ºC)
HR_MED	Average Relative Humidity (%)
PRECIP	Precipitation: monthly accumulated (mm/month)
EVAPO	Tank A evaporation: monthly accumulated (mm/month)
ETP Penn	Potential Evapotranspiration “Pennman” (mm/month)
VIENTO	Accumulated wind: monthly average (km/day)
HELIOF	Heliophany or Hours of sun: monthly average (hs/day)

National Directorate of Meteorology (Direccion Nacional de Meterología- DNM) and Uruguayan Institute of Meteorology (Instituto Uruguayo de Meterología- INUMET)

The National Directorate of Meteorology was the National Meteorological Service of Uruguay from 1979 to October 25, 2013, when the Uruguayan Parliament approved Law No. 19,158, thus creating the Uruguayan Institute of Meteorology.

The mission of INUMET is: “To provide public meteorological and climatological services, consisting of observing, recording and predicting the weather and climate in the national territory and adjacent oceanic areas, and other areas of interest, in accordance with the applicable conventions.” (Estadísticas climatológicas | Inumet, 2020)

There are 12 climatic stations in the country with recorded data since 1961. The station Prado is located in Montevideo and the station Carrasco is located less than 4 km from Montevideo.

The daily rainfall data is available in the web site but there is not an easy way to export it to an external file and the visualization allows only looking at the data for one selected day at the time. The monthly data is not available to visualize or export from the website.

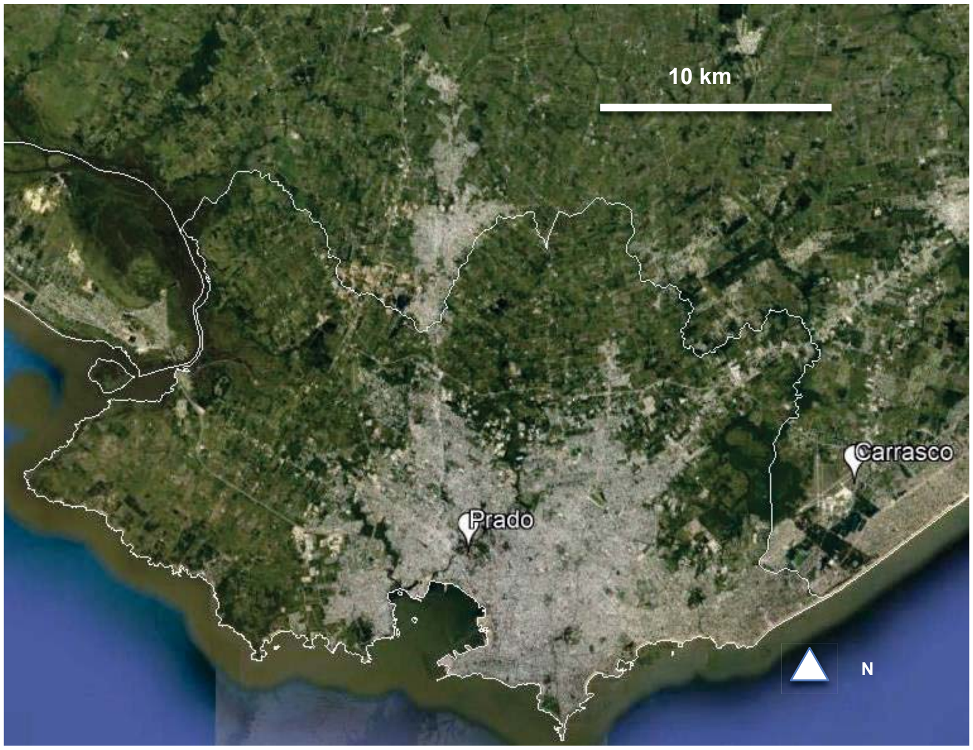

Figure B-2: Location of the INUMET Montevideo climatic stations

Table B-2: Statistical data of the INUMET climatic stations Prado and Carrasco from 1972 to 2020 (Estadísticas climatológicas | Inumet, 2020)

	STATION PRADO											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
TMED	23	22.5	20.6	17.2	14	11.1	10.9	11.7	13.4	16	18.6	21.3
TX	38.8	39.9	36.2	33.6	29.6	26.4	26.8	29.5	30.6	34.2	35.6	40.8
TN	9.4	9	5.9	1.4	1	-5.6	-2.6	-2.8	-0.4	3	5	7.6
TXM	28.4	27.5	25.5	22	18.6	15.1	15	16.2	18	20.5	23.7	26.5
TNM	18	17.9	16.2	12.9	10.2	7.7	7.2	7.8	9.1	11.5	14.2	16.3
HR	68	69	73	75	78	82	80	77	74	71	71	67
P	1010.8	1012.3	1013.8	1015.4	1016.5	1017.1	1018.6	1017.8	1017.9	1015.5	1013.2	1011.4
HS	294.9	230.6	222.8	179.6	164.2	129.7	139.7	164.4	182.3	239	248.9	285.3
PV	19	18.8	17.6	14.7	12.5	10.8	10.4	10.6	11.4	12.9	15.2	17
VEL	4	3.8	3.6	3.3	3.3	3.4	3.5	3.6	3.9	4.2	3.9	4
RR	87	101	105	86	89	83	86	88	94	109	89	84
FRR	6	7	6	6	6	7	7	6	6	7	7	6

	STATION CARRASCO											
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
TMED	22.7	22.3	20.5	17.2	13.9	11	10.7	11.5	13.2	15.7	18.3	21.1
TX	39.3	39.8	36.2	31.6	30.2	27.8	29.8	29.6	34.3	34.9	36.4	39.9
TN	11.4	10.9	9.4	5.6	2.8	0.3	-0.5	0.8	1.5	4.7	6.7	9.7
TXM	27.9	27	25	21.7	18.5	15	15	16	17.6	20.3	22.8	26.1
TNM	17.8	17.8	16.1	12.6	9.6	7	6.8	7.3	8.7	11.2	13.5	16.5
HR	69	72	73	76	79	82	82	77	75	73	70	68
P	1011.2	1012.4	1014.1	1015.6	1016.2	1017.7	1018.3	1018.2	1018.4	1015.4	1013.2	1011.8
HS	297.4	236.7	237.7	190.4	171	142.4	154.5	172.6	208.2	242.6	250.3	291.7
PV	19.1	19.3	17.7	14.9	12.5	10.7	10.5	10.5	11.4	13.1	14.8	17.1
VEL	6.1	5.7	5.5	5.2	5.2	5.5	5.6	5.6	6.1	6	6	6.1
RR	92	92	106	87	90	79	89	92	93	107	94	78
FRR	6	6	7	6	7	7	8	6	6	7	7	6

KEY	
TMED	Average monthly temperature (ºC)
TX	Absolute maximum monthly temperature (ºC)
TN	Monthly absolute minimum temperature (ºC)
TXM	Average monthly maximum temperature (ºC)
TN	Average monthly minimum temperature (ºC)
HR	Monthly average Relative Humidity (%)
P	Atmospheric pressure (at mean sea level), monthly mean (hPa)
HS	Accumulated direct insolation time per month, monthly mean (hrs)
PV	Average monthly vapor pressure (hPa)
VEL	Speed (horizontal wind), monthly average (m/s)
RR	Accumulated precipitation per month, monthly average (mm)
FRR	Days with precipitation> = 1mm, monthly average

Table B-3: Statistical Evaporation data of the DNM climatic station Prado from 1958 to 1999 (Terra et al., 2011)

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
ET_{tank} (mm/month)	202.1	160.2	134.5	88.9	62.1	45.3	45.8	65.2	91.1	129.1	160.8	192.7

Montevideo City Hall, Sanitation Studies and Projects Service (SEPS)

The SEPS of the Montevideo City Hall has installed a Hydrometeorological Network in November of 2013, with 15 different stations across the department. Ever since more equipment has been installed or removed, in Table B-4 the current state of the network is presented. The network has three types of stations, Meteorological station, Pluviometric station, and Anemonic and Pluviometric station. Their measurements are described in Table B-5.

In Figure B-3 the locations of the stations are presented. For all of the stations the measurement of rainfall is recorded with a 5 minutes frequency and the records are available in an excel document.

Table B-4: Hydrometeorological Network state until January 2020

Nº	NAME/LOCATION	ID	TYPE OF EQUIPMENT	CURRENT STATE
1	Anexo IM	AN	Meteorological station	Functional
2	Punta Carretas	PC	Meteorological station	Functional
3	Centro Comunal Zonal 9	CZ9	Meteorological station	Functional
4	Terminal Colón	CN	Meteorological station	Functional
5	Centro Comunal Zonal 18	CZ18	Meteorological station	Functional
6	CAIF	CA	Meteorological station	Functional
7	Arroyo Seco	AS	Meteorological station	Functional
8	Lucas Piriz	LP	Pluviometric station	Functional
9	Museo Blanes	MB	Anemonic and Pluviometric station	Functional
10	PAGRO	PA	Pluviometric station	Functional
11	Centro Comunal Zonal 7	CZ7	Pluviometric station	Functional
12	Policlínica Casavalle	CV	Pluviometric station	Functional
13	Áreas Verdes	AV	Pluviometric station	Functional
14	Policlínica Giraldez	GZ	Pluviometric station	Functional
15	Policlínica La Paloma	PLP	Pluviometric station	Functional
16	Planta de Lixiviados	PL	Pluviometric station	Functional
17	Jardín 348	J348	Pluviometric station	Functional
18	Biblioteca Evaristo Ciganda	EC	Pluviometric station	Functional since end of 2019
19	Acosta y Lara	AL	Pluviometric station	Stolen 28/02/2015
20	Tres Cruces	3C	Meteorological station	Out of use 1/09/2019

Table B-5: Type of stations in the Montevideo Hydrometeorological Network

TYPE	MEASUREMENTS
Meterological station	Rainfall Wind Temperature Preasure Humidity
Pluviometric station	Rainfall
Anemonic and Pluviometric station	Rainfall Wind

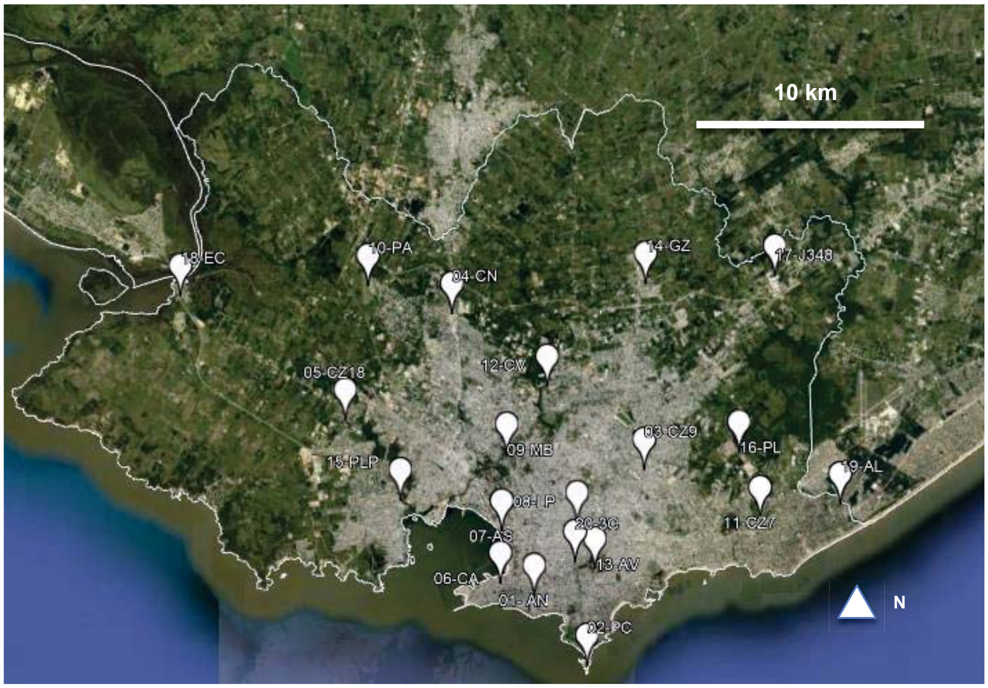

Figure B-3: Montevideo Hydrometeorological Network

In The Historic Rainfall Report 2014-2019 currently being developed by the SEPS, there is an analysis of the stations function and missing data. Figure B-4, extracted from the report, shows the percentage of days that the equipment was not recording data from 2014 to 2019. This could be due to malfunction, problems with battery or connectivity or non-operational equipment.

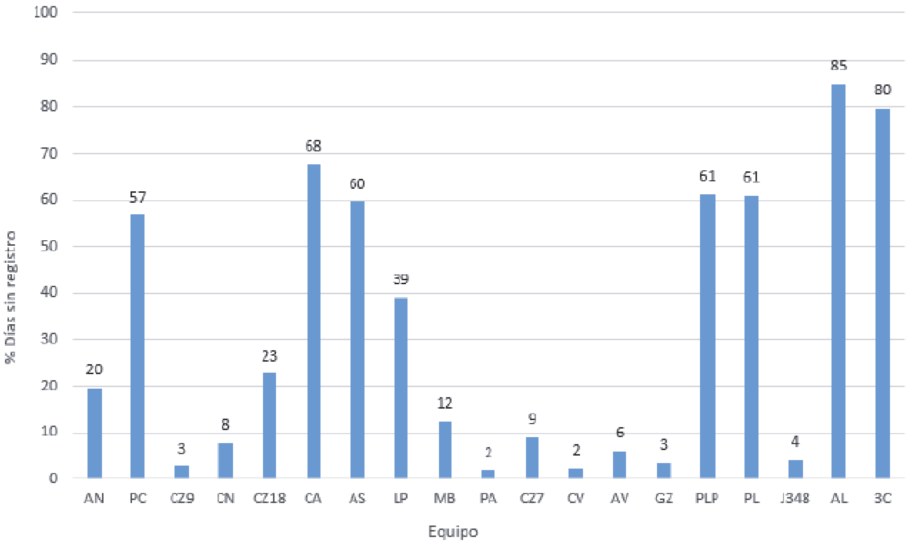

Figure B-4: Percentage of days without data for Montevideo stations extracted from Estudios y Proyectos de Saneamiento de la Intendencia de Montevideo (Sanitation Studies and Projects of Montevideo City Hall), n.d.

As it is shown in Figure B-4 only 8 out of 19 stations have less than 10% days of missing data for the period 2014 -2019.

Other analysis made by The Historic Rainfall Report 2014-2019 (Sanitation Studies and Projects of Montevideo City Hall, n.d) is the correlation between historical data using the double mass method comparing the accumulated rainfall of the SEPS rain gauges with the INUMET Prado station. The plotting is presented in Figure B-5 and the correlation index in Figure B-6.

The INUMET Prado station data is selected to compare the SEPS stations data due to its location and reliability, since it is long term daily data (since 1972 to the date) collected by the official meteorological and climatological national services.

As seen in the graphs there is a logical better correlation to the stations that miss less data.

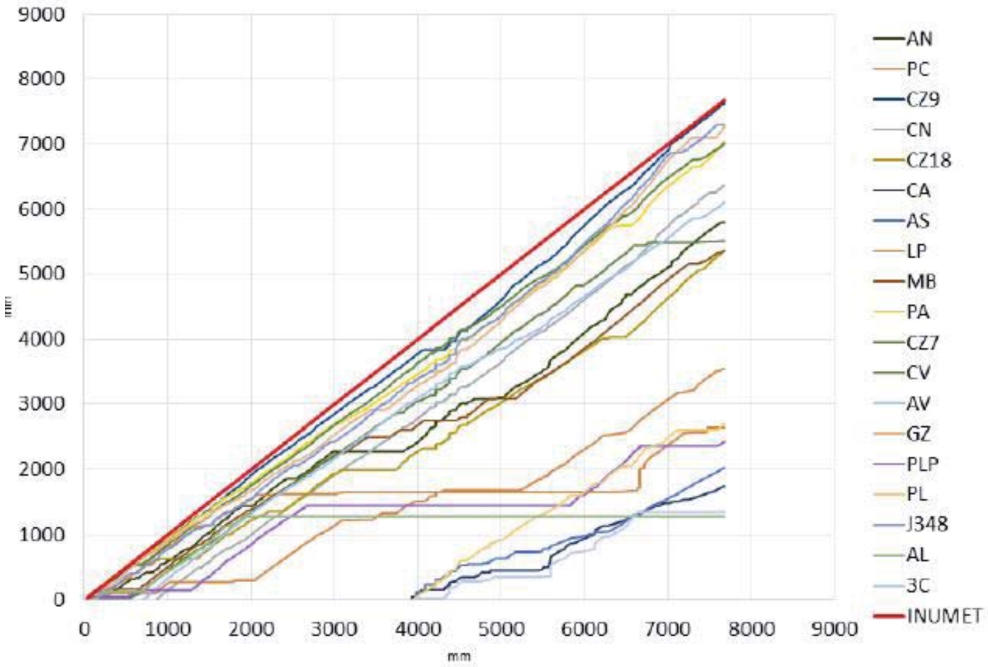

Figure B-5: Double mass analysis SEPS stations recorded rainfall data vs INUMET Prado station recorded data (Sanitation Studies and Projects of Montevideo City Hall, n.d.)

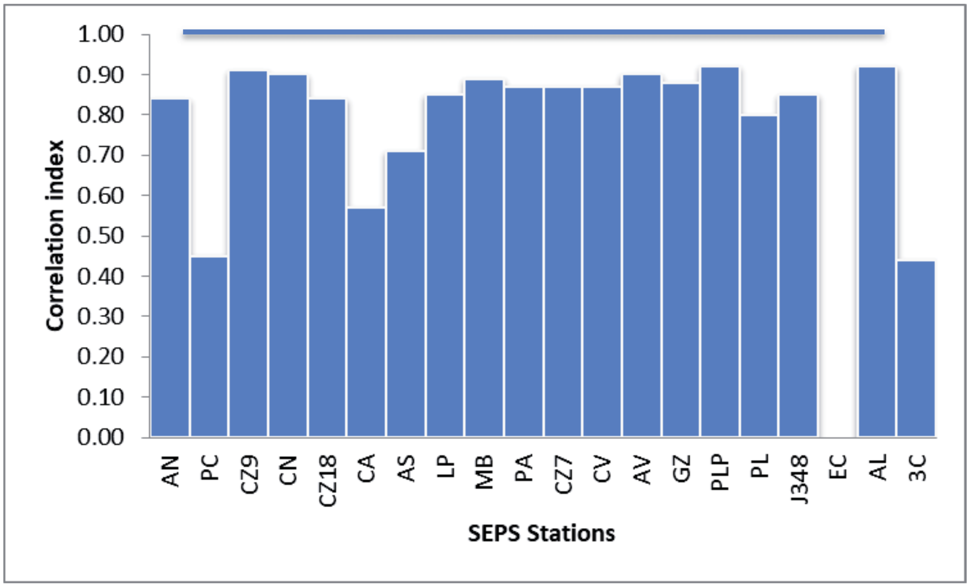

Figure B-6: SEPS stations data correlation index to INUMET Prado station. Figure created with data extracted from Sanitation Studies and Projects of Montevideo City Hall, n.d.

Other organizations

Other national organizations had study the Evapotranspiration for the importance of this parameter for their operations.

The National Directorate of Hydrography (Dirección Nacional de Hidrografía- DNH) has as objectives: to promote the development of port activity and manage, maintain and develop waterways. The DNH had study the evaporation data of the DNM stations in evaporation tanks in 1988 (Anido, 2012), this is presented in Table B-6.

Table B-6: Statistical Evaporation data from DNH study in 1988 for the DNM/INUMET climatic station Prado (Anido, 2012)

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
ET $_{tank}$ (mm/day)	7.1	6	4.3	3.2	2.4	1.5	1.7	2.1	3.2	4.5	5.5	6.8

The National Administration of Power Plants and Electric Transmissions (Administración Nacional de Usinas y Trasmisiones Eléctricas- UTE) is a public company in the Energy Sector which is in charge of generation, transmission, distribution and commercialization of electrical energy in the country. Since the major source of energy at the time was hydraulic energy, UTE had calculated the potential evapotranspiration using DNM data in 1980 (Anido, 2012),

Table B-7: Thornthwaite Potential Evapotranspiration data from the UTE study in1980 for the DNM/INUMET climatic station Prado (Anido, 2012).

MONTH	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEPT	OCT	NOV	DEC
ETP (mm/month)	126.0	106.0	93.0	61.0	40.0	25.0	25.0	33.0	40.0	61.0	85.0	113.0