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MARINA BATALINI DE MACEDO

OTIMIZAÇÃO DE TÉCNICAS COMPENSATÓRIAS DE DRENAGEM URBANA EM CLIMA SUBTROPICAL

VERSÃO CORRIGIDA

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Dissertação apresentada à Escola de Engenharia de São Carlos, da Universidade de São Paulo, como parte dos requisitos para obtenção do título de Mestre em Ciências: Engenharia Hidráulica e Saneamento

Orientador: Prof. Dr. Eduardo Mario Mendiondo

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Prof. Dr. **Eduardo Mario Mendiondo** **(Orientador)** (Escola de Engenharia de São Carlos/EESC)	Aprovada.
Prof. Dr. **Nilo de Oliveira Nascimento** (Universidade Federal de Minas Gerais/UFMG)	APROVADA
p/ Profa. Dra. **Sylvie Barraud** (Laboratoire DEEP/INSA Lyon)	APROVADA

Coordenadora do Programa de Pós-Graduação em Engenharia Hidráulica e Saneamento:
Profa. Associada **Maria Bernadete A. Varesche Silva**

Presidente da Comissão de Pós-Graduação:
Prof. Associado **Luís Fernando Costa Alberto**

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“If there is magic on this planet, it is contained in water”

Loran Eisley

RESUMO

MACEDO, M. B. (2017). **Otimização de técnicas compensatórias de drenagem urbana em clima subtropical**. Dissertação, Escola de Engenharia de São Carlos, Universidade de São Paulo.

A drenagem urbana no Brasil esteve focada historicamente no tratamento hidráulico para a condução do escoamento superficial. A partir da década de 90 se inicia uma mudança de paradigma com o estudo de técnicas compensatórias (TCs), visando adaptar o cenário local para compensar os efeitos da urbanização sobre o escoamento superficial, de forma a manter o ciclo hidrológico o mais próximo possível do natural. No entanto, existe ainda uma lacuna quanto a integração das variáveis quali-quantitativas e sua compreensão. No mais, as regiões de clima temperado estiveram no centro dos estudos, havendo pouco conhecimento sobre a influência de outros climas em sua eficiência. Assim, a presente pesquisa teve como objetivo avaliar a operação de uma estrutura de bioretenção em uma região de clima subtropical, quanto a sua capacidade de tratamento da poluição difusa e retenção hídrica de forma integrada. Para tal, foram monitorados dois dispositivos em escalas distintas, sendo essas laboratório e campo. Os resultados obtidos indicaram um uso promissor da bioretenção em reduzir os riscos de enchente, reduzindo a vazão de pico e o volume total transferido à jusante, assim como a carga total de poluentes. No entanto, adaptações nas etapas de implantação e operação são necessárias para clima subtropical. As características específicas desses locais, como solos altamente intemperizados e regimes de chuva de alta intensidade em pequeno intervalo de tempo, afetam a eficiência de retenção hídrica e retenção de poluente. Novos estudos avaliando diversos locais, escalas de aplicação, e fatores-chave para o tratamento devem ser realizados.

Palavras chave: Bioretenção; Eficiência generalizada; Poluição difusa; Escoamento superficial.

ABSTRACT

MACEDO, M. B. (2017). **Optimizing low impact development (LID) practices in subtropical climate**. Dissertation, São Carlos School of Engineering, University of São Paulo, São Carlos.

The urban drainage in Brazil has been focused historically in the hydraulic conduction of the runoff. From the 1990's a paradigm shift was initiated with the study of LID practices, aiming at adapting the local scenario to compensate the urbanization effects on runoff and reestablish the water cycle as close as possible to the natural. However, there is still a gap regarding the integration of qualitative-quantitative variables and their comprehension. In addition, the temperate climate regions have been in the center of the studies, with still few knowledge about other climates influence in its efficiency. Therefore, this research aimed to evaluate the operation of a bioretention structure in a subtropical climate region, regarding mainly its pollutant treatment capacity and water retention, in an integrated way. The results indicate a positive use of the bioretention in reducing the exceedance risks, by reducing the peak flow, the total volume and the pollutant load transferred downstream. However, adaptations the implementation and operation stages are necessary for subtropical climates. The local specific characteristics, such as soil highly weathered and rainfall with high intensities in short intervals of time, affect the water and pollutant retention efficiency. Further studies evaluating different applications locals and scales, and treatment key factors must be performed.

Key-words: Bioretention; Integrated efficiency; Diffuse pollution, Runoff.

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LIST OF VARIABLES

A_{field}	Bioretention surface area in field (m²)
A_{lab}	Bioretention surface area in laboratory (m²)
API 30	Antecedent precipitation index (mm)
A_w	Catchment area (1000m²)
C(t)	Concentration, at time t ($mg.L^{-1}$)
DLoad	Difference between accumulated inlet and outlet load present in runoff, representing the effective removal in the LID practice (g)
DPe(t)	Difference between the accumulated inlet and outlet runoff in the LID practice, representing the device effective retention (mm)
$Eff_{pollutant\ ret}$/ Eff_{quali}	Design pollutant retention efficiency, equivalent to the design qualitative efficiency
$Eff_{real,pollutant\ ret}$/ $Eff_{real,quali}$	Actual pollutant retention efficiency, equivalent to the actual qualitative efficiency
$Eff_{real,runoff\ ret}$ /$Eff_{real,quanti}$	Actual water retention efficiency, equivalent to actual quantitative efficiency
Eff_{ret}	Water retention efficiency
$Eff_{runoff\ ret}$ /Eff_{quanti}	Water retention design efficiency, equivalent to the quantitative design efficiency
$Eff_{TC}(t)$	Integrated efficiency
EMC	Event mean concentration ($mg.L^{-1}$)
$H_{equivalent}$	Equivalent useful depth (m)
H_{gravel}	Total depth of gravel layer (m)
H_{sand}	Total depth of sand layer (m)
H_{soil}	Total depth of soil layer (m)
I(t)	Infiltrated discharge by the LID practice ($m^3.s^{-1}$)
Imed	Main rainfall intensity ($mm.h^{-1}$)
$I_{med\ lab}$	Mean rainfall intesity in laboratory ($mm.h^{-1}$)
K	Hydraulic conductivity ($cm.s^{-1}$)
$Load_{in}$	Total inlet accumulated load into the LID practice (g)
$M_I(t)$	Infiltrated/treated pollutant mass by the LID practice (g)

$\mathbf{M_{in}(t)}$	Pollutant mass in the inflow runoff (g)
$\mathbf{M_{out}(t)}$	Pollutant mass in the outflow (g)
$\mathbf{M_{P}(t)}$	Pollutant mass in the precipitation directly incident over the bioretention basin (g)
$\mathbf{M_{s}(t)}$	Pollutant mass storared in the bioretention basin (g)
$\mathbf{P(t)}$	Precipitation directly incident over the bioretention basin (mm)
$\mathbf{Pe_{entrada}(t)}$	Cumulated inlet water depth, representing the device inflow (mm)
$\mathbf{Q(t)}$	Water flow at time t ($L.min^{-1}$)
$\mathbf{Q_{in}(t)}$	Inflow drained to the LID practice ($m^3.s^{-1}$)
$\mathbf{Q_{med\ field}}$	Mean inflow, in field ($L.min^{-1}$)
$\mathbf{Q_{out}(t)}$	LID practice outflow ($m^3.s^{-1}$)
$\mathbf{q_s}$	Design outflow, being determined as a constant depth over time ($mm.min^{-1}$)
$\mathbf{S(t)}$	Storage volume in the bioretention basin (m^3)
$\mathbf{t}$	Analyzed period of time (s)
$\mathbf{t_{detention(j)}}$	Required detention time for the j-th particle to decant (h)
$\mathbf{t_{field}}$	Duration of the event in field (h)
$\mathbf{t_i}$	Duration of campaign *i* in laboratory (h)
$\mathbf{t_r}$	Design rainfall duration (min);
$\mathbf{t_{retention}}$	Basin retention time (h);
$\mathbf{V_{control}}$	Control volume, equivalent with total inlet volume (L)
$\mathbf{V_{i,total}}$	Total inlet volume, considering campaign *i* (L)
$\mathbf{V_{in}(t)}$	Inlet volume (m^3)
$\mathbf{V_{out}(t)}$	Outlet volume (m^3)

LIST OF ABBREVIATIONS

BMP	Best Management Practices
CNPq	National Counsel of Technological and Scientific Development
COD	Chemical organic demand
EESC/USP	School of Engineering of São Carlos /University of São Paulo
FAPESP	São Paulo State Research Foundation
IAC	Agronomic institute of São Paulo
IBGE	Brazilian Institute of Geography and Statistics
LID	Low Impact Development
MAPLU2	Stormwater Management in the Urban Environment Project
SUDS	Sustainable Urban Drainage Systems
TOC	Total organic carbon
WSUD	Water Sensitive Urban Drainage

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1 GENERAL INTRODUCTION

From the 1950s, Brazil underwent an accelerated urbanization process, leading to structural social and environmental modifications in the country's situation. The need to move around the city resulted in the construction of road networks, changing the natural landscape, the relief, sealing the soil and changing the watersheds profile. This process of urbanization was made in a confusing scenario of planning, where in many cities planning is non-existent or is poorly done and with misconceptions, leading to structural environmental problems in their execution. Also, it is normal cases such as large urban centers (e.g.. São Paulo, Rio de Janeiro and Belo Horizonte) where it was made a proper planning, but the execution is not done in total agreement with the plan and also the growth of the informal city by means of irregular housing and favelas stand as an additional difficulty.

Consequently, there was an increase in the runoff generation, and natural phenomenon of water cycle have become urban problems. In this scenario, the urban drainage in Brazil has been focused, historically, in the hydraulic conduction of the runoff (PÔMPEO, 2000), still prevailing nowadays.

However, since the 1990s, the Brazilian research centers in urban drainage started to study alternative systems, such as Low Impact Development (LID) practices, and their adaptations to the local scenario. Based on the research developed by groups of Europe, USA, and Australia, ways of offsetting the urbanization effects on the runoff and stormwater started to be studied. Baptista et al. (2005) made a review and discussed these systems and their typologies. The developed concepts generate a paradigm change in how to treat urban drainage, and the incorporation of these concepts in Urban Master Plans increased, although still small.

This new approach has several denominations, such as LID systems, Sustainable Urban Drainage Systems (SUDS), Water Sensitive Urban Drainage (WSUD) and Best Management Practices (BMP) (ROSA et al., submitted). According to Fletcher et al. (2012), these techniques range from induced infiltration, retention, (bio)filtration, generation control, to landscape and urban space integration. A multidisciplinary approach, including environmental education and social participation, is required. It is possible to notice that these new concepts are based on the same principle, reestablishing the water cycle prior urbanization, increasing the infiltration intro the ground. This process contributes to an integrated efficiency in the runoff quali-quantiative control, retaining volume, peak flows, and allowing a pollutant load removal.

Despite two decades of LID research in Brazil, there is still little practical incorporation. Once the drainage problems are in macro scale, the public managers prefer macro drainage structures, such as large reservoirs, due to the lack of qualification in diffuse and small structures (CANHOLI, 2005). There is also a prejudice on the part of civil society, which has difficulties in associating small solutions with problems of macro scale. However, some studies have already been developed, especially with infiltration trenches and wells (LUCAS, 2011; GUTIERREZ, 2011; and LUCAS et al., 2015).

Moreover, the studies produced until today have been focused in temperate climate regions (DAVIS, 2007; BRATIERES et al., 2008; DAVIS, 2008; WINSTON et al., 2016, WANG et al., 2015 and 2016), where the geo climatic, sanitary and social condition is very different from those in subtropical climate areas. In the subtropical regions, it is common to have higher temperatures and more intense rainfall events, then tropical climates. Moreover, the context of urban planning and services are also poorly, leading to structural differences in the application of alternative urban drainage systems. Therefore, studying adaptations and monitoring LID practices in tropical and subtropical regions is still a lack.

The present study aimed to evaluate the use of a bioretention system in micro drainage and laboratory scale, verifying its efficiency in the runoff control and in the treatment of diffuse pollution. By monitoring the quali-quantitative variables, it was possible to obtain an integrated analysis of this experimental device. The monitoring also allowed to identify the typical pathologies in operating these systems under subtropical climate, evaluating the application of a bioretention in the context of Brazil (which are very close from the context of other cities in Latin America), raising the maintenance needs for its proper performance and to increase the practical incorporation.

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1.1 Text organization

These master’s thesis is organized in 6 chapters, containing a chapter with the general methodology applied in the collection of experimental data, three chapters with the results and discussion for each specific purpose, closing with a general conclusion and recommendations.

The general methodology used as the basis for all field and laboratory experiments is presented in **chapter two**. The collection points, as well as the selected method and instrument to the acquisition of quantitative data and qualitative samples gathering, are discussed with more details.

Chapter three discusses the pathologies identified during the operation of the bioretention applied in the field, in the University of São Paulo/São Carlos. Low water infiltration, low storage volume, and erosion in the soil layer were identified as the most common problems and consequence of the subtropical condition. Therefore, evaluation measures and maintenance actions were proposed to reestablish the proper operation and the design efficiency.

In **chapter four**, the quali-quantitative performance results are presented, for the bioretention applied in the field. The quantitative, qualitative and integrated efficiency values were calculated and compared with the design values, when they exist. The results were compared with the data obtained by other studies conducted in temperate climate, allowing to verify if the techniques behavior is similar for both climatic conditions. Differences in the runoff retention and pollutant removal rate were found. In this chapter, it was also made an evaluation of the *first flush* phenomenon, to the studied catchment.

A comparison of laboratory and field scales under controlled conditions is presented in **chapter five**. Conditions for hydric similarity were applied. The results showed similar results for both scales in quantitative terms, but different for analysis of pollutant removal.

Finally, **chapter six** presents a general conclusion and recommendations for future studies.

1.2 Research hypothesis

The use of bioretention systems to urban drainage in subtropical climate, as an alternative to the classical drainage systems, allows retaining the runoff affluent to the waterbody, facilitating its infiltration and reducing the risks of pollutants carrying. Therefore, the volume and pollutant mass mitigation help to reduce the impacts downstream, under urbanization scenarios. Planning properly the operation and maintenance of LID practices, according to the climatic and catchment occupation conditions, guarantees an optimization of the water and mass retention efficiency during its lifetime.

1.3 Purpose

1.3.1 General purpose

Evaluate the integrate efficiency (quali-quantitative) of LID practices in mitigating exceedance risks of urban drainage, by controlled and non-controlled experiments in bioretention systems under subtropical climate, aiming the optimization of the operation and maintenance.

1.3.2 Specific purpose

- Optimize, physically and economically, the operation and maintenance of the bioretention system applied in field under subtropical climate, quantifying the efficiency variation after the maintenance actions;
- Evaluate the water and pollution mass balance in stormwater, by controlled and non-controlled experiments under subtropical climate.

1.4 Relationship between objectives, methodology, and products

A flowchart of the research is shown in Figure 1.1, correlating the specific purposes, the applied methods and the products generated. Each product here presented corresponds to a thesis chapter and an article submitted to a journal, aiming to respond the research purposes.

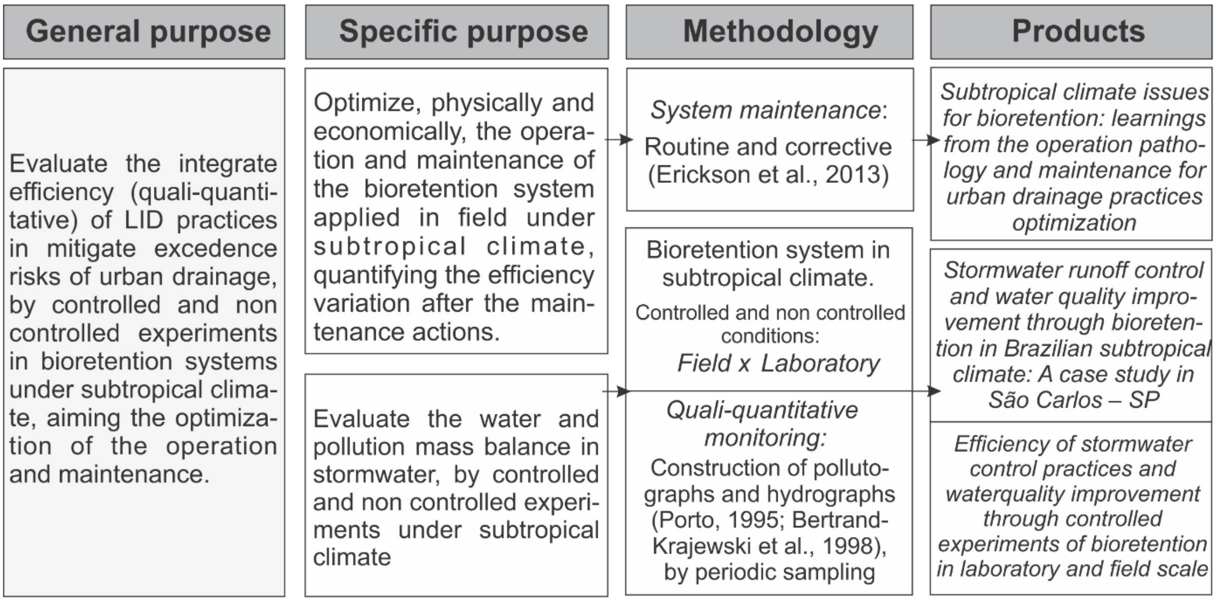

Figure 1.1 - Flowchart of the research, interconnecting objectives, methodology, and products.

References

Baptista, M. B., de Oliveira Nascimento, N., & Barraud, S. (2005). *Técnicas compensatórias em drenagem urbana*. Porto Alegre, ABRH. 266p. (in Portuguese)

Bratieres, K., Fletcher, T. D., Deletic, A., & Zinger, Y. A. R. O. N. (2008). Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water research*, *42*(14), 3930-3940. doi: http://dx.doi.org/10.1016/j.watres.2008.06.009

Canholi, A. (2005). *Drenagem urbana e controle de enchentes*. São Paulo, Oficina de Textos. 302p. (in Portuguese)

Davis, A. P. (2007). Field performance of bioretention: Water quality. *Environmental Engineering Science*, *24*(8), 1048-1064. doi:10.1089/ees.2006.0190

Davis, A. P. (2008). Field performance of bioretention: Hydrology impacts. *Journal of Hydrologic Engineering*, *13*(2), 90-95. doi: http://dx.doi.org/10.1061/(ASCE)1084-0699(2008)13:2(90)#sthash.HCIrHj3b.dpuf

Fletcher, T. D., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources*, *51*, 261-279. doi: http://dx.doi.org/10.1016/j.advwatres.2012.09.001

Gutierrez, L. A. R. (2011). *Avaliação da qualidade da água de chuva e de um sistema filtro-vala-trincheira de infiltração no tratamento do escoamento superficial direto predial* *em escala real em São Carlos SP*. Thesis. Universidade Federal de São Carlos. (in Portuguese).

Lucas, A., H. (2011). *Monitoramento e modelagem de um sistema filtro-vala-trincheira de infiltração em escala real*. Thesis. Universidade Federal de São Carlos. (in Portuguese).

Lucas, A., H.; Sobrinha, L. A.; Moruzzi, R. B.; Barbassa, A. P. (2015). Avaliação da construção e operação de técnicas compensatórias de drenagem urbana: o transporte de finos, a capacidade de infiltração, a taxa de infiltração real do solo e a permeabilidade da manta geotêxtil. *Engenharia Sanitaria e Ambiental*, 20(1), 17-28. doi: http://dx.doi.org/10.1590/S1413-41522015020000079923. (in Portuguese).

Pompêo, C. A. (2000). Drenagem urbana sustentável. *Revista Brasileira de Recursos Hídricos*, *5*(1), 15-23. doi: 10.21168/rbrh.v5n1.p15-23. (in Portuguese)

Rosa, A.; Macedo, M. B., D.; Souza, V. C.; Mendiondo, E. M. Sustainable Urban Drainage: delineation of a scientific domain of knowledge production. *Urban Water,* submitted.

Wang, J., Zhang, P., Yang, L., & Huang, T. (2015). Adsorption characteristics of construction waste for heavy metals from urban stormwater runoff. *Chinese Journal of Chemical Engineering*, *23*(9), 1542-1550. doi: http://dx.doi.org/10.1016/j.cjche.2015.06.009

Wang, J., Zhang, P., Yang, L., & Huang, T. (2016). Cadmium removal from urban stormwater runoff via bioretention technology and effluent risk assessment for discharge to surface water. *Journal of contaminant hydrology*, *185*, 42-50. doi: http://dx.doi.org/10.1016/j.jconhyd.2016.01.002

Winston, R. J., Dorsey, J. D., & Hunt, W. F. (2016). Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Science of the Total Environment*, 553, 83-95. doi: http://dx.doi.org/10.1016/j.scitotenv.2016.02.081

2 GENERAL METHODOLOGY

Two main modules were selected to conduct the research: a) evaluation in the laboratory from a prototype, which allows simulating different subtropical conditions, such as rainfall intensity. This module also has didactic purposes for the study of LID practices; b) evaluation in the field, which allows visualizing the effects of applying bioretention systems in micro drainage scale.

Therefore, the general methodology follows the schematic flowchart of Figure 2.1, containing four main stages: (1) evaluating the use of bioretention from simulations performed with the prototype, in laboratory; (2) stormwater qualitative monitoring in the inlet and outlet structures of the system, evaluating the pollutant removal efficiency; (3) quantitative monitoring in the inlet and outlet structures, evaluating the volume and peak flow retention; and (4) maintenance.

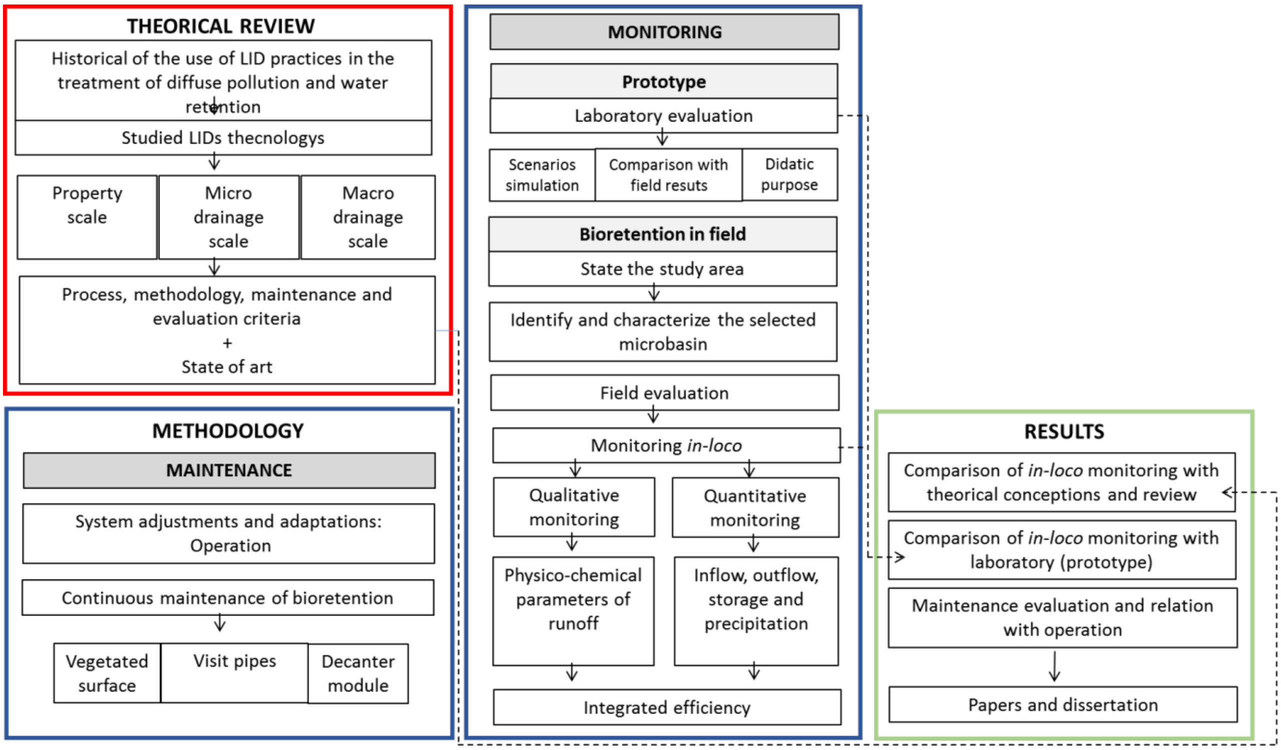

Figure 2.1 – Methodology flowchart, with the structure of research development.

2.1 Water and mass balance

The pollutant mass balance and water balance representing the bioretention system is shown in Figure 2.2 and equations 2.1 and 2.2, adapted from Erickson et al. (2013). The variables to be determined experimentally vary for the prototype and and real scale.

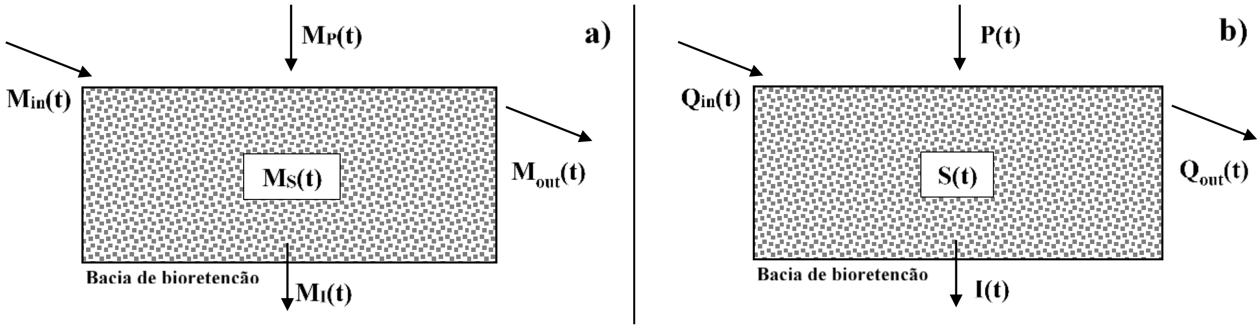

Figure 2.2 - (a) Pollutant mass balance of the system; (b) Water balance of the system.

$$M_s(t) = (M_{in} + M_P) - (M_{out}(t) + M_I(t)) \tag{2.1}$$

$$S(t) = V_{in}(t) - V_{out}(t) = (Q_{in}(t).t + P(t).A_w) - (Q_{out}(t).t + I(t).t \tag{2.2}$$

where:

A_w = Catchment surface [m²];

I(t) = Percolated flow into the ground [L/min];

$M_I(t)$ = Infiltrated/treated pollutant mass by the LID practice [g];

$M_{in}(t)$ = Pollutant mass in the inflow runoff [g];

$M_{out}(t)$ = Pollutant mass in the outflow [g];

$M_s(t)$ = Stored pollutant mass, including positive or negative reactions due to internal processes, i.e. sorption, degradation, etc., in the bioretention basin [g];

$M_P(t)$ = Pollutant mass in the precipitation, directly over the bioretention basin [g];

P(t) = Direct precipitation over the bioretention basin [mm]

$Q_{in}(t)$ = Inflow discharge [L/min];

$Q_{out}(t)$ = Outflow discharge [L/min];

S(t) = Storage volume in the bioretention basin [L];

t = Analyzed time interval [min]

$V_{in}(t)$ = Inlet volume [L];

$V_{out}(t)$ = Outlet volume [L].

These equations are presented throughout the chapters, considering the specificities for each results evaluation.

2.2 Qualitative monitoring

2.2.1 Variables that characterize the catchment pollution and its laboratory analysis methodology

In a first moment, the water quality parameters to be evaluated were selected from literature and review in stormwater characterization. Tucci (2002) affirm that the main water quality indicators are the one representing organic pollution and metals. May (2004) characterized the rainwater from physical-chemical and biological variables, among them color, turbidity, iron, series of solids, dissolved oxygen, biochemical demand of oxygen (BOD_5) and total coliforms. Dietz (2007) found as main parameters in LID studies the total nitrogen, total phosphorus, series of solids and metals, and realized that are still few analyses on the effect of these practices on the temperature and microorganisms (pathogens, coliforms, etc.). More specifically to the city of São Carlos, the research of Galavoti (2011) and Vasconcelos (2008) characterized the rainwater drained by a roof, in a peripheral and few urbanized region. They obtained similar parameters that the other studies. Despite the importance of oils, greases and hydrocarbons to analyze the stormwater quality in places with automobile traffic, the application site is still few urbanized and with light traffic, not justifying these parameters incorporation in the analysis. However, it is important that with the advance of the urbanization in this catchment, we incorporate these parameters in the evaluation and analyses.

After the review, a list of the water quality variables to be analyzed in the first moment and the analytical method to be used were elaborated (Table 2.1). These variables may change during the study if their absence is observed. The analyses methodology was in accordance with the Standard Methods for the Examination of Water and Wastewater.

Table 2.1 – Water quality variables to be analyzed and method employed

Variable	Method
Temperature	Portable thermometer
Color	Spectrophotometer
Turbidity	Turbidimeter
pH	pHmeter
Metals (Fe, Cu, Zn, Cd, Cr, Pb, Ni, Mn)	Atomic absorption spectrophotometry
COD	5220D
TOC	5310 TOC
Nitrite	4500-NO_2^-
Nitrate	4500-NO_3^-
Ammonia	4500-NH3
Phosphate	4500-P
Sedimentable Solids	2540

2.2.2 Collection methodology

To the device in the field, the water samples were collected at five different points, located along the bioretention cell, with the purpose of evaluating its spatial-temporal performance. The data obtained support the understanding of the system practical operation. It is important to analyze the variables evolution along the device to know how the biofiltration process occurs in the longitudinal profile. In addition, it is also important evaluating the variables behavior over time and the clogging effects. In this study, we also raised data to characterize the *first flush* phenomenon in the application catchment.

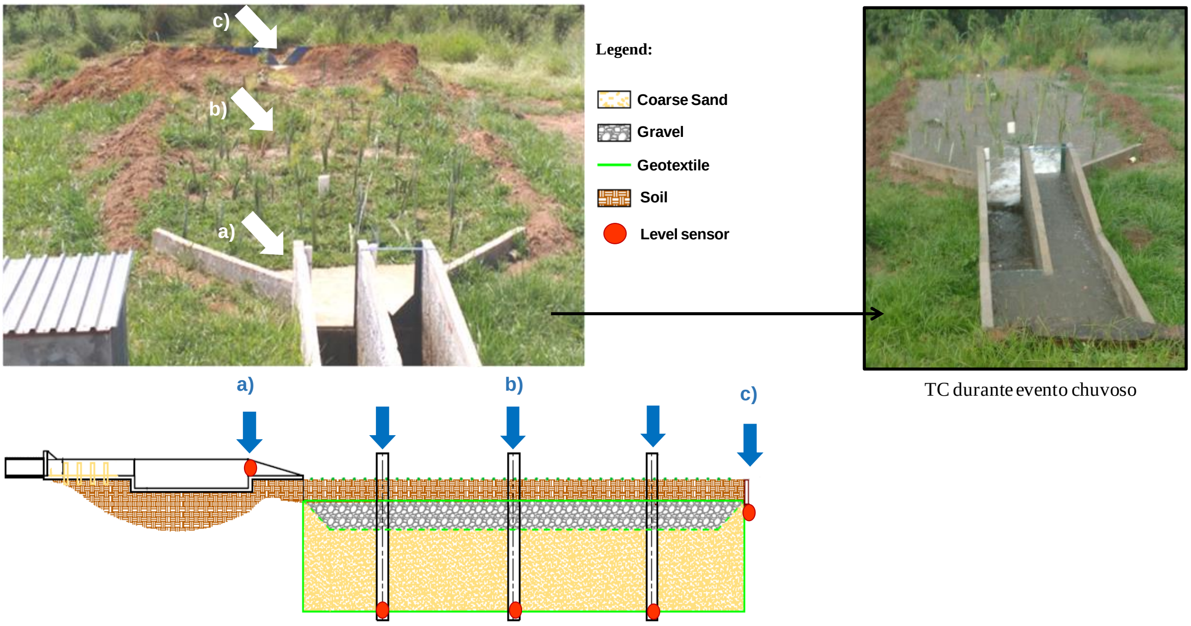

Figure 2.3 - Schematic location of the water sample collection points and level sensor installation, with its actual representation – (a) inlet point; (b) Visit pipes distributed lengthwise; c) outlet point.

Figure 2.3 shows the location of the collection points. Are they:

a) Inlet point: Located at the decanter inlet, allowing to characterize the stormwater inflow ($M_{in}(t)$) and the *first flush* phenomenon. These data can be compared with those of other sites with different land use and occupation characteristics, analyzing if there are significant differences in the water quality.

b) Visit pipes: Three pipes located along the bioretention cell, which allows obtaining the spatial-temporal behavior of the storage (Ms(t)).

c) Outlet point: Located in the outlet weir, allowing to characterize the device effluent water ($M_{out}(t)$). This point is essential to determine the system efficiency and it represents the actual pollutant load going directly to the waterbody when the bioretention is working.

The amount of pollutants in the rainwater directly incident over the device ($M_P(t)$) was considered insignificant, due to the small volume contribution (not passing 3% in all experiments). The infiltrated/treated pollutant load ($M_I(t)$) can be obtained from the resolution of equation 2.2.

To obtain the variables temporal behavior, we collected samples continuously, during pre-defined intervals. The total sampling duration was defined as 4x the catchment time of concentration, in this case considered equal to the rainfall duration, as proposed by Nakamoto (2014). Once during the bioretention sizing it was adopted rainfall durations ranging from 20 to 30 min, the maximum collection interval was settled as 2h.

As the inlet point also have the purpose of characterizing the *first flush*, the samples were collected every 5 min, using an automatic sampler. The total number of samples is limited to the sampler capacity, that, in this case, the maximum capacity is 14 bottles of 1L. To perform all laboratory analyses it is necessary a sample volume of 2L. Then, 7 samples for each monitored event were collected, corresponding to the first 35 min of rain (considered enough to the *first flush* evaluation). This procedure was adapted from Silva (2009).

In the visit pipes and outlet point, the samples were collected manually, with a time interval of 20 min. The samples were storage in proper recipients and kept refrigerated during transportation to the laboratory. The flowchart summarizing all the information for each sampling point is shown in Figure 2.4.

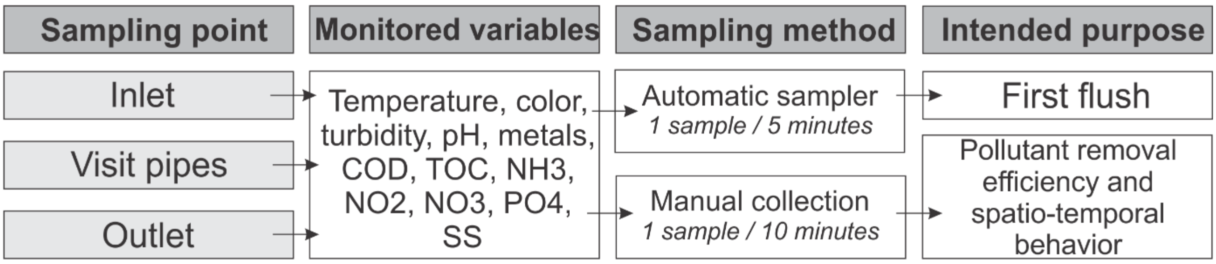

Figure 2.4 - Flowchart representative of the collection methodology and its purpose.

For the laboratory scale experiment, we consider three collection points: inlet ($M_{in}(t)$), outlet ($M_{out}(t)$), and infiltration ($M_I(t)$). The collections were done every 10 minutes, interval settled to elaborate well-defined pollutographs.

5.3 Quantitative monitoring

In order to determine the real runoff retention capacity for the chosen and sized LID practice and its influence in the infiltration process, it is necessary quantifying the water balance variables. With the balance settled, the water retention efficiency can be calculated, using the equation 2.3.

$$Eff_{ret} = DPe(t)/Pe_{in}(t) \tag{2.3}$$

where:

Eff_{ret} = Water retention efficiency;

$DPe(t)$ = Difference between the accumulated input runoff depth, from rainfall, and accumulated outlet runoff depth, representing the effective retention in the LID practice [mm];

$Pe_{in}(t)$ = Entrance water depth, representing the design precipitation or the real inflow [mm];

The quantitative monitoring of the bioretention system in the field was done in the same five points for qualitative sampling. However, the data measurement varies according to the point (Figure 2.2). In all points, a level sensor with data logger (model HOBO Water Level U20L-02) was used, with 5 min of acquisition interval time. The observation points are:

a) Inlet point: The inflow ($Q_{in}(t)$) is quantified by a composite section weir (triangular + rectangular).

b) Visit pipes: In those points, the purpose is to evaluate the actual storage capacity (S(t)). Once the visit pipes were already installed, level sensors were inserted inside the pipes, collecting continuously the water level in the filtering media.

c) Outlet point: In this point, we obtain the bioretention outflow ($Q_{out}(t)$), i. e., the actual flow transferred to the waterbody. The quantification is made using a triangular weir.

The rainfall directly incident on the device surface (P(t)) was quantified by a rain gauge *in situ*. To obtain the percolated flow (I(t)), the equation 2.2 must be solved.

For the experiments in the laboratory scale, the monitored variables are only the percolated flow (I(t)) and outflow ($Q_{out}(t)$), once the inflow and the rainfall directly incident on the surface (Qin(t) + P(t)) are simulated and remains constant over time (according to the pumping system installed and previous calibrated). The quantification of I(t) and $Q_{out}(t)$ is done manually, from the volume collected in a given time interval. Humidity sensors (model CS616) were also installed inside the prototype to observe the storage process. The experiments in the prototype have a total duration interval of up to 1 h, with different inflow and rainfall intensities.

5.4 Maintenance

Erickson et al. (2013) divide the maintenance actions into three levels: routine maintenance, which should be regular and frequent; non-routine maintenance, which is irregular and less frequent; and major maintenance, which should occur rarely, only for extreme situations. The routine and non-routine maintenance have as they main purpose preventing and reducing possible problems and risks. On the other hand, the major maintenance must be performed when there are structural problems in the practice, and rehabilitation actions or even rebuilt are needed. The system evaluation is considered as the first stage of routine maintenance.

Also for the system evaluation, Erickson et al. (2013) suggests three levels: visual inspection, which needs to be done weekly and *in situ*; monitoring, allowing evaluate the efficiency variation throughout its operation and to identify possible problems; and testing, which are performed at a lower frequency, when any problem is identified during the operation.

References

Dietz, M. E. (2007). Low impact development practices: A review of current research and recommendations for future directions. *Water, air, and soil pollution*, *186*(1-4), 351-363. doi: 10.1007/s11270-007-9484-z

Erickson, A. J., Weiss, P. T., & Gulliver, J. S. (2013). Optimizing stormwater treatment practices. New York, *Springer Science & Business Media*, 330p.

Galavoti, R. C. (2011). *Proposta de um modelo de gestão integrada de águas urbanas em escala de lote residencial : alcances e limitações*. Thesis. Universidade of São Paulo - EESC. (in Portuguese).

May, S. (2004). *Estudo da viabilidade do aproveitamento de água de chuva para consumo não potável em edificações.* Master thesis. Universidade de São Paulo - Escola Politécnica. (in Portuguese)

Nakamoto, R. (2014). *Dimensionamento e simulação de estrutura compensatória em um sítio experimental-demonstrativo*. Trabalho de conclusão de curso. Universidade of São Paulo - EESC. (in Portuguese).

da Silva, G. B. L., Moura, T. M., Koide, S., & Aldo, N. (2009). Avaliação da infiltração em revestimentos com superfícies permeáveis. *Ingeniería del agua*, *16*(3), 175-188. doi: http://dx.doi.org/10.4995/ia.2009.2953

Tucci, C. E. M. (2002). Gerenciamento da drenagem urbana. *Revista Brasileira de Recursos Hídricos*, 7(1), 5-27. doi: 10.21168/rbrh.v7n1.p5-27

Vasconcelos, A. F. (2008). *Análise da qualidade da água pluvial para sistemas de aproveitamento com separadores automáticos.* Trabalho de conclusão de curso. Universidade of São Paulo - EESC. (in Portuguese).

3 SUBTROPICAL CLIMATE ISSUES FOR BIORETENTION: LEARNINGS FROM THE OPERATION PATHOLOGY AND MAINTENANCE FOR URBAN DRAINAGE PRACTICES OPTIMIZATION

A modified version of this chapter has been submitted as: Marina Batalini de MACEDO, Altair ROSA, César do LAGO, Eduardo Mario MENDIONDO, Vladimir Caramori Borges de SOUZA. **Subtropical climate issues for bioretention: learnings from the operation pathology and maintenance for urban drainage practices optimization.** Journal of Management Environment

Abstract

The use of LID practices for runoff control is increasingly being used as an integrated solution in urban drainage, ensuring hydrological balance close to the pre-urbanized period and decreasing the pollutant carriage to urban rivers. Regarding bioretention, it already has a broad knowledge about the peak flow detention and the removal capacity for a great pollutants variety, under many filtering media types, especially at laboratory scale. However, the number of field studies in micro drainage scale, which analyzes the true operation of these devices, are still low, mainly in subtropical climate conditions. This paper presents the operation of a bioretention cell applied in a micro-drainage scale in Sao Carlos city, SP, Brazil. Many pathologies were diagnosed through the rainy events monitoring, therefore, this study aims to present the knowledge acquired by its operation, suggesting risks mitigations and adaptations. The results of the system water balance indicated low infiltration rates in the soil, resulting in erosion. Some structural adaptations were made over the cell, like semi-direct injection, to overcome these problems. The proposed maintenance improved the water retention efficiency in the bioretention, helping to reestablish the water balance prior urbanization. The subtropical and local conditions should be incorporated into the sizing and design stages, in order to reduce later risks.

Keywords: Runoff; Stormwater; LID practices; Maintenance needs; SUDS; Infiltration rate.

3.1 Introduction

The change in the land use and occupation, due to the urbanization process, normally results in an increase of the impervious area, runoff and diffuse pollution. Therefore, situations like river contamination and floods in urban centers are increasingly more frequents. The classic urban drainage systems are not capable to treat qualitatively the runoff and are not even able to reestablish the water balance close to the pre-urbanized scenario. Thus, the development of sustainable and financially viable alternative urban drainage systems is growing, not only with research for laboratory scale but also on its real field application.

These alternative urban drainage systems present a variety of denominations, among them: Low Impact Development (LID), Best Management Practice (BMP), Water Sensitive Urban Design (WSUD) and Sustainable Urban Drainage System (SUDS), varying according to the authors (ROSA et al., submitted). These new approaches range from non-structural measures (participative planning and environmental education, e.g.) to structural measures (techniques and devices) for source control and micro drainage scale (FLETCHER et al., 2012; MARSALEK & SCHREIER, 2009). Green roof, infiltrating trenches, wetponds and bioretention basins are examples of techniques and devices. In the last years, many studies have focused on evaluating the water retention efficiency and the pollutants removal by these devices. However, a wide number of these research were conducted in laboratory scale (BRATIERES et al., 2008; LIU et al., 2014; WANG et al., 2015; WANG et al., 2016) still having little field application (DAVIS, 2007; DAVIS, 2008; HATT et al., 2009, WINSTON et al., 2016). In addition, studies in the field are still recent and focus on a short period of time, having still a lack of knowledge on the effects and problems in long term.

Since the 1990s, the maintenance need for a good operation and performance of the LID through time was already pointed. Lindsey et al. (1992) did a study with many LID practices types and verified that the operation conditions drop significantly in only four years. They also verified that almost half of it was not working according to the initial project and two-thirds needed maintenance. It has been also realized that the infiltration basins was the technique that required higher maintenance needs, associated not only with vegetation but also to sediments, waste and stabilization problems, consequently resulting in erosion. In the same decade, EPA have already elaborated a user manual for several SUDS, including bioretention, highlighting the maintenance need and the constant inspection importance (EPA, 1999).

However, recent studies still highlight the problems caused by lack of maintenance and inspection, showing that this activity is being neglected in many cases. Blecken et al. (2015) review an extensive number of LID practices with long field application times, verifying which were the main problems occurred and the maintenance need. They realized that after the construction, a great part of the devices are forgotten or it is assumed by the managers that these would work indefinitely, leading to operational failures and a drop of the efficiency values. Specifically for bioretention, the most common problems observed were the surface clogging, caused mainly by internal erosions due to a concentrated flux through the bioretention basin. Brown & Hunt (2012) showed that the lack of maintenance measures affects the bioretention performance, leading to an overflow even for small rainfall events, and a reduction in pollutant removal rates. In this same direction, Flynn et al. (2012) and Schlüter & Jefferies (2005) also evaluated the negative effect by a lack of maintenance on several SUDS (filter drain, infiltration trench, bioretention) in a long-term operation in the United States and in Scotland, respectively. All these failures, presented by many authors, result in a drop of the device efficiency, leading to a loss of public faith in these alternative techniques.

Another interesting study that raised bioretention adversities was developed by Denich & Bradford (2008). This paper was conducted in the laboratory and had its focus on problems found in cold weather. Some problems that they found out to be the main obstacles are: the snow effect, salt and sand load in the system, quality and quantity possible trade-off with groundwater, clogging and the effects of low temperatures on biochemical process.

As to LID practices in tropical climate regions, Lim and Lu (2016) evaluated a project that installed many different practices in Singapore. In this study, they highlight the importance of long-term monitoring, both for constant evaluation of the technique and to list the maintenance needs over the years. Moreover, for tropical and subtropical climate regions, it is important remembering to perform a maintenance activity in order to prevent mosquito proliferation, since some can transmit epidemic diseases. Barret (2003) had also included this activity as one of the most important.

Based on the problems found, each study here presented has proposed maintenance actions and evaluation routines. Blecken et al. (2015) found as common maintenance need for all practices the access for personal to the site and required equipment. Specifically for bioretention, they obtained as main maintenance needs the vegetation upkeep (inspecting and cleaning the inlet and overflow structure) and preserving the surface infiltration rates. Lim e Lu (2016) present the erosion control (mainly at the system inlet) and keeping the vegetation growth as a maintenance routine, recommending higher frequency during the first operation year, to prevent the establishement of weed. Davis et al. (2009) alert that the exact type of maintenance varies depending on the contribution area (use, occupation, and stabilization). However, they still list as main activities the removal of waste and mulch layer (to maintain the infiltration rates fixed), and the removal and replacement of the filtering media top layers (to revitalize the performance in qualitative aspect). For the pervious floor, Winston et al. (2016) proposed the mechanical, regenerative-air and vacuum street sweeping, hand-held vacuuming, high-pressure washing and milling of porous asphalt, as maintenance methods to regenerate the performance.

Houle et al. (2013) and Barret (2003) developed studies to quantify the costs and labor demand to attend the project goals, for different types of LID technologies. Houle et al (2013) found that the annual cost for vegetated systems, as bioretention, is the lowest, and the highest for wet and dry ponds. Barret (2003) also verified that the routine requiring more labor demand was the inspection, since it has to be done weekly. Moreover, Flynn et al. (2012) raised as main maintenance for bioretention the care with vegetation, especially the irrigation. The annual cost raised for this activity was 74 dollars/m^3.

Operating LID systems and maintaining the efficiency according to the sizing project requires a frequent maintenance, since the routine actions to the major maintenance (ERICKSON et al., 2013). Each system will present different maintenance needs, according to local application (variations in climate conditions, soil use and occupation and socioeconomic factors). Few studies have focused on tropical and subtropical regions, where, the climate conditions and the socioeconomic factors are distincts from the temperate regions. In addition, despite the great amount of studies in laboratory scale, when the systems are applied in the field some adversities not identified in the laboratory can influence the performance and the efficiency.

Therefore, this study aims to present the implantation and operation of a bioretention system in a subtropical region, raising all the adversities and pathologies found during the process and the maintenance proposed as solution and risk adaptation. At a first moment, we describe the implantation area and the evaluation method for the efficiency. Posteriorly, it was identified the pathologies that took place during the rainy events and the maintenance measures suggested. Finally, these solutions were evaluated as its capacity to restore the performance.

3.2 Methodology

3.2.1 Area and bioretention descriptions

The bioretention practice is located in campus 2 of the University of Sao Paulo (USP) – Sao Carlos, located in the city of Sao Carlos – SP, and it is inserted in the sub-catchment of Mineirinho's river, which composes the urban watershed of Sao Carlos (Figure 3.1).

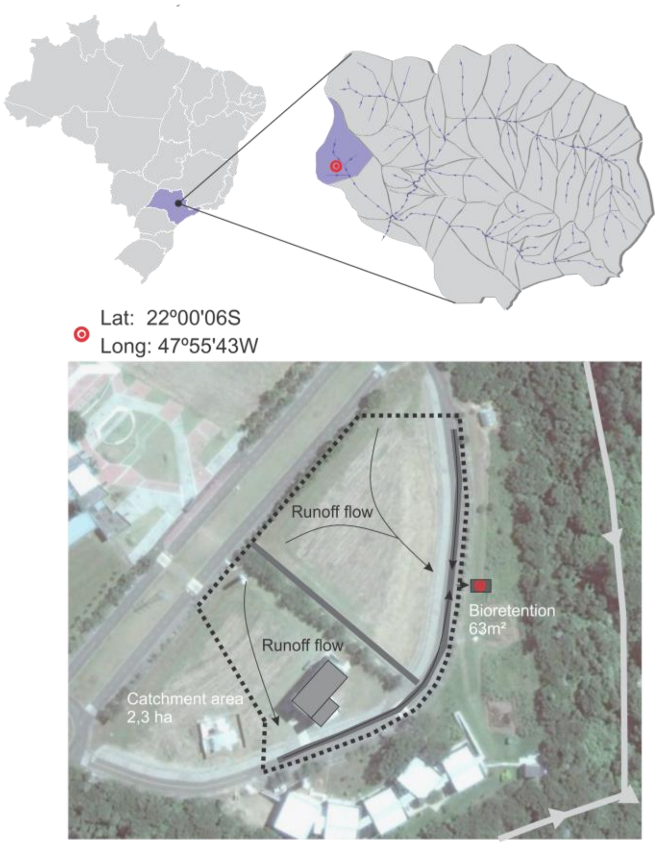

Figure 3.1 - Location of the bioretention in the urban watershed of São Carlos. In highlight: Dotted line representing the catchment perimeter, the continuous line representing pedestrian and vehicle via, building block at the bottom left, and bioretention basin identified by a red point.

The LID practice receives runoff contribution of a 2.3ha catchment surface, considered a micro-drainage scale. The represented area still has a low paving, and the greater part is composed by short vegetation coverage. The main runoff contribution is from roads, pathways and the impervious area related to the laboratory building (Figure 3.1). The campus is still in expansion, having approximately 15% of occupied area in 2016. According to the campus director's plan, it is expected that for the year of 2025 the occupation will be around 50% and, in 2050, around 75% - a fast expansion, which will result in an increase in the runoff generation.

The device construction and implementation were concluded in 2015. The bioretention cell has a 60.63m² area and 3.2 depth. It is composed of two filtering layers (sand and gravel, as shown in Figure 3.2), covered by the region natural soil, with sandy-loamy characteristics. This surface layer is vegetated in order to preserve the landscape integration and soil stabilization.

3.2.2 Determining the water balance and the runoff retention efficiency

Verifying the applicability of the bioretention system runs through to determine its runoff retention efficiency and its capacity to reestablish the pre-urbanization conditions. For this purpose, it is necessary to quantify the system water balance, identifying its maximum storage capacity, the effective storage occurring in the cell and the remaining discharge to the receiving waterbody. Figure 3.2 and equation 3.1 (adapted from ERICKSON et al., 2013) presents the water balance scheme and its equations.

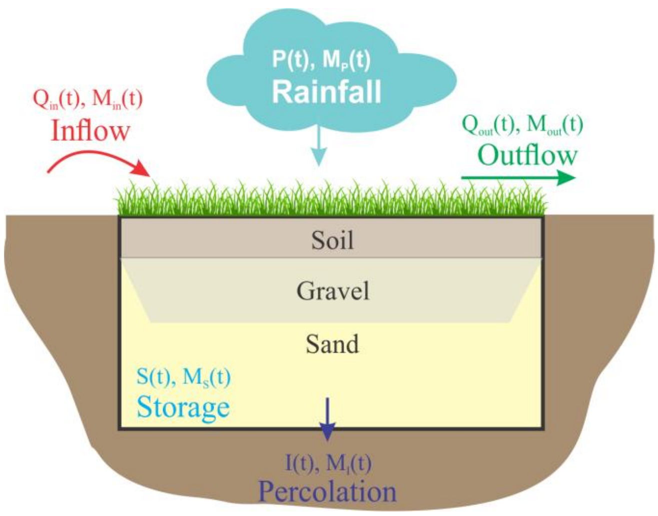

Figure 3.2 - Water balance scheme.

$$S(t) = V_{in}(t) - V_{out}(t) = (Q_{in}(t)t + P(t)A_w) - (Q_{out}(t)t + I(t)t) \tag{3.1}$$

where:

$S(t)$ = Storage volume in the bioretention basin [m³];

$V_{in}(t)$ = Inlet volume [m³];

$V_{out}(t)$ = Outlet volume [m³];

$Q_{in}(t)$ = Inflow drained to the LID practice [m³/s];

$P(t)$ = Precipitation directly incident over the bioretention basin [mm];

A_w = Catchment area [1000m²];

$I(t)$ = Infiltrated discharge by the LID practice [m³/s];

$Q_{out}(t)$ = LID practice outflow [m³/s];

t = Analyzed period of time [s].

The quantification of the variables $Q_{in}(t)$, $S(t)$ and $Q_{out}(t)$ was done through field data acquisition at: a) entrance – the inflow discharge $Q_{in}(t)$ is quantified by composed weirs (triangular and rectangular). This weir configuration allows a higher amplitude for data quantification (triangular for lower discharges and rectangular for the higher; b) visit pipes - in these points, the objective is to evaluate the LID storage capacity $S(t)$, obtaining the water level inside the bioretention cell; c) outlet – at this point the outflow discharge $Q_{out}(t)$ is obtained, i.e., the discharge not infiltrated and the one to be transferred to the stream, being quantified by a triangular weir. The water level acquisition in all the points was done by a level sensor and data logger (HOBO Water Level U20L-02). We settled the level acquisition time as 5 min.

The directly incident precipitation $P(t)$ was obtained by a rain gauge installed *in situ*. At last, the infiltrated discharge $I(t)$ is obtained by the equation 3.1 and Figure 3.2.

This data are then used to calculating the water retention efficiency, by the equation 3.2., through the percentage difference between the water depth accumulated at the device inlet and outlet. The efficiency varies according to the device time of usage, once the clogging level in the filtering media increases over time (MACEDO, 2015). Clogging is a natural process, which occurs in time due to the accumulation of solid particles arising from the carriage of particles to inside the cell and the growth of biofilm formed by microorganisms. In order to avoid the clogging process, it is necessary to perform routine and preventive maintenance in the system, according to Erickson et al. (2013). However, once clogged, corrective maintenance, like changing the filtering media, is necessary to restore the projected efficiency.

$$Eff_{ret} = DPe(t)/Pe_{in}(t) \tag{3.2}$$

where:

Eff_{ret} = Water retention efficiency;

$DPe(t)$ = Difference between the accumulated inlet and outlet runoff in the LID practice, representing the device effective retention [mm];

$Pe_{in}(t)$ = Cumulated inlet water depth, representing the device inflow [mm].

3.2.3 Maintenance

During the LID devices operation, it is necessary to perform routine maintenance to make the system work as projected. According to Blecken et al. (2015), one of the major mistakes made by the decision makers in applying these alternative systems is not predicting the maintenance labors. Consequently, the system performs efficiencies lower than expected and projected, leading to a lack of faith by the population.

During the operation of the bioretention here studied, we predicted a routine maintenance after each rainfall event, which was basically vegetation cares, cleaning the visit pipes and the sandbox, and mosquito proliferation cares. However, several pathologies were observed during its operation, requiring corrective maintenance: (1) low infiltration rates at the top layer; (2) unstructured soil, originating erosion near the outlet structure; (3) difficulty to fix the vegetation. Tests were done for each of these diagnosed pathologies, to understand better the local characteristics and them relation with the involved process.

Test 1 – Determining the soil type

The physico-chemical properties of soil can vary with its weathering level, particle size, originating material, and others. Then, determining the soil type allows identifying a set of common characteristic that interferes in the bioretention process, once the soil type affects, mainly, the infiltration capacity and the chemical processes of the pollutant sorption and desorption (ALLEONI et al., 2009; REICHERT et al., 2010).

Therefore, the determination of soil type was done through granulometric analysis and sieving of granular material (NBR 7181), at the geotechnical laboratory of the EESC/USP. We also analyzed the IBGE (Brazilian Institute of Geography and Statistics) map, which presents the soil classification for all Brazilian territory, IAC (Agronomic Institute) map that presents the soil classification of Sao Paulo state, and an ODA (1995) study, which presents the classification and description of Sao Carlos’ soils.

The granular material analysis allows identifying the soil texture (silt, clay or sand), while the soil maps allow identifying the structural characteristics and mineral composition of the material (e.g., dystrophic red latosol indicates high rates of clay in sand structure, with high iron rates and low nutrient content).

Test 2 – Permeability by Guelph permeameter

To evaluate the soil infiltration capacity, it was planned to do a permeability test next to the visit pipes, using the Guelph permeameter. In this test, the hydraulic conductivity is determined *in situ*, with haste and precision (BAGARELLO et al., 1999; KANWA et al., 1990; REYNOLDS & ELRICK, 1987). However, this test is restricted to soils that do not have high compaction. Thus, the permeability analysis by this method can be restricted.

Test 3 – Permeability by variable load

Complementing the Guelph test, the soil permeability was also evaluated through the variable load test (NBR 14545). For this test, the specimen was collected *in situ* and conducted to the laboratory.

Test 4 – Infiltration capacity of the filtering media

Testing the water infiltration capacity in the filtering media aims to evaluate the LID practice clogging level. Knowing the media is composed of 70% sand and 30% gravel with a mean permeability coefficient of 30.07 cm s^{-1}, the standard time considering no clogging for the liquid flatness inside the bioretention was determined. Then, by tests in the field we determined the actual time for liquid flatness. For this test, a volume of 60 L was inserted in each of the visit pipes, since it is the maximum capacity of the visit pipe. Comparing the standard time with the actual time, it is obtained a possible proportion of clogging.

3.3 Results and discussion

3.3.1 Determining the water balance

The first monitored events, regarding water balance for the bioretention system, were conducted during precipitation events, shown in Table 3.1. These events present great variation intervals for the precipitated volumes (2.6 to 39 mm) and for the mean intensity. The events also have different characteristics. Events 1 and 2 are less intense and represent the first rainfall after a dry month, then, leading to lower runoff volume in a higher time interval. Regarding event 3, it was the one with higher precipitated volume. The antecedent precipitated index of 30 days (API 30) shows that this event occurred after a rainy period, including a previous rainfall in the same day. Then, we conclude that the soil conditions favored a runoff high speed.

Table 3.1 – Precipitation data of field monitored events

	Days with no precipitation	**P total (mm)**	**Imed (mm/h)**	**API 30 (mm)**	**Total depth in (mm)**	**Total depth out (mm)**
Event 1	29	5.8	1.26	0	1.02	0.68
Event 2	1	2.6	0.89	3.6	0.28	0.08
Event 3	0	39	3.93	31.2	11.50	3.93

Figure 3.3 shows the inflow hydrographs (representing the catchment runoff), the outflow hydrographs (the discharge reaching the receiving waterbody) and the incident precipitation over the area. For each event, it is clear that the reduction of the total volume transferred to the receiving waterbody does not exceed 72%, varying from 33% (event 1) and 71.4 % (event 2). In addition, for event 1 (Figure 3.3a) and event 2 (Figure 3.3b), it is possible to notice that the bioretention system reduced almost 30% of the peak flow, for lower peaks and precipitations less intense. However, in event 3 the runoff speed was high enough to erode the soil at the device outlet structure, not allowing the outflow quantification.

As to the storage, considering the bioretention cell project parameters, 3.2m depth and 60.63 m^2 of surface area, with a filtering media composed of sand and gravel, the total storage capacity is of 58.2m^3. However, for the monitored events, the maximum storage volume occurred in event 3. In this case, the water level reached a maximum level of 11% of the total bioretention cell height, storing 5.5 m^3 (Figure 3.4c), equivalent to 10% of the total storage capacity. For the events 1 and 2, the water level does not exceed 8% and 2% of the total height, respectively (Figures 3.4a and b). It can be realized that the practice is storing a volume much lower than projected, meanwhile, there is a significant water loss draining on the surface, leading also to soil loss problems. These results indicate low infiltration capacity and high compaction in the top vegetated layer.

It is also possible to observe that the water balance data is biased, due to the losses in the water level quantification, especially of the outlet structure and, consequentially, in the outflow (Figure 3.5a). From these biases, high erosion, significant soil and vegetation loss and low infiltration were identified as the main pathologies presented in the construction and operation of the bioretention basin (Figure 3.5b). To present a viable and efficient solution to these pathologies, it was necessary to investigate the causes. Then, the soil type, the infiltration capacities of the vegetation layer and filtering media were studied.

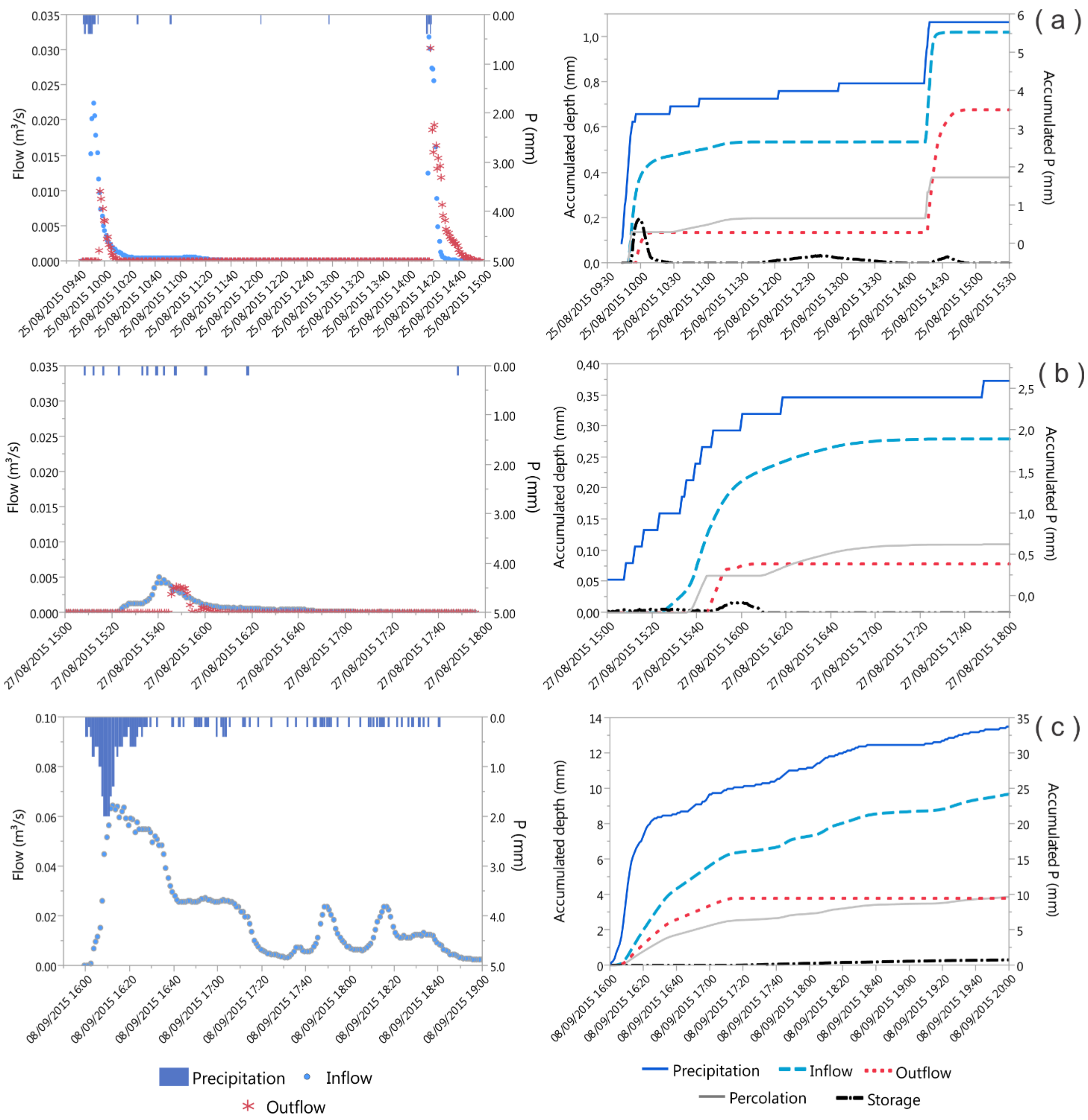

Figure 3.3 - Bioretention basin inflow and outflow hydrographs: (a) event 1 ; (b) event 2; and (c) event 3.

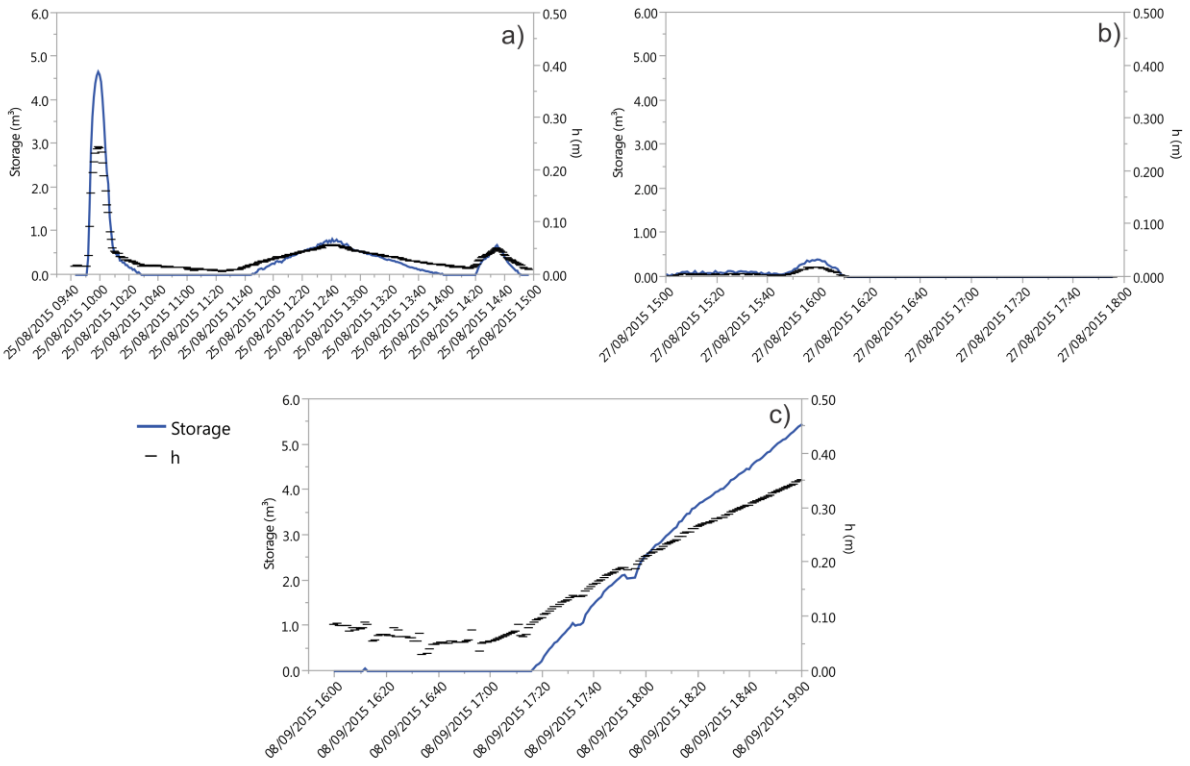

Figure 3.4 - Temporal variation of storage volume for the bioretention basin. The curve S(t) represents the stored volume versus time, and h is the water level within the visit pipes to: (a) event 1; (b) event 2; and (c) event 3.

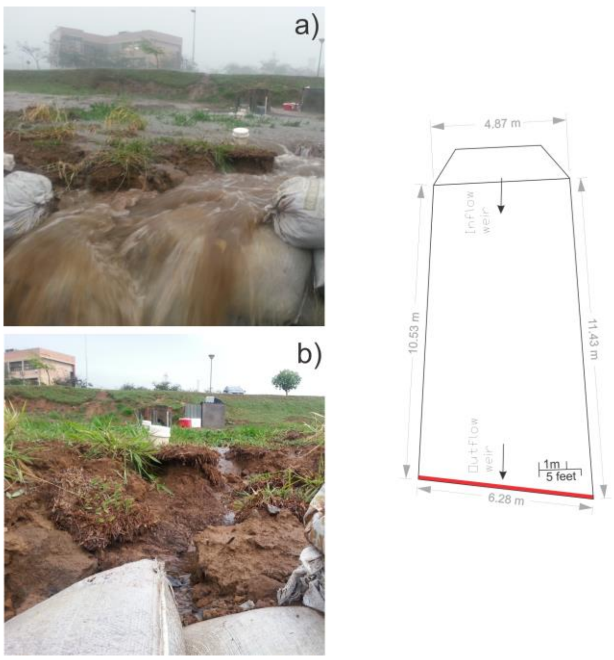

Figure 3.5 - Pathologies found in the bioretention basin that resulted in quantification errors for the water balance, and efficiency decrease. The superficial runoff with high speed could not be quantified (a), resulting in erosion of the vegetated layer (b). The pictures represent the place in red in the scheme.

3.3.2 Determining the soil type and its characteristics

From the maps provided by the IAC, IBGE and the study of Oda (1995), it was observed that the predominant soils in Sao Carlos are Red Oxisol + distrophenic, Yellow-Red Oxisol and Red Latosols, i.e., the predominance of latosol class. These soil types are characterized as highly weathered and deep, and they are very common in tropical and subtropical regions due to geo-climatic conditions in these regions. Usually, they are soils with high clay content (greater than 35%) and low coarse sand content (less than 10%) (ODA, 1995).

The granulometric and sieving analysis were complementary done, in order to identify with higher precision the soil type found in the vegetated layer of the bioretention cell. The results of granulometric distribution presented 20% clay, 10% silt, and 70% sand, being the main composition by medium sized sand (40%) and 25% fine sand. Through this analysis, the soil composition is identified as medium size sand and fine clay, dark brown with organic matter. For the sieving analysis of the granular material, it was obtained as result a fine to medium yellow sand with a medium boulder.

Although the granulometric analysis found higher sand rate when compared to clay, it is possible to observe a low infiltration capacity in the bioretention cell, verified by the low storage volume obtained by the sensors and the water balance (Figure 3.4). The low infiltration causes a high superficial water speed and, consequentially, soil loss and erosion. Therefore, it is necessary to identify if the low infiltration capacity is associated with the vegetated layer or to a possible clogging of the filtering media.

As to the soil permeability, in a first moment, the evaluation was made using the Guelph permeameter, done *in situ*. Two points were tested inside the bioretention surface, at 30 and 40 cm depth. However, the test could not be concluded, because even after 30 minutes no infiltration was registered. This result indicates soils with a high level of compaction.

Therefore, to obtain the hydraulic conductivity (K), a specimen was collected and conducted to the laboratory for an analysis of permeability through the variable load. From this test, the K value obtained was 1.62×10^{-4} $cm.s^{-1}$. According to Casagrande and Fadum (1940), this result demonstrates low permeability, a characteristic of fine sand, silt and clayey soils.

However, it is important that new permeability tests can be performed *in situ*, along the bioretention surface and in different points at the catchment area, in order to evaluate if the compaction is due to problems in the execution and building. These analyses *in situ* can also give more accurate results in terms of hydraulic conductivity coefficient.

The filtering media was also investigated as to the possibility of clogging. Infiltration tests have been done in the visit pipes. Considering a pipe volume of 60L and the mean permeability of sand and crushed stone of 30.07 $cm.s^{-1}$, the expected time, without clogging, was 1.5 minutes. In this field test, the real time of infiltration was of 2 minutes for all pipes, thereby concluding that there is not likely clogging of the filtering media.

3.3.3 Proposed maintenance solutions

After investigating the mains pathologies and its causes, some maintenance actions were proposed, so the bioretention could work according to the projected efficiency. The extreme precipitation events, with a high runoff speed, led to erosion at the outlet structures of the bioretention. Consequently, water losses occurred at the side borders, not infiltrating and not passing through the water treatment, and not accomplishing the LID practice goals. In this way, the first maintenance proposed was to restore the soil layer, which supports the vegetation.

The erosion process is favored in places where the soil is unstructured, e.g., places with high slope and taluses (COUTO et al., 2010), conditions found close to the outlet structure. Therefore, replace the soil would not be sufficient to prevent a new occurrence of this adversity in the future, requiring complementary actions. Thus, it was also proposed the use of a biomantle with direct seeding, and installed physical barriers (Figure 3.6).

Figure 3.6 - Image of the bioretention basin outlet structure after soil restitution, biomantle installation and physical barrier for soil retention, as maintenance proposals. The pictures represent the place in red in the scheme.

The use of biomantle is a technique already commonly used in talus recovering on roads and helps to avoid erosion processes given by both physical and biological means. It is composed of a synthetic grid guaranteeing the soil stabilization, and organic matter that will serve as subtract to plant growth, besides helping to fix the seeds in the soil (COUTO et al., 2010). The vegetation growth and establishment are also important to structure the soil because the roots act as aggregation mechanism.

The low infiltration at the bioretention cell (identified by the water storage below its capacity) has also contributed to the erosion process because it has contributed for a high runoff speed. Besides, the infiltration is important to attenuate the peak flow and the total water volume to be transferred downstream, as also to the water treatment process.

After investigating the soil characteristics (granulometry, permeability and soil type), it can be concluded that the soil presents sandy-clay characteristics with low permeability coefficient, common in tropical and subtropical regions, where the climate condition leads to a high weathering level (BIGARELLA et al., 1994; PIPIKIN & TRENT, 1997; RESENDE et al., 1997). Soils in presence of clay, with no structure, tend to have permeability reduced, due to the particle size that drops the porosity (REICHERT et al., 2010). Complementarily, the bioretention cell passed through a compaction process, by the precipitation itself, the people traffic on its surface and by an eventual use of machinery during its construction phase, contributing to a permeability decrease.

Considering the soil limitations and the logistic and financial infeasibility of using another soil type, it was proposed the semi-direct injection of the runoff into the filtering media as a maintenance measure to raise the infiltration and water retention into the cell, as presented in Figure 3.7. This procedure consisted of making holes in the soil until it reaches the gravel layer, where the water does not have any limitation for its passage and infiltration, once the infiltration test in the filtering media presented positive results, suggesting that there is no clogging. Then, a part will be directly infiltrated into the filtering layer and the rest continues to pass through the soil, which is the reason to be called semi-direct injection. Figures 3.7a and 3.7b shows the holes configuration and disposal in the practice surface, in its schematic way and its real representation. It was chosen a hive type configuration, where the perforation lines are dislocated sideway, in order that the runoff will necessarily reach a hole. To avoid accidents, the holes were filled with sand and gravel (Figure 3.7c), not compromising the infiltration capacity.

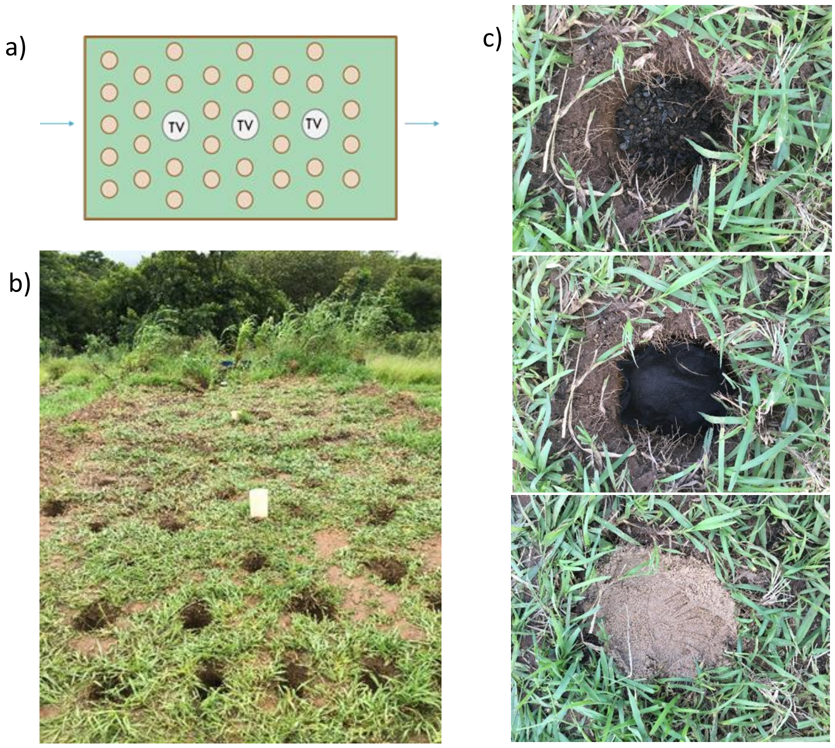

Figure 3.7 - Semi-direct injection as proposed maintenance to improve the infiltration into the bioretention cell – (a) Schematic figure showing the holes disposal in hive configuration; (b) The real representation of the hive configuration in the bioretention surface; (c) Holes filled with crushed stone and sand to avoid accidents.

Finally, the vegetation diversification at the top layer was also proposed as maintenance measures (Figure 3.8), including plants with rapid fixation and with long and fasciculate roots. This diversification aims to active two goals, (1) assists in the fixating and structuring the soil, helping on its uncompacting and avoiding the erosion process, (2) help in the water quality improvement. In order to attend the second objective, it was chosen macrophytes already used in water treatment techniques (wetlands), in Brazil, being: *Sansevieria trifasciata* and *Cyperus papyrus*. For landscape integration and to help in the soil fixation, grasses already present in the location were also chosen (*Brachiaria sp.* and *Sorghum sudanense*). Despite the grasses not having the objective to treat the water, its fasciculate roots help to hold the soil, preventing the erosion (REICHERT et al., 2010).

Figure 3.8 - Vegetation diversification by increasing the number os species, as macrophytes and grass to improve soil structure and pollutants treatment.

Considering that the practice is located in a subtropical region, it is important to consider the necessary maintenance to reduce the risk of diseases whose vector reproduce in water and are epidemics in tropical countries, like *dengue-fever*, *zika virus disease*, and *chikungunya*. Therefore, it is important to perform the routine maintenance (ERICKSON et al., 2012) weekly. This maintenance aims to exhaust the water in possible accumulating places, like the sandbox and cavities formed in the soil, in low infiltration places. As risk prevention method, is also recommend the chlorine application in places with possible water accumulation previously to the rainy event for a disinfectant action.

3.3.4 Proposed maintenance evaluation

To evaluate the effectiveness of the proposed maintenance in raising the infiltration capacity into the cell and reducing the impacts caused by the high runoff speed, two events post maintenance were monitored (Table 3.2). These events represent a sequence of rainfalls after the dry season in the region. During these events, the erosion process did not occur as previously.

Table 3.2 – Events field data – after the maintenance

	Days with no precipitation	P total (mm)	Imed (mm/h)	API 30 (mm)	Total depth in (mm)	Total depth out (mm)
Event 4	1	6.8	7.16	13.14	1.92	0.34
Event 5	3	9	1.54	7.23	1.77	0.11

For these events, Figure 3.9 shows the hydrographs representing the temporal behavior of the device after the maintenance. The runoff directly transferred to the receiving waterbody was reduced in over 75% for both events. As to peak flows, in event 4 it can be observed a reduction of 35% and for event 5 almost 60%, values greater than the ones found before the maintenance.

In addition, it was investigated if there was an increasing of superficial infiltration to the filtering media, from the observation of storage levels (Figure 3.10). For both events, the maximum level reaches a value around 30%, corresponding a volume of 13m^3. Despite these values are still low compared to the maximum capacity projected, they represent a significant improvement compared to the events pre-maintenance.

By the analyzed results, it can be concluded that the proposed adaptations and maintenance accomplish the goals of restructuring the vegetated layer soil and preventing the erosive process. Raising the water infiltration into the cell resulted in a higher storage volume and a reduction in the runoff speed and the soil displacement. Consequently, a significant reduction in the volume transferred to the receiving waterbody was observed. Thus, the maintenance helped the bioretention to have its operation closer to the project objective, contributing to reestablish the water balance prior urbanization, once the volume and the peak flow transferred were lower and the percolation was greater.

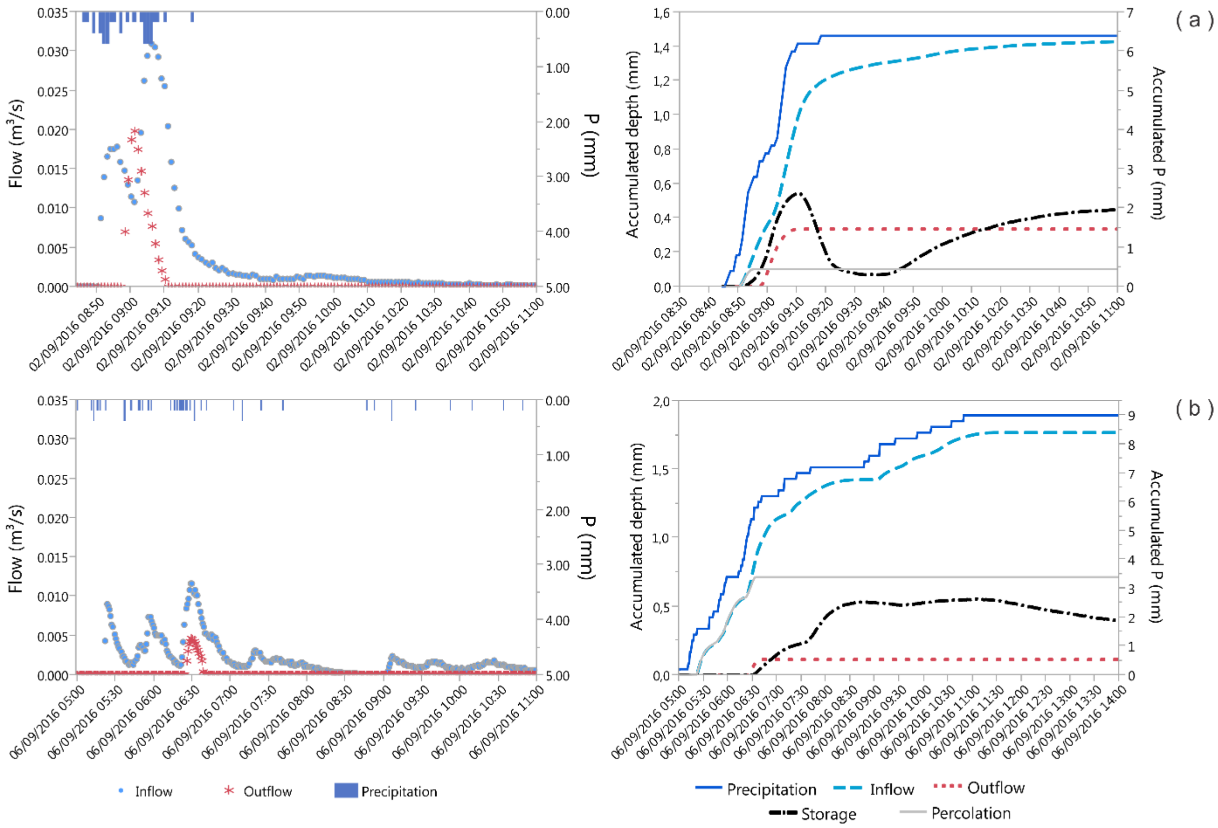

Figure 3.9 - Bioretention inflow and outflow hydrographs, after the maintenance: (a) Event 4; (b) Event 5.

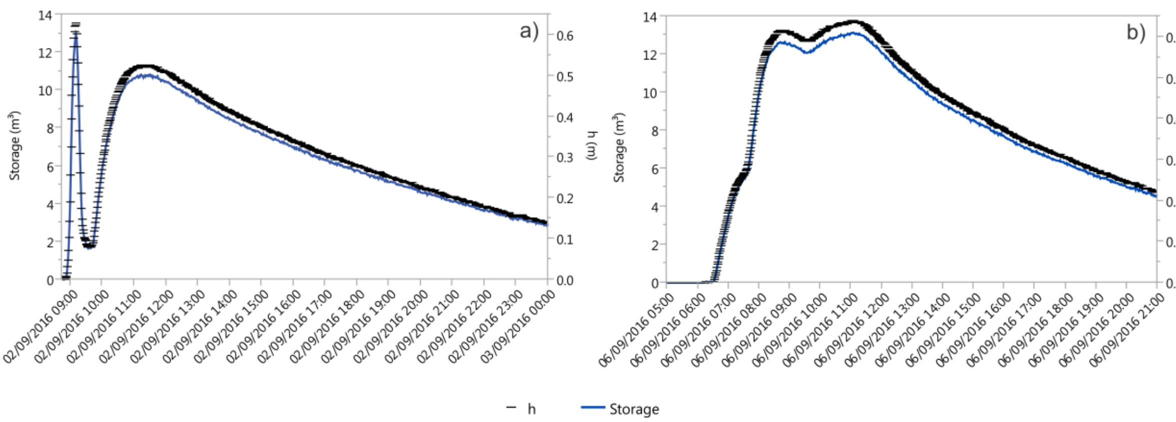

Figure 3.10 - Temporal variation of the bioretention basin storage after the maintenance. The S(t) curve represents the storage trough time, and h represents the water level inside the visit pipes for (a) event 4, and (b) event 5.

To facilitate the verification of proposed action effectiveness it was elaborated Table 3.3, with comparative data between the events pre and post maintenance. Regarding the cumulated water depth for the events 4 and 5, we found a reduction in the volume transferred to waterbody of 76% e 94%, respectively. On the other hand, in events pre-maintenance this percentage did not surpass 71%, situation occurred even for the smaller precipitation event, of only 2.6mm. Another important difference also occurred for the storage peak. As discussed previously, in event 4 and 5 the approximate storage volume is of $13m^3$, a significant increase in the total storage volume when compared with the pre-maintenance events, in the order of 70%.

Table 3.3 – Comparison between the water balance pre and post maintenance

Event	**API 30**	**Peak flow in (m^3/s)**	**Peak flow out (m^3/s)**	**Storage peak (m^3)**	**Cumulated depth (mm)**					**Eff (%)**
					Precip.	**In**	**Out**	**Percolated**	**Storage**	
Pre maintenance										
1	0	0.0319	0.0302	4.65	5.8	1.02	0.68	0.38	0.20	33
2	3.6	0.0050	0.0037	0.67	2.6	0.28	0.08	0.11	0.03	71
3*	31.2	0.0644	0.386	5.5	39	11.5	3.93	4.60	0.41	66
Average	-	*0.0338*	*0.0242*	*3.61*	*15.4*	*4.27*	*1.56*	*1.7*	*0.21*	*63*
Post maintenance										
4	13.14	0.0308	0.0199	12.94	6.4	1.43	0.34	0.10	0.55	76
5	7.23	0.0116	0.0047	13.15	9.0	1.77	0.11	0.71	0.55	94
Average	-	*0.0212*	*0.0123*	*13.05*	*7.7*	*1.6*	*0.23*	*0.41*	*0.55*	*86*

* In this event the outflow was not measured, but estimated by percolation rates

3.4 Conclusion

In tropical and subtropical climate regions, with high temperatures, rainy and dry seasons well defined and intense precipitation events, the conditions to operate LID practices, especially bioretention, varies when compared to temperate climates. Due to these characteristics, it should be taken special attention to the pathologies related to soil and its infiltration capacity, resulting in structural problems like erosion, leading to water bypass in the system. Some maintenance solutions to these pathologies were presented in this study, for example, the runoff semi-direct injection, physical barriers, and the fast fixation vegetation establishment, in order to mitigate the soil compaction effects and high runoff speed. Monitoring pre and post maintenance events, it can be concluded that:

- The fast fixation vegetation helped in structuring the soil, not resulting in erosive processes after the maintenance;

- The semi-direct injection helped to increase the water volume infiltrated into the filtering media, raising the storage volume in 70%;
- After the maintenance, the mean water retention efficiency increased from 66% to 86%, highlighting the importance in preventive and corrective maintenance to optimize the LID practices operation.

These results indicate the necessity of incorporating maintenance activities since the conception stage. The pathologies presented here should be considered in the sizing phase for future LID practices in tropical and subtropical regions.

References

Alleoni, L. R. F.; de Mello, J. W. V.; da Rocha, W. S. D. (2009). *Química e mineralogia do solo – Parte 2: Eletroquímica, adsorção e troca iônica no solo.* Viçosa, Sociedade Brasileira de Ciência do Solo. 130p. (in Portuguese)

Bagarello, V., Iovino, M., & Reynolds, W. D. (1999). Measuring hydraulic conductivity in a cracking clay soil using the Guelph permeameter. *Transactions of the ASAE, 42*(4), 957-964. doi: 10.13031/2013.13276

Barrett, M. E. (2003). Performance, cost, and maintenance requirements of Austin sand filters. *Journal of water resources planning and management*, *129*(3), 234-242. doi: http://dx.doi.org/10.1061/(ASCE)0733-9496(2003)129:3(234)

Bigarella, J. J., Becker, R. D., & dos Santos, G. F. (1994). *Estrutura e origem das paisagens tropicais e subtropicais: Fundamentos geológico-geográficos, alteração química e física das rochas*. Ed. da Univ. Federal de Santa Catarina. (in Portuguese)

Blecken, G. T., Hunt III, W. F., Al-Rubaei, A. M., Viklander, M., & Lord, W. G. (2017). Stormwater control measure (SCM) maintenance considerations to ensure designed functionality. *Urban Water Journal*, *14*(3), 278-290. doi: http://dx.doi.org/10.1080/1573062X.2015.1111913

Bratieres, K., Fletcher, T. D., Deletic, A., & Zinger, Y. A. R. O. N. (2008). Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water research*, 42(14), 3930-3940. doi: http://dx.doi.org/10.1016/j.watres.2008.06.009

Brown, R. A., & Hunt, W. F. (2012). Improving bioretention/biofiltration performance with restorative maintenance. *Water Science and Technology*, *65*(2), 361-367. doi: 10.2166/wst.2012.860

Couto, L.; Gonçalves, W.; Coelho, A. T.; De Paula, C. C.; Garcia, R.; Azevedo, R. F.; Locatelli, M. V.; Advíncula, T. G. L., Brunetta, J. M, F. C.; Costa, C. A. B.; Gomide, L. C.; Motta, P. H. (2010). *Técnicas de bioengenharia para revegetação de taludes no Brasil.* MG-Boletim Técnico do CBCN, 118p. (in Portuguese)

Davis, A. P. (2007). Field performance of bioretention: Water quality. *Environmental Engineering Science*, *24*(8), 1048-1064. doi:10.1089/ees.2006.0190

Davis, A. P. (2008). Field performance of bioretention: Hydrology impacts. *Journal of Hydrologic Engineering*, *13*(2), 90-95. doi: http://dx.doi.org/10.1061/(ASCE)1084-0699(2008)13:2(90)#sthash.HCIrHj3b.dpuf

Davis, A. P., Hunt, W. F., Traver, R. G., & Clar, M. (2009). Bioretention technology: Overview of current practice and future needs. *Journal of Environmental Engineering*, *135*(3), 109-117. doi: http://dx.doi.org/10.1061/(ASCE)0733-9372(2009)135:3(109)#sthash.A5jTVcr7.dpuf

Denich, C., & Bradford, A. (2009). Cold climate issues for bioretention: Assessing impacts of salt and aggregate application on plant health, media clogging, and groundwater quality. In *Low impact development for urban ecosystem and habitat protection* (pp. 1-10). doi: http://dx.doi.org/10.1061/41009(333)3

EPA, S. (1999). Storm Water Technology Fact Sheet–Bioretention. *Office of Water, EPA 832-F-99*, *12*.

Erickson, A. J., Weiss, P. T., & Gulliver, J. S. (2013). Optimizing stormwater treatment practices. New York, *Springer Science & Business Media*, 330p.

Fletcher, T. D., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources*, *51*, 261-279. doi: http://dx.doi.org/10.1016/j.advwatres.2012.09.001

Flynn, K. M., Linkous, B. W., & Buechter, M. T. (2012). Operation and maintenance assessment for structural stormwater BMPs. In *World Environmental and Water Resources Congress 2012: Crossing Boundaries* (pp. 3662-3673). doi: http://dx.doi.org/10.1061/9780784412312.368#sthash.6JWSqjpD.dpuf

Hatt, B. E., Fletcher, T. D., & Deletic, A. (2009). Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology*, *365*(3), 310-321. doi: http://dx.doi.org/10.1016/j.jhydrol.2008.12.001

Houle, J. J., Roseen, R. M., Ballestero, T. P., Puls, T. A., & Sherrard Jr, J. (2013). Comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management. *Journal of environmental engineering*, *139*(7), 932-938. doi: http://dx.doi.org/10.1061/(ASCE)EE.1943-7870.0000698

IAC – Instituto Agronômico de Campinas. (2016). *Mapa pedológico do Estado de São Paulo*. Available in: < http://www.iac.sp.gov.br/solossp/pdf/mapa_pedologico_Solos_Estado_de_Sao_Paulo.pdf>. Acess: 26 jul, 2016. (in Portuguese)

IBGE – Instituo Brasileiro de Geografia e Estatística. (2016). Mapas de solo do Brasil. Available in: <ftp://geoftp.ibge.gov.br/informacoes_ambientais/pedologia/mapas/brasil/solos.pdf>. Acess: 26 jul, 2016. (in Portuguese)

Kanwar, R. S., Rizvi, H. A., Ahmed, M., Horton, R., & Marley, S. J. (1990). Measurement of field-saturated hydraulic conductivity by using Guelph and velocity permeameters. *Transactions of the ASAE*, *132*(6). doi: 10.13031/2013.31239

Lim, H. S., & Lu, X. X. (2016). Sustainable urban stormwater management in the tropics: An evaluation of Singapore's ABC Waters Program. *Journal of Hydrology, 538,* 842-862. doi: http://dx.doi.org/10.1016/j.jhydrol.2016.04.063

Lindsey, G., Roberts, L., & Page, W. (1992). Inspection and maintenance of infiltration facilities. *Journal of Soil and Water Conservation*, *47*(6), 481-486.

Liu, J., Sample, D. J., Owen, J. S., Li, J., & Evanylo, G. (2014). Assessment of selected bioretention blends for nutrient retention using mesocosm experiments. *Journal of environmental quality*, *43*(5), 1754-1763. doi:10.2134/jeq2014.01.0017

Macedo, M. B. ; Rosa, A. Mendiondo, E. M.; Souza, V. C. B. (2015). *Otimização da eficiência de técnicas compensatórias de bioretenção em clima subtropical.* In: XXI Simpósio Brasileiro de Recursos Hídricos. (in Portuguese)

Marsalek, J., & Schreier, H. (2009). *Innovation in stormwater management in Canada: The way forward*. Water Quality Resources Journal of Canada, 44(1), v-x.

Oda, S. (1995). *Caracterização de uma rede municipal de estradas não-pavimentadas*. Master Thesis. Universidade of São Paulo - EESC. (in Portuguese).

Pipkin, B. W., Trent, D. D., Hazlett, R., & Bierman, P. (2013). *Geology and the Environment*. New York, Cengage Learning.

Reichert, J. M.; Reinert, D. J.; Suzuki, L. E. A. S.; Horn, R. (2010). *Física do solo – II Mecânica do solo*. Viçosa, Sociedade Brasileira de Ciência do Solo. (in Portuguese)

Resende, M.; Curi, N.; Rezende, S. B. E Corrêa, G. F. (1997). *Pedologia: base para distinção de ambientes.* Viçosa, NEPUT. (in Portuguese)

Reynolds, W. D., & Elrick, D. E. (1987). A laboratory and numerical assessment of the Guelph permeameter method. *Soil Science*, *144*(4), 282-299. doi: /soilsci/toc/1987/10000

Rosa, A.; Macedo, M. B., D.; Souza, V. C.; Mendiondo, E. M. Sustainable urban drainage: delineation of a scientific domain of knowledge production. *Water research*, submitted.

Schlüter, W., & Jefferies, C. (2005). The real issues with in-ground SUDS in Scotland. In *10th International Conference on Urban Drainage, Copenhagen, Denmark, August 21-26, 2005*. Institute of Environment & Resources, Technical University of Denmark/IAHR/IWA. doi: http://hdl.handle.net/10373/998

Wang, J., Zhang, P., Yang, L., & Huang, T. (2015). Adsorption characteristics of construction waste for heavy metals from urban stormwater runoff. *Chinese Journal of Chemical Engineering*, *23*(9), 1542-1550. doi: http://dx.doi.org/10.1016/j.cjche.2015.06.009

Wang, J., Zhang, P., Yang, L., & Huang, T. (2016). Cadmium removal from urban stormwater runoff via bioretention technology and effluent risk assessment for discharge to surface water. *Journal of contaminant hydrology*, *185,* 42-50. doi: http://dx.doi.org/10.1016/j.jconhyd.2016.01.002

Winston, R. J., Dorsey, J. D., & Hunt, W. F. (2016). Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Science of the Total Environment*, *553,* 83-95. doi: http://dx.doi.org/10.1016/j.scitotenv.2016.02.081

4 STORMWATER RUNOFF CONTROL AND WATER QUALITY IMPROVEMENT THROUGH BIORETENTION IN BRAZILIAN SUBTROPICAL CLIMATE: A CASE STUDY IN SÃO CARLOS – SP

A modified version of this chapter has been submitted as: Marina Batalini de MACEDO, Altair ROSA, César do LAGO, Eduardo Mario MENDIONDO, Vladimir Caramori Borges de SOUZA. **Stormwater runoff control and water quality improvement through bioretention in Brazilian subtropical climate: A case study in São Carlos – SP.** Journal Environment Engineering

Abstract

In urban centers, the increase of runoff caused by the rising cases of paving is becoming more and more a serious problem. Therefore, low-impact development (LID) practices, such as bioretention, emerged as an alternative solution for the current urban drainage systems. Most studies have focused on runoff retention or, exclusively, water quality, and they are often conducted in laboratory scale. Additionally, there are still few studies addressing the particularities of subtropical regions. This paper aims to provide knowledge about the operation and integrated quali-quantitative performance of bioretention systems in field scale, placed in a subtropical climate region. For this purpose, the quali-quantitative data were collect over three precipitation events, during the dry season to quantify the water and pollutant mass. A reduction in peak flows was observed for the three events, with an average delay about 10min. The bioretention system was also able to reduce most of the pollutant loads, except for NO_3 in the smallest event, and Fe in the highest. This study presents great results in runoff retention and water quality treatment, despite storage restriction due to tropical soil characteristics (highly weathered soils with high clay content). Further research must focus on adapt the current concept of bioretention systems to the subtropical and tropical regions.

Key-words: LID; SUDS; Efficiency; Urban drainage; First flush; Subtropical climate.

4.1 Introduction

The rapid and unplanned urbanization and the development of large urban centers in the last decades have caused an increase of soil sealing and, consequently, higher runoff. The runoff is being conducted faster and with a higher speed for urban rivers, causing flood problems and loss of water quality (EPA, 1983). In Brazil, the greatest amount of disasters is associated with extreme precipitation events (SANTOS, 2007; YOUNG et al., 2015), especially in the cities which do not have proper urban drainage systems. Places of higher environmental vulnerability are also often socially fragile and can be considered as an aggravating factor.

Therefore, the development and implementation of alternative urban drainage systems, known as LID practices, aims to reestablish the pre-urbanization water balance, increasing soil infiltration, slowing and reducing the peak flow and the total volume transferred to the receiving waterbody. These practices vary from small scales, as source control, to the application in micro and macro drainage (FLETCHER et al., 2013). Different technologies, such as green roofs, permeable pavements, infiltration trenches and bioretention, can also be applied.

The bioretention allows both quantitative control of runoff retaining part of the volume in a storage basin and the qualitative control, reducing diffuse pollution to be transported to the river. Due to this dual function of bioretention, scaling methodologies are made to calculate the design efficiency of the runoff retention itself (SILVEIRA & GOLDENFUN, 2007), the retention of loads of pollutants (AKAN & HOUGHTALEN, 2003) and biological treatment (McAULEY, 2009).

Before studying the pollutant retention efficiency for its deployment, it is important to understand which water quality treatment processes are involved in the system. Within the bioretention premises, it is assumed that the pollutants treatment occurs by multiple physical, chemical and biological processes. According to Erickson et al. (2013), physical processes of filtration, infiltration and biological processes of degrading the biomass are responsible for the treatment. Besides, Laurenson et al. (2013) say that chemical, biological and physical processes reach the treatment of bioretention techniques, including sedimentation, filtration, sorption and reduction, withdrawal by vegetation biomass and assimilation by microbiota.

Several studies have focused on presenting only quantitative or qualitative aspects of various LID techniques (DAVIS, 2007; BRATIERES et al., 2008; DAVIS, 2008; WINSTON et al., 2016), with special focus on nutrient removal (LUELL et al., 2011; BROWN & HUNT, 2012; MANGAKA et al., 2015) and, increasingly, on metal removal capacity (WANG et al., 2015 and 2016). Latest studies have shown the practice performances integrating qualitative and quantitative aspects (Hatt et al., 2009; Lucke & Nichols, 2015) and analyzing new perspectives for the water reuse and utilization of the surface for food production (Hatt et al., 2007; Ohnuma, 2008; Galavoti, 2011; Richards et al., 2015; NG et al., 2016).

Most of the research in this field are developed in temperate regions, where the rain and temperature regimes are different from tropical and subtropical climate regions. Therefore, one important contribution is researching LID practices efficiency in these regions, comparing if there are significant differences in its application. Lucas (2011), Gutierrez (2011) and Lucas et al. (2015) presented some studies that begin to address this issue to different types of LID practices, such as trenches and infiltration ditch in different regions of Brazil. However, the focus on bioretention has not been much studied yet. Given the importance of improving water quality in bioretention systems and the important influence that local environmental characteristics have in their efficiency, it is recommended developing new studies to determine the operating performance of those devices in subtropical climate regions.

This paper aims to evaluate the quali-quantitative integrated efficiency of a bioretention technique at the region of Sao Carlos – SP, Brazil. These results intend to increase the understanding of the use of this new technology in subtropical climate region and how the physical characteristics can affect these techniques' efficiency.

4.2 Methodology

This study was conducted in the field with a bioretention device applied at Campus 2 of University of Sao Paulo/Sao Carlos (USP/SC) in order to evaluate LID practice performance in reducing impacts transferred to urban rivers. The device is located right beside the Mineirinho River in a permanent protection area (Figure 4.1a). The system is operating since the beginning of 2015.

In this section, a study area and bioretention characterization are conducted, in order to determine all the relevant characteristics that contribute to the further analysis of the results, such as the type of pollution arising with the runoff. Subsequently, the equations used for water balances and pollutant retention balances quantification are presented. Finally, it is presented how to estimate the water retention and pollutant retention efficiencies representing, respectively, the device qualitative and quantitative efficiency, and the integrated quali-quanti efficiency as a way to evaluate the general performance.

4.2.1 Study area and bioretention characterization

The Campus 2 of USP/SC was inaugurated in 2005 and is still expanding. In 2015 about 15% of its total area was occupied and this occupation is expected to reach 50% by the year 2050, leading to a significant increase in the runoff. Therefore, it was chosen a sizing methodology with modular expansion over time, according to the increasing runoff generation caused by changes in the soil use and occupation conditions (Rosa et al., submitted).

As to the LID catchment characterization, it has a total area of 2.3ha, representing an urban drainage system on the micro drainage scale. The area is not much developed and the waterproof parts of asphalt roads, pedestrian pathways, and classroom buildings have the most significant contribution to generating runoff (Figure 4.1b). However, these areas combined do not totalize 25%, while the remaining 75% is mostly underbrush.

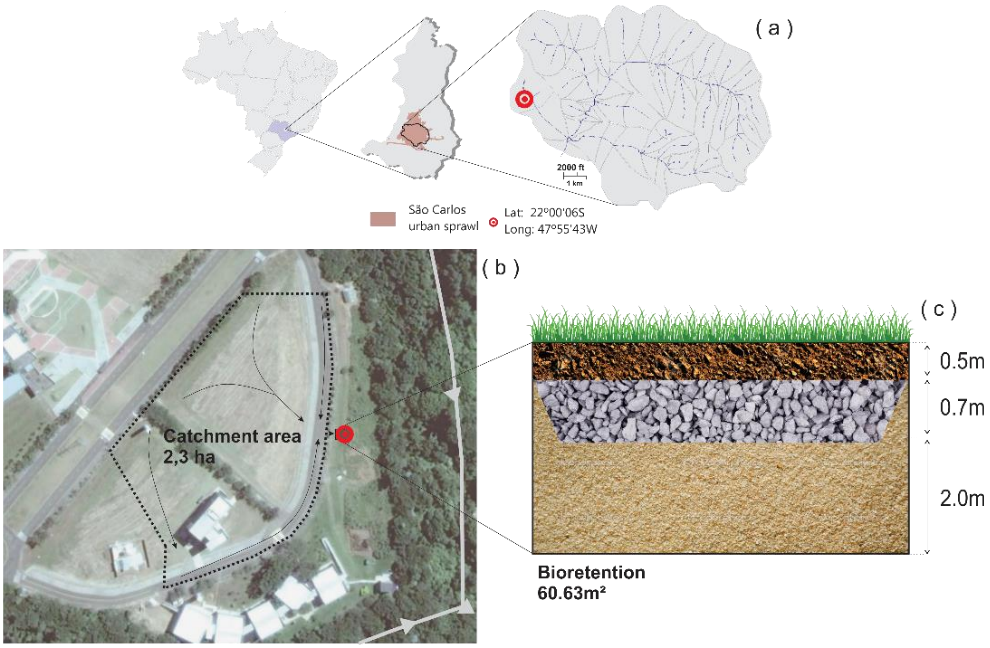

Figure 4.1 - Bioretention LID practice study area. In (a) its location in the urban basin of Sao Carlos, SP, Brazil; in (b) the contribution area with its details; and (c) the internal composition of bioretention.

The bioretention device has a total surface area of 60.63m² and a depth of 3.2m. Inside the device, there are a composite filter media divided into three layers – soil, gravel, and sand, with an average porosity of 35% (Figure 4.1c). The top layer is composed of soil from the region, which serves as a mean for the vegetation growth, and has approximately 50cm. As for the intermediate layer, it is composed of gravel at approximately 70cm deep. Finally, the bottom layer of sand presents greater thickness at 2m deep. Layers of gravel and sand together are responsible for retaining the greatest part of the runoff volume, with approximately 58m³ of total volume, and serving as means for the biofilm establishment aiding in the water treatment.

4.2.2 Determining qualitative and quantitative aspects

<u>Water and pollutant mass balance</u>

In order to determine the system performance, whether quantitative or qualitative, it is necessary to quantify the variables of the system balance, which are: input runoff and direct precipitation; output runoff and infiltration; and storage within the basin. In this case, as the assessment is made for both water variables, like volume and flow, and for pollutants mass variables, it is necessary to determine the water and pollutant masses balance. Equations 4.1 and 4.2 (adapted from Erickson et al, 2013) and the Figure 4.2 shows the scheme and calculation of the balance.

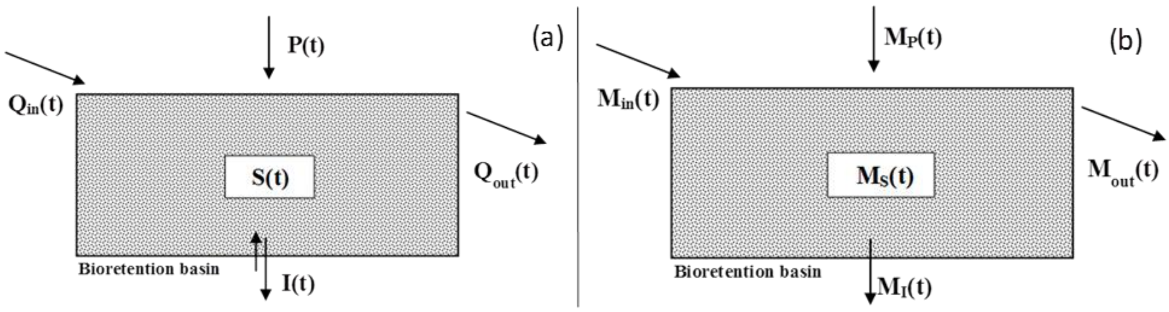

Figure 4.2 - System balance scheme with the variables to be quantified: (a) water balance (b) mass balance.

$$S(t) = V_{in}(t) - V_{out}(t) = (Q_{in}(t)t + P(t)A_w) - (Q_{out}(t)t + I(t)t) \quad (4.1)$$

where:

A_w = Catchment surface [1000m²];

$I(t)$ = Percolated flow into the ground [m³/s];

$P(t)$ = Direct precipitation over the bioretention basin [mm]

$Q_{in}(t)$ = Inflow discharge [m³];

$Q_{out}(t)$ = Outflow discharge [m³/s];

$S(t)$ = Storage volume in the bioretention basin [m³];

t = Analyzed time interval [s]

$V_{in}(t)$ = Inlet volume [m³];

$V_{out}(t)$ = Outlet volume [m³];

For each of the water balance variables, the data were collected in the field at different points, presented in Table 4.1.

Table 4.1 - Water balance variables and form of data acquisition in the field

Variable	**Measurement point**	**Measurement apparatus**	**Measurement instrument**
Inflow - $Q_{in}(t)$	Inlet channel	Composed section weir (triangular + rectangular)	Level sensor
Storage - S (t)	Inside the filter media	Perforated pipes located in the extension of the bioretention basin	Level sensor
Outflow - Q_{out} (t)	Output section	Triangular weir	Level sensor
Precipitation - P (t)	Catchement	Rain gauge	
Percolation - I(t)	Obtained by equation		

A rainy event can reach high peak flows, as well as small flows at the beginning and at the end of the rain. Thus, for the input quantification, it was adopted a weir with composed section, since this measure allows a wider range of flow rates (a triangular section for small flow rates and a rectangular section for higher flow rates). The storage was calculated from the liquid level measured by inserting level sensors into perforated pipes along the basin extent, with a total depth equivalent to that of the basin. The percolation was obtained by solving the equation 4.1, after determining all variables.

$$M_s(t) = (M_{in} + M_P) - (M_{out}(t) + M_I(t)) \tag{4.2}$$

where:

$M_I(t)$ = Infiltrated/treated pollutant mass by the LID practice [g];

$M_{in}(t)$ = Pollutant mass in the inflow runoff [g];

$M_{out}(t)$ = Pollutant mass in the outflow [g];

$M_s(t)$ = Stored pollutant mass in the bioretention basin [g];

$M_P(t)$ = Pollutant mass in the precipitation directly incident over the bioretention basin [g];
t = Analyzed time interval [min].

The water samples were obtained in different points at the LID practice (input - $M_{in}(t)$, storage - $M_S(t)$ and output - $M_{out}(t)$). The samples were collected at regular intervals of no more than 2 hours from the beginning of the precipitation event. Parameters indicating contamination by organic matter, nutrients and metals were analyzed. The analyzed parameters were: Chemical Oxygen Demand (COD), Total Organic Carbon (TOC), phosphate (PO_4), nitrite (NO_2), nitrate (NO_3), ammonia (NH_3), iron (Fe) and zinc (Zn). The load values for input and output were determined considering the Event Mean Concentration – EMC – (equation 4.3) and the total duration of each monitored event hydrographs, as shown in equation 4.4. The laboratory analysis of each parameter was based on the methodology proposed in the Standard Methods for Examination of Water and Wastewater (APHA et al., 1915).

$$EMC = \frac{\int C(t)Q(t)\,dt}{\int Q(t)\,dt} = \frac{\sum C(t)Q(t)\,\Delta t}{\sum Q(t)\,\Delta t} \tag{4.3}$$

$$Load = \int C(t)Q(t)\,dt = \sum C(t)Q(t)\,\Delta t \tag{4.4}$$

where:
$C(t)$ = Concentration, at time t [mg/L];
$Q(t)$ = Water flow at time t [L/min];
Δt = Considered time interval [min]

<u>Runoff characterization - first flush analysis</u>

The runoff characterization for each pollutant was also made to complement the bioretention performance analysis. First, it was investigated the occurrence of the first flush phenomenon in the catchment, i.e. if there is a higher pollutant dragging by the first runoff portions. This characterization allows evaluating the bioretention effect in retaining these pollutants and which is the most important volume fraction to be retained for qualitative treatment purposes.

Thus, the curves M(V) were constructed for each pollutant, according to equation 4.5, by Bertrand-Krajewski et al. (1998), but previously used by other authors (HELSEL et al, 1979; GEIGER, 1984). According to Bertrand-Krajewski et al. (1998), the first flush phenomenon is observed if the curve M(V) of the analyzed pollutant is above the quadrant bisector, or when 80% of the total pollutant mass is transported in the first 30% of rain volume.

$$\frac{\sum_{i=1}^{j} C_i Q_i \Delta t_i}{\sum_{i=1}^{N} C_i Q_i \Delta t_i} = f\left(\frac{\sum_{i=1}^{j} Q_i \Delta t_i}{\sum_{i=1}^{N} Q_i \Delta t_i}\right) = f\left(\frac{\sum_{i=1}^{j} V_i}{\sum_{i=1}^{N} V_i}\right) \tag{4.5}$$

where:

C_i = Concentration for the time interval [mg/L];

j = index between 1 and N;

N = Numbers of measurements;

Q_i = Water flow in the referent time interval [L/min];

V_i = Runoff volume during the referent time interval [L].

Δt_i = Gathering time interval [min];

Complementarily, it was also used the method proposed by Su & Mitchell (2003), that uses the potential function linearization (equation 4.6) to determine if a first or last flush effect is noted. Through this method, it is possible to conclude that there is a first flush if the slope parameter *b* value varies from 0 to 1.

$$F(X) = X^b \leftrightarrow \ln\big(F(X)\big) = b.\ln(X) \tag{4.6}$$

4.2.3 Calculation of bioretention efficiencies

The LID practice efficiency can be estimated during the sizing and design stage. There are several equations and methods to estimate the runoff and pollutant retention efficiencies, as proposed by Akan & Houghtalen (2003) and Silveira & Goldenfum (2007). In order to verify if the device is working properly, it is important to quantify its actual efficiency, both quantitative and qualitative.

Water retention efficiency

The water retention efficiency represents the practice *quantitative efficiency*, in other words, it is related to the amount of water retained. Silveira & Goldenfum (2007) present equation 4.7 to calculate the project efficiency, aiming only the runoff retention. Throughout the time, the actual water retention efficiency tends to fall due to the effects of clogging occurring in the filtering media (Macedo et al., 2015), which can be reestablished with maintenance activities. Therefore, the actual quantification of water retention efficiency allows an evaluation of the device operation and the need for preventive and corrective maintenance (Erickson et al., 2013). In this paper, it is proposed to calculate the actual efficiency by equation 4.8.

$$Eff_{runoff\ ret} = Eff_{quanti} = \frac{Pe_{in} - q_s . t_r}{Pe_{in}} \quad (4.7)$$

$$Eff_{real,runoff\ ret} = Eff_{real,quanti} = DPe(t)/Pe_{in}(t) \quad (4.8)$$

where:

$Eff_{runoff\ ret}$ *and* Eff_{quanti}= Water retention design efficiency, equivalent to the quantitative design efficiency;

$Eff_{real,runoff\ ret}$ *and* $Eff_{real,quanti}$ = Actual water retention efficiency, equivalent to actual quantitative efficiency;

DPe =Difference between the accumulated input runoff depth, from rainfall, and accumulated outlet runoff depth, representing the effective retention in the LID practice [mm];

Pe_{in} = Entrance water depth, representing the design precipitation or the real inflow [mm];

q_s = Design outflow, being determined as a constant depth over time [mm/min];

t_r = Design rainfall duration [min];

Pollutant retention efficiency

Likewise, pollutant retention efficiency represents the practice q*ualitative efficiency*, in other words, the one related to the parameters that affect the water quality. A project value can also be determined for this parameter, according to the sizing method. For example, Akan & Houghtalen (2003) present the equation 4.9 in their sizing for detention basins, aiming the removal of suspended solids. To evaluate the actual operation efficiency, it was used equation 4.10. It should be remembered that for each pollutant it shall be an efficiency value, and a final average can be made into a single value of qualitative efficiency for the bioretention practice.

$$Eff_{pollutant\ ret} = Eff_{quali} = 0.9 \sum_{j=1}^{N_{TSS}} \frac{t_{retention}}{t_{detention(j)}} \quad (4.9)$$

$$Eff_{real,pollutant\ ret} = Eff_{real,quali} = {DLoad}/{Load_{in}} \quad (4.10)$$

where:

$Eff_{pollutant\ ret}$ *and* Eff_{quali}= Design pollutant retention efficiency, equivalent to the design qualitative efficiency;

$Eff_{real,pollutant\ ret}$ *and* $Eff_{real,quali}$ = Actual pollutant retention efficiency, equivalent to the actual qualitative efficiency;

DLoad = Difference between accumulated inlet and outlet load present in runoff, representing the effective removal in the LID practice [g];

j =j-th suspended soil particle fraction, varying from 1 to $N_{TSS;}$

$Load_{in}$ = Total inlet accumulated load into the LID practice [g].

$t_{detention(j)}$ = required detention time for the j-th particle to decant [h];

$t_{retention}$ = basin retention time [h];

4.3 Results and discussion

4.3.1 Quantitative analysis

The precipitation events monitored to assess the bioretention performance occurred in the middle of the dry season in the city of Sao Carlos (August and September) in 2015. The events took place on 08/25/2015, 08/27/2015 and 09/08/2015. Table 4.2 shows the characteristics of each of the events, including the interval for water gathering qualitative analysis. The presented data shows that the event 1 occurred after a long dry period, with an interval of 29 days without rain, which resulted in an Accumulated Precipitation Index for 30 days – API 30 of 0mm. In the event 2, despite it being preceded by rain in a short period of time (1 day without raining), there is still a small API 30, with a value of 3.6mm. It may also be noted that the two events presented low magnitude (low precipitation depth and low precipitation intensity). As for the third event, there was a precipitation event on the same day (0 days without raining), and it had a high precipitation depth, totalizing 39mm. Comparing the last event with the other two, the API 30 has increased significantly, with a value of 31.2mm. These different conditions of each of the events result in differences in the total volume that needs to be retained into the device. The Table 2 shows that the entire inlet water depth for the event 3 is almost 10 times bigger than the first event, which will affect its operation.

Figure 4.3 shows the temporal behavior of each water balance variables over the precipitation events. From the temporal behavior analysis, it is possible to verify the device capacity to retain part of the drained water volume, to delay and to reduce peak flows. Additionally, verifying if there is an increase in water percolation into the ground allows noticing the device capacity in reestablishing the pre-urbanization water balance.

Table 4.2 - Monitored precipitation events summary

	Days without precipitation	P total (mm)	Imed (mm/h)	API 30 (mm)	Total depth in (mm)	Total depth out (mm)
Event 1	29	5.8	1.26	0	1.02	0.68
Event 2	1	2.6	0.89	3.6	0.28	0.08
Event 3	0	39	3.93	31.2	11.50	3.93

In the event 1 (Figure 4.3a), total precipitation was 5.8mm, there were two precipitation peaks for the same event, causing two peaks flows with values of 0.06 and 0.09mm/min. On the first, the reduction in peak flow from the input to the output in the order of 50% and a 10min delay is clearly visible. In this time interval, the storage peak reaches a value of 0.2mm. However, on the second peak in this same event, it is not possible to observe the same processes taking place. There is almost no reduction of the inflow peak to outflow peak, in addition to the storage in the bioretention basin being low if compared to the first, reaching slightly more than 0.025mm. With this different behavior for the same event with two peaks of precipitation and runoff, a significant reduction of the technique efficiency for the second peak became clear. This may be explained by the topsoil saturation, preventing the infiltration to the basin, where the water storage should occur.

The event 2 (Figure 4.3b) presented a total precipitation of 2.6mm, with only a single precipitation peak, leading to one peak flow, with a value of 0.013mm/min. Under these conditions, it was possible to observe a reduction in output peak flow to less than 70% of the input with a delay of 10min. The maximum storage in this situation is of 0.017mm.

In the event 3 (Figure 4.3c), it was observed a total precipitation much higher than in the first two, with a total of 39mm. In this event, a clear precipitation peak, with some intensification over time, can be seen. This behavior leads to an important peak flow (0.16mm/min, up to 5x higher than the previous events peaks) and small peaks over time due to the precipitation intensification. It was also possible to observe a higher superficial speed in the soil layer, leading to erosion, soil loss and failure to quantify the outflow (MACEDO et al., submitted). Thus, the outflow hydrograph was estimated using the practice mean percolation rate. In this event, the higher storage peak in bioretention basin was observed, reaching a value of 0.25mm after 3 hours of the beginning of the precipitation, and tending to keep increasing.

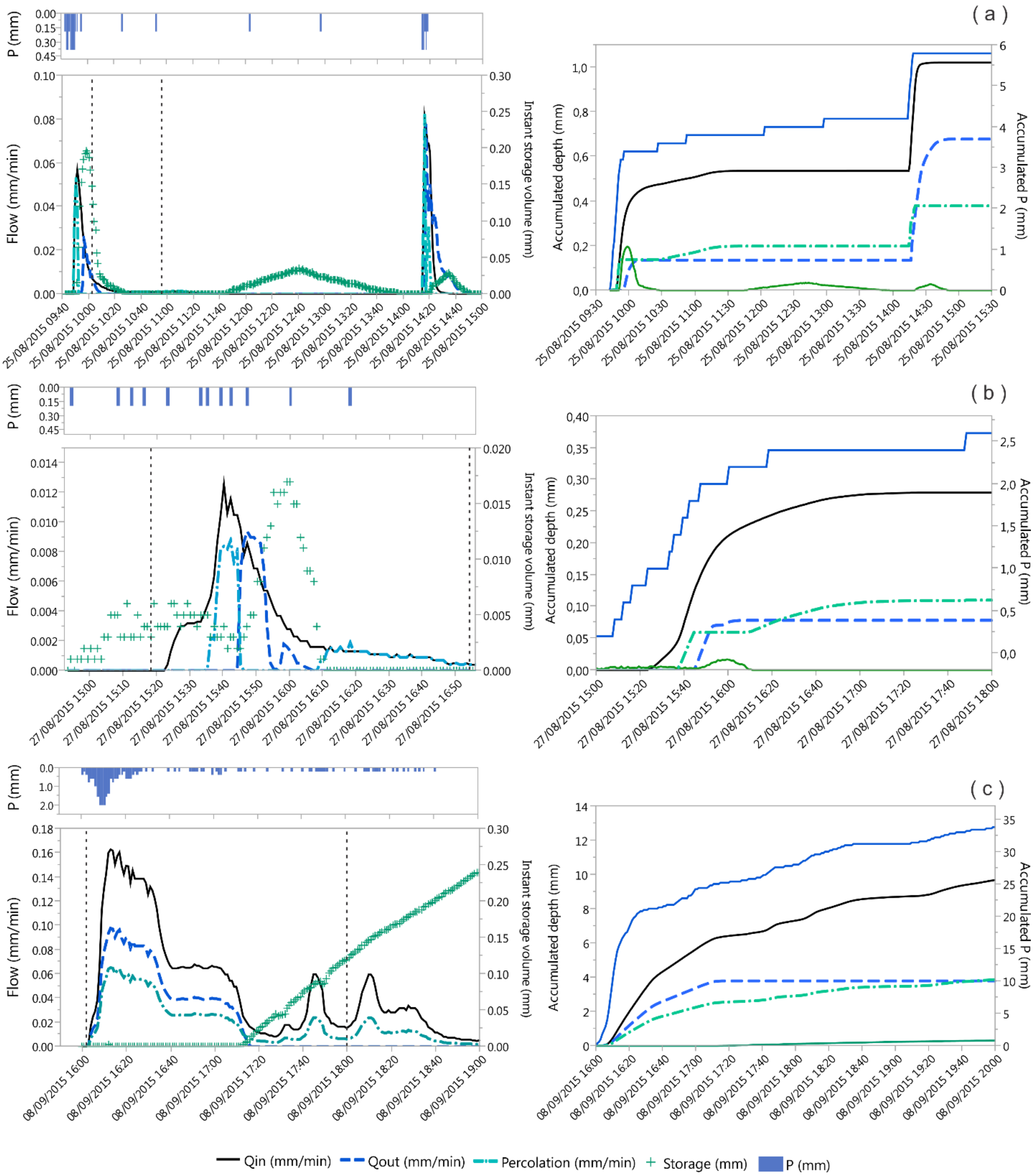

Figure 4.3 - Hydrographs charts containing the input and output, infiltration and instant stored volumes for (a) event 1 (b) event 2 and (c) event 3. The gathering interval for qualitative analysis is shown dashed.

Besides the temporal behavior, it was also obtained the concentrated variable values of water balance, used to calculate the water retention efficiency, or in other words, the practice quantitative efficiency. From these results, shown in Table 4.3, it is possible to observe that in all cases there was a reduction of the total volume being transferred to the receiving waterbody. At last, the LID practice has a percolation rate that remained almost constant for the three events, with an average of 38%. The input and output variables quantification allowed calculating their actual quantitative efficiency. This value was lower for the first event, with only 33% of volume retention, and higher for the third event, which presented 71% efficiency. The average efficiency for the three events was 57%. When compared to the design efficiency (98%), it is clear that this value is lower than planned.

Table 4.3 - Water balance, percolation rates and quantitative efficiency

	Water balance						**Eff**	
	Total precipitation (mm)	**Volume in (mm)**	**Volume out (mm)**	**Volume perc. (mm)**	**Storage peak (mm)**	**Percolation ratio**	**real, quanti**	**quanti (project)**
Event 1	5.80	1.02	0.68	0.38	0.20	37%	33%	
Event 2	2.60	0.28	0.08	0.11	0.03	39%	71%	98%
Event 3	38.00	11.50	3.93	4.60	0.41	40%	66%	

Hatt et al. (2009), Lucke & Nichols (2015) and Winston et al. (2016) found, in their different studies, that bioretention has a high capacity to attenuate peak flows, with reduction values above 80%, reaching 96%. Davis (2008) also noted that, besides peak flow attenuation, there was also a delay in its occurrence, by a factor of two or more. However, the value for the total volume reduction is less pronounced. For Hatt et al. (2009) it has an average of 33%, while for Winston et al. (2016), it has 46%. Comparing these results with those obtained in this study, there is an inversion of the importance and magnitude of the attenuation capabilities of the bioretention basin evaluated. This practice achieved greater retention values for the total volume than the simple peak flow attenuation.

As it is shown in Table 4.2 from the storage temporal behavior and concentrated balance presented, the storage on the bioretention basin was low, unable to reach not even 10% of its total storage capacity. Macedo et al. (submitted), investigated the possible pathologies present in the bioretention construction and operation causing the low storage. These authors observed that the conditions of the region soil (highly weathered, with clayey composition) decreased the surface infiltration capacity into the basin, leading both to the low storage and to structural problems such as erosion and soil loss. This paper also presented measures to mitigate these effects.

4.3.2 Qualitative analysis

In addition to the quantitative aspects, a runoff qualitative analysis was done to evaluate its water treatment capacity before and after the bioretention,

The first analysis was performed to characterize the runoff related to the catchment, which enters the bioretention practice. First, the presence of the first flush phenomenon for the seven pollution parameters analyzed in this study was investigated. This characterization was important for this specific catchment studied because of the characteristics of the pollution particles deposition, the area size, the concentration time and, particularly, the installed drainage system interference in the presence or absence of this phenomenon. Moreover, determining whether most of the pollution is carried from the initial or final runoff fraction contributes to a proper sizing, once it allows identifying the major portion of the volume that must be retained.

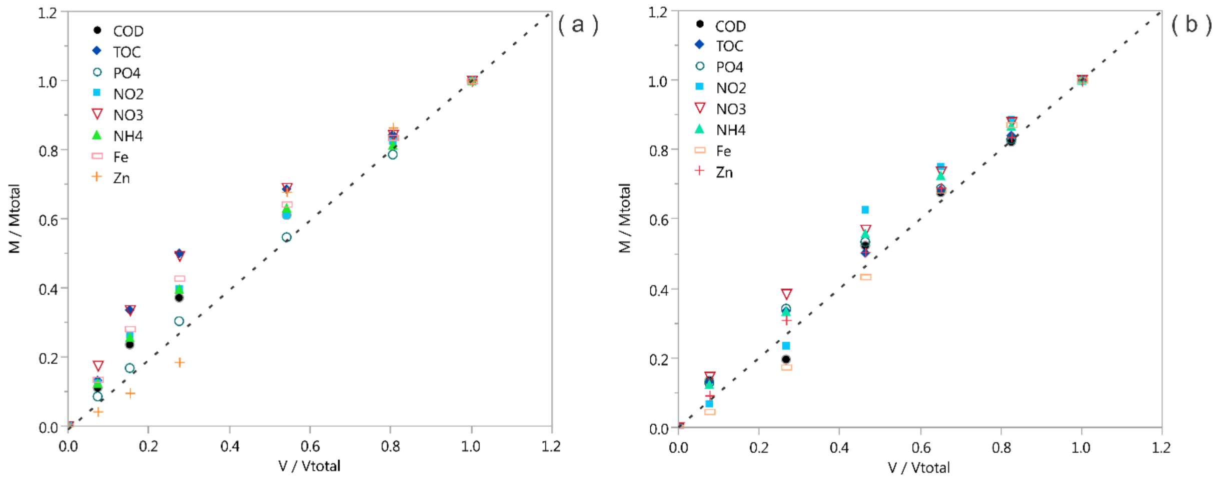

Figure 4.4 - Curves M(V) for first flush analysis, to (a) event 2 and (b) event 3 - The dotted line is the quadrant bisector.

Figure 4 shows the mass X volume graphics (M(V)), and the results of the analysis of the first flush in the events 2 and 3. According to Bertrand-Krajewski et al. (1997), the phenomenon occurs when, at least, 80% of the pollutants are being carried by the first 20% of runoff. Therefore, in the event 2 (Figure 4.4a) only Zn presents values below the bisector, yet, only for the first 40% runoff volume, not making clear the presence or absence of the first flush. As for the other parameters, through a visual analysis, all the curves are above the bisector. However, in the event 3 (Figure 4.4b), this visual analysis is not very clear – the curve M(V) almost coincides with the bisector for most of the pollutants. To confirm numerically the presence or absence of the first flush, the potential equation linearization proposed by Su & Mitchell (2003) was made. Then, evaluating the value of the slope *b*, the phenomenon occurrence can be determined (for First Flush, *b* is between 0 and 1). The results of this analysis are presented in Figure 4.5.

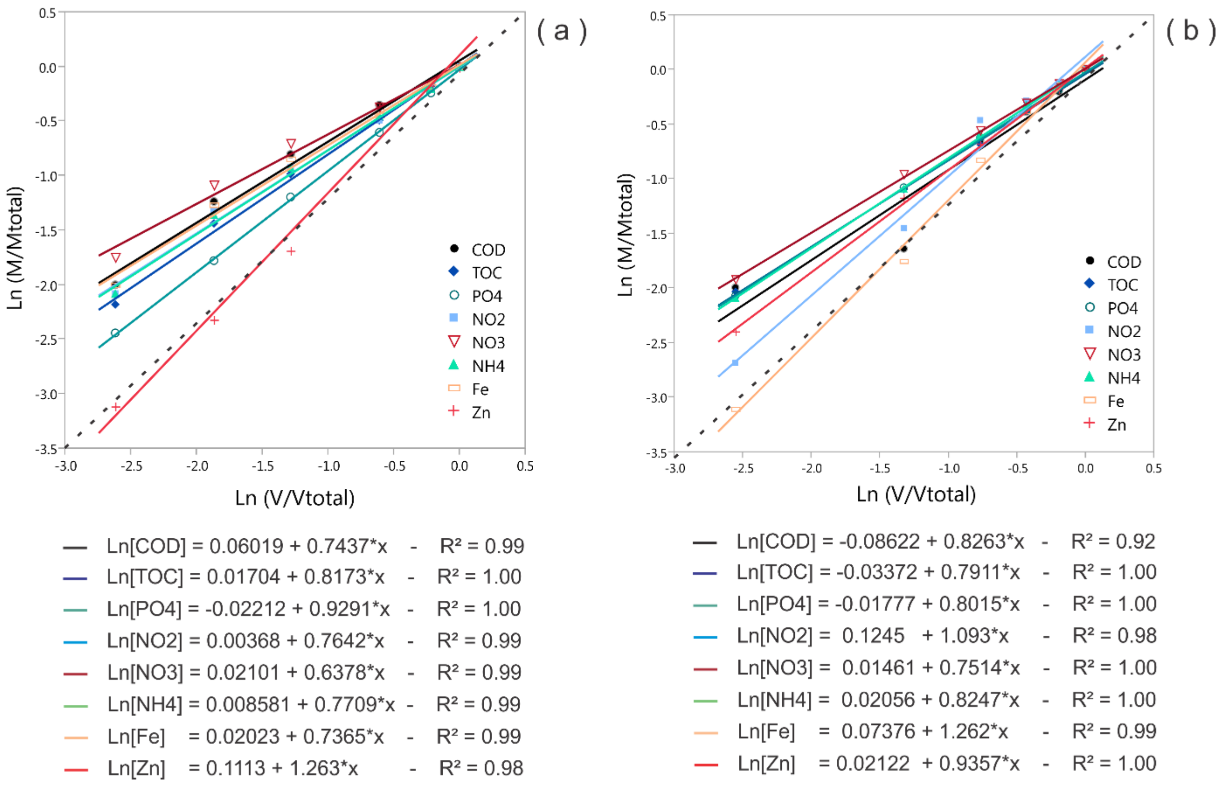

Figure 4.5 - First flush linearization parameters for (a) event 2 e (b) event 3 – The dotted line is the quadrant bisector.

For the second event (Figure 4.5a), only Zn has a slope *b* value above 1, which shows numerically that there is no first flush for this parameter. At last, the PO_4 has a value close to 1, and cannot be stated with precision if there is the occurrence of the phenomenon. For the other parameters, the *b* value ranges from 0.6378 to 0.8173 for NO_3 and TOC respectively. On the other hand, the event 3 (Figure 4.5b) shows a slightly higher *b* variation from 0.82639 to 0.7514, demonstrating a reduction in the phenomenon intensity. In addition, the Fe and NO_2 presented a *b* value higher than 1 and Zn, close to 1, indicating that the phenomenon does not occur for these parameters in this event.

The first visual analysis of the curve M(V) already shows that the phenomenon is more accentuated in the event 2 than for the event 3. This result was expected due to the higher rain volume in event 3 and the antecedent rainfall, resulting in a prewash of the soil and floor. Additionally, the event 2 represents one of the first rains after a long drought period, leading to a higher pollution accumulation in the soil, which tends to be carried by the first runoff volume portions. Visual analysis is numerically confirmed by M(V) linear curve, showing that the first flush phenomenon occurred for both events, with the exception of Zn and PO_4 for the event 2 and Fe and NO_2 to event 3. The event 3 also presented this phenomenon in a less intense way.

Reference studies on this phenomenon, as Bertrand-Krajewski et al. (1997) and Deletic (1998), evaluated urban areas with micro-drainage systems combined or separated, for different pollutants. In both studies, it was found that there is an occurrence of the phenomenon for some pollutants, varying according to the rain intensity, catchment, among others. Chow & Yusop (2014) conducted some studies more focused on tropical climate, with catchment raging for 4 to 31 ha, which were residential, commercial and industrial areas. As a result, they observed strong first flush for organic pollution parameters for all areas. These other studies results are in agreement with those obtained in this paper, where it was possible to observe the first flush for almost all pollutants in a micro-drainage area. As for Chow & Yusop (2014), parameters that represent organic pollution showed a higher intensity, varying only for some metals and nutrients in each event.

After characterizing the runoff, the input and output pollutographs were made for the events 2 and 3 in terms of loads (Figure 4.6 and 4.7). It is possible to assess the temporal behavior of pollution parameters, especially for the pollutants leaving the practice and being transferred to the receiving waterbody.

In event 2 (Figure 4.6) it is noted that the input and output pollutographs follow the hydrograph format for all parameters, and the pollution peak coincides with the peak flow. In addition, the incoming loads are, in all cases, higher than the output loads, demonstrating the bioretention ability to perform qualitative treatment under low precipitation condition. As for the event 3 (Figure 4.7), in which the precipitation was higher and longer, the pollutograph are not as well defined as for the event 2, having an even larger output than input loads to some pollutants, with Fe being the most expressive.

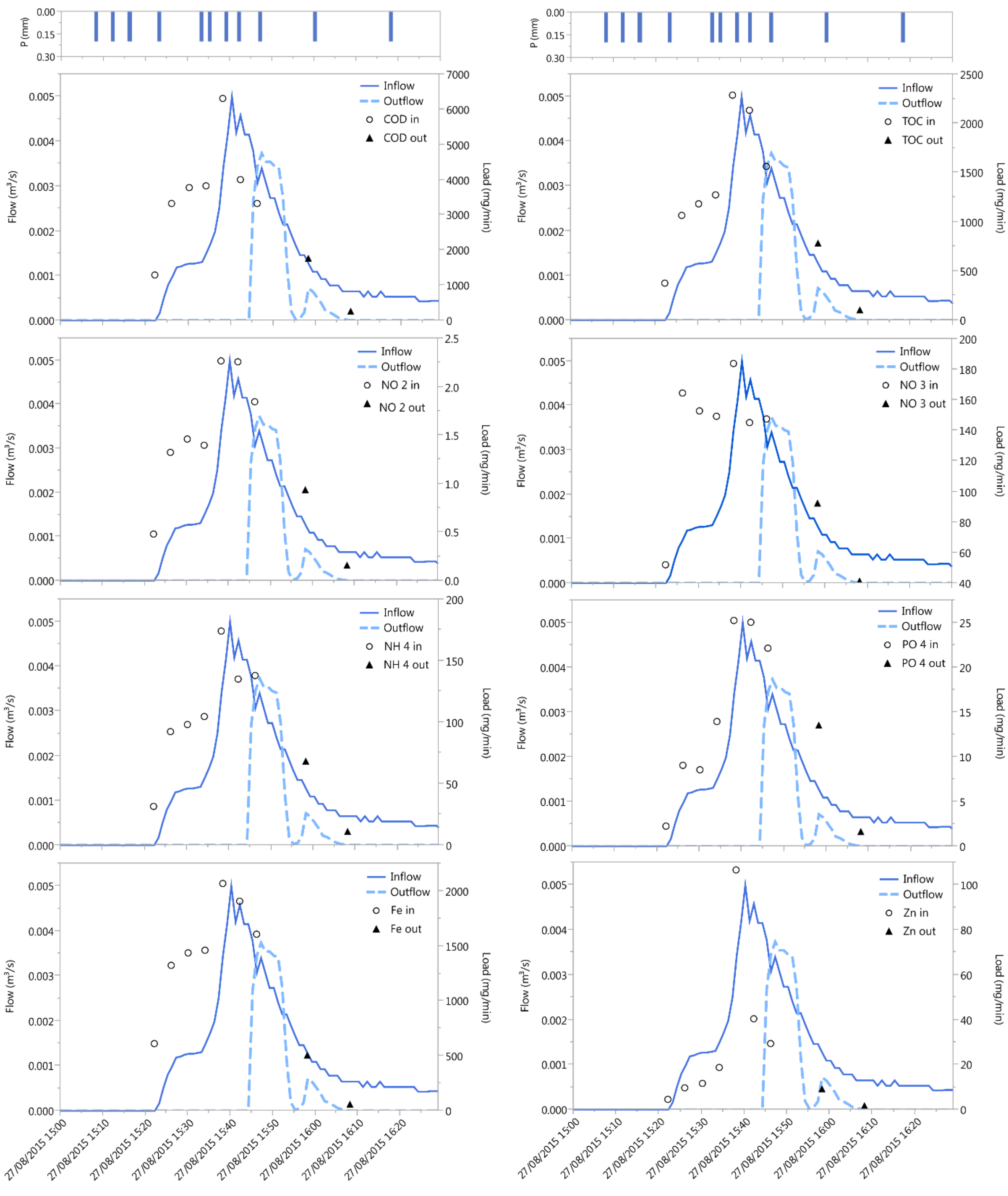

Figure 4.6 - Pollutographs for event 2 - Each frame represents a pollutant analyzed.

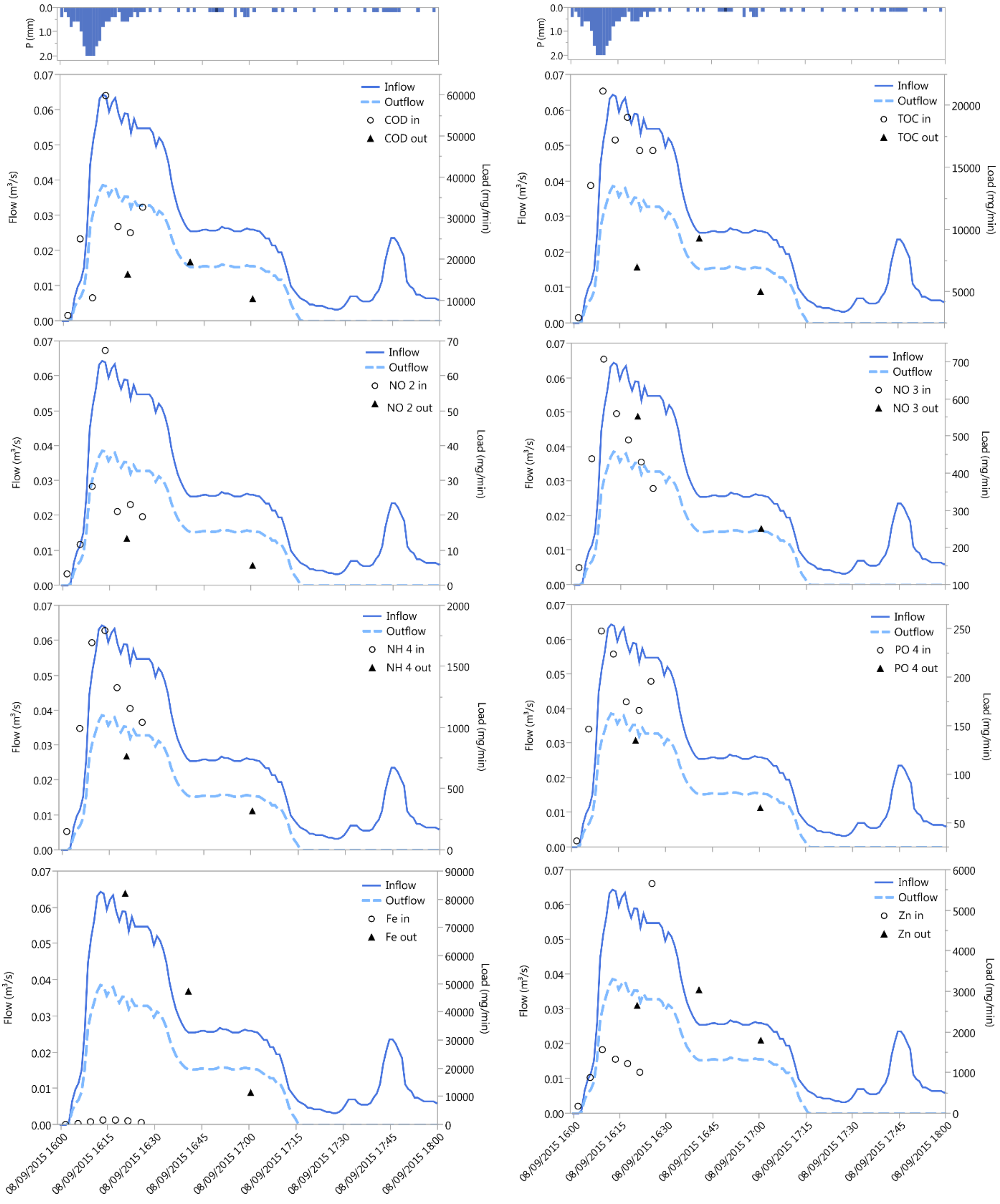

Figure 4.7 - Pollutographs for event 3 – Each frame represents a pollutant analyzed.

Beside the parameters temporal variation, a concentrated mass balance was made in order to calculate the pollutant removal efficiency, also called qualitative efficiency or removal rate. This is singular for each pollutant, on each event. The results are shown in Table 4.4.

Table 4.4 - Mass balance and qualitative efficiency

			COD	**TOC**	**PO_4**	**NO_2**	**NO_3**	**NH_4**	**Fe**	**Zn**
Event 1	EMC (mg/L)	In	37	10.71	0.13	0.009	1.49	1.4	15.54	0.143
		Out	41	10.94	0.13	0.012	10.05	1.79	36.59	0.123
	Load (g)	In	408.89	118.36	1.44	0.10	16.47	15.47	171.73	1.58
		Out	132.15	35.26	0.42	0.04	32.39	5.77	117.93	0.40
	$Eff_{ret\ pollution}$		67.7%	70.2%	70.8%	61.1%	-96.7%	62.7%	31.3%	74.9%
Event 2	EMC (mg/L)	In	26.6	10.17	0.11	0.01	1.02	0.8	10.71	0.23
		Out	17.34	7.46	0.13	0.01	1.14	0.68	4.76	0.09
	Load (g)	In	176.47	67.44	0.72	0.08	6.80	5.28	71.05	1.50
		Out	32.27	13.89	0.24	0.02	2.13	1.27	8.85	0.17
	$Eff_{ret\ pollution}$		81.7%	79.4%	66.9%	76.9%	68.7%	75.9%	87.5%	88.7%
Event 3	EMC (mg/L)	In	9.89	5.59	0.06	0.01	0.16	0.43	0.34	0.09
		Out	11.40	5.26	0.08	0.01	0.33	0.44	1.74	0.09
	Load (g)	In	2698.31	1525.86	16.96	2.49	44.79	116.87	92.57	24.74
		Out	1063.22	490.71	7.68	0.73	30.92	41.47	161.86	8.64
	$Eff_{ret\ pollution}$		60.6%	67.8%	54.7%	70.6%	31.0%	64.5%	-74.8%	65.1%

From the values shown in Table 4.4, the water quality parameters COD and TOC, representing organic contamination, showed the best efficiency for the three events, from 60 to 80%. As for the nutrient contamination (this study investigated the phosphate, nitrite, nitrate and ammonia), the removal efficiencies vary widely within the events – for nitrate the removal ranges from approximately 69% to 31%, when comparing the event 2 and 3, also having a nitrate export over the device for the event 1. Similar behaviors are observed for the phosphate, which has 20% variations in removal efficiency for the three events. As to the metals, Fe and Zn, the efficiencies are generally high. However, in the event 3, there was a significant export of Fe (-74.8%), possibly as a result of soil loss due to erosion, leading to an entrainment of Fe particles out of the practice.

Based on the literature (Table 4.5), the values for nutrients removal rate seems to have a large variation, according to the site. Liu et al. (2014), Bratieres et al. (2008), who developed studies in lab scale, and Hatt et al. (2009), who developed in field scale, found a removal rate between 80 to 98% of phosphorus. Moreover, Luell et al. (2011) found low phosphorus removal in field scale, in order of 3.2%. Dietz (2007) has already stated that soil characteristics have much influence on the efficiency of nutrient removal, ranging from high removal rates to nutrient exportation.

On the other hand, total nitrogen, nitrite and nitrate removal rates found in Hatt et al. (2009) and Luell et al. (2011) are in the range of 7 - 55%. In addition, Manganka et al. (2015) observed that the antecedent dry period has an important role in the treatment, mainly in the evaluation of nitrogen series. They state that long drought contributes to the reduction of nitrite and ammonia on the practice exit while increasing nitrate load, which confirms the occurrence of nitrification within the bioretention basin.

The results obtained for the event 1, which had a drought period of 29 days, show a nitrate export of 96.7% and a nitrite and ammonia removal of approximately 60%. Therefore, it is remarkable the fact that the bioretention practice presented in this paper has an efficiency range observed in other studies, for the parameters representing nutrient contamination.

As for metals, studies with bioretention had been more focused on the analysis of Cu, Pb, and Zn, having little discussion above Fe (Table 4.5). For Zn, the removal rate ranged from 62% (Davis, 2007) to 84% (Hatt et al. 2009), a variation range close to the one obtained in this study (Table 4.4).

Considering the low storage in the bioretention basin, observed for the three analyzed events, and the high runoff speed on its surface, it raises the possibility that pollutant removal rates could be higher since the most part of water treatment occurs inside the bioretention basin.

Table 4.5 - Pollutant removal rates presented in the literature

Author	**Filtration media**	**Removal rate (%)**									
		Cu	**Pb**	**Cd**	**Zn**	**TSS**	**TP**	**PO_4**	**TN**	**NH_4**	**$NO_{2,3}$**
Wang et al. (2016) *	Fine sand			>95							
	Zeolite			>95							
	Sand			>95							
	Quartz sand			>99							
Wang et al. (2015) *	Construction wastes	>90	>90	>90							
Liu et al. (2014) *	Terra Solve						98.8				
	Biofilter						96				
	VT mix						98.2				
Winston et al. (2011) **	ISZ					50.4	3.2		47.6	54.8	75.6
Manganka et al. (2015) *Dry period*						80.78	75.33	73.41	47.93	82.21	64.95
Manganka et al. (2015) *Rainy period*						41.81	36.42	37.81	38.7	49.31	23.24
Brown and Hunt (2012)	ISZ 0.9m					89	19		-274		32
Davis (2007)***		57	83		62	47	79				83
Yu and Stanford (2007)		16			50	85	55				
Hsieh and Davis (2005)*			64 - 98			29 - 96	4 - 99			2 - 49	1 - 43
Hsieh and Davis (2005)			>98			>96	>70			>20	>9
Hatt et al. (2009)		67	80	-	84	76	-		-	64	
Bratieres et al. (2008) *	Soil, sand, gravel with none vegetation					99	81		-204		

*Lab scale, ** Overflow and underdrain, ***EMC rates

4.4 Conclusion

The qualitative and quantitative performance of bioretention cell were analyzed for three precipitation events that occurred after a long drought period. It is concluded, in quantitative aspects, that:

- The main contribution of the bioretention practice was reducing the peak flow transferred to the receiving waterbody, with a wide variation from 10 to 70%, besides contributing to a delay of 10 minutes in the peak flow;
- The quantitative efficiency, done based on the total retained volume, presented a variation from 33% to 66%, and a mean value of 57% and it was lower than expected;
- A low storage volume in bioretention basin was observed, leading to conclude that the device is not operating according to its maximum capacity. Maintenance measures are necessary to recover its performance and new sizing and design methods focus on subtropical climate are need;
- Problems such as highly weathered soils with high clay content, common characteristics of tropical and subtropical regions, are listed as main causes of low infiltration.

In qualitative aspects:

- The first flush is present in the catchment area for all pollutants, with exception of Zn, Fe, and NO_2. For events with larger precipitated volumes, the phenomenon becomes blander.
- The pollutant retention efficiency with the highest value is for pollutants representing organic pollution (COD, TOC) and the lowest for nitrate and iron, even with export in some events. The mean removal efficiency obtained was 67%.

Maintenance measures must be adopted to ensure proper infiltration into the bioretention filtering media and increasing this efficiency. Further research must focus on adapt the current concept used to install bioretention systems, aiming the subtropical and tropical regions.

References

Akan, A. O., & Houghtalen, R. J. (2003). *Urban hydrology, hydraulics, and stormwater quality: engineering applications and computer modeling*. John Wiley & Sons.

Athayde, D. N., Shelley, P. E., Driscol, E. D., Gaboury, D., & Boyd, G. B. (1983). Results of the Nationwide Urban Runoff Program: Final Report. *Washington, DC: US Environmental Protection Agency, Water Planning Division*.

Bertrand-Krajewski, J. L., Chebbo, G., & Saget, A. (1998). Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. *Water Research*, *32*(8), 2341-2356. doi: http://dx.doi.org/10.1016/S0043-1354(97)00420-X

Bratieres, K., Fletcher, T. D., Deletic, A., & Zinger, Y. (2008). Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water research*, *42*(14), 3930-3940. doi: http://dx.doi.org/10.1016/j.watres.2008.06.009

Brown, R. A., & Hunt, W. F. (2012). Improving bioretention/biofiltration performance with restorative maintenance. *Water Science and Technology*,*65*(2), 361-367. doi: 10.2166/wst.2012.860

Chow, M. F., & Yusop, Z. (2014). Sizing first flush pollutant loading of stormwater runoff in tropical urban catchments. *Environmental Earth Sciences*, *72*(10), 4047-4058. doi: 10.1007/s12665-014-3294-6

Davis, A. P. (2007). Field performance of bioretention: Water quality.*Environmental Engineering Science*, *24*(8), 1048-1064. doi:10.1089/ees.2006.0190

Davis, A. P. (2008). Field performance of bioretention: Hydrology impacts.*Journal of Hydrologic Engineering*, *13*(2), 90-95. doi:10.1089/ees.2006.0190

Deletic, A. (1998). The first flush load of urban surface runoff. *Water research*, *32*(8), 2462-2470. doi: http://dx.doi.org/10.1016/S0043-1354(97)00470-3

Dietz, M. E. (2007). Low impact development practices: A review of current research and recommendations for future directions. *Water, air, and soil pollution*, *186*(1-4), 351-363. doi: 10.1007/s11270-007-9484-z

Erickson, A. J., Weiss, P. T., & Gulliver, J. S. (2013). Optimizing stormwater treatment practices. New York, Springer Science & Business Media, 330p.

Fletcher, T. D., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources*, *51*, 261-279. doi: http://dx.doi.org/10.1016/j.advwatres.2012.09.001

Galavoti, R. C.(2011). *Proposta de um modelo de gestão integrada de águas urbanas em escala de lote residencial : alcances e limitações*. Thesis, USP - EESC, São Carlos. (in Portuguese)

Geiger, W. F. (1984). Characteristics of combined sewer runoff. In *Proceeding de la 3ème conférence internationale «Urban Storm Drainage», Göteborg* (pp. 4-8).

Gutierrez, L. A. R. (2011) *Avaliação da qualidade da água de chuva e de um sistema filtro-vala-trincheira de infiltração no tratamento do escoamento superficial direto predial em escala real em São Carlos SP*. Thesis. Universidade Federal de São Carlos. (in Portuguese)..

Hatt, B. E., Deletic, A., & Fletcher, T. D. (2007). Stormwater reuse: designing biofiltration systems for reliable treatment. *Water Science and Technology*, *55*(4), 201-209. doi: 10.2166/wst.2007.110

Hatt, B. E., Fletcher, T. D., & Deletic, A. (2009). Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale.*Journal of Hydrology*, *365*(3), 310-321. doi: http://dx.doi.org/10.1016/j.jhydrol.2008.12.001

Helsel, D. R., Kim, J. I., Grizzard, T. J., Randall, C. W., & Hoehn, R. C. (1979). Land use influences on metals in storm drainage. *Journal (Water Pollution Control Federation)*, 709-717. doi: http://www.jstor.org/stable/25039892

Laurenson, G., Laurenson, S., Bolan, N., Beecham, S., & Clark, I. (2013). Role of Bioretention Systems in the Treatment of Stormwater. *Advances in agronomy*.

Lim, H. S., & Lu, X. X. (2016). Sustainable urban stormwater management in the tropics: An evaluation of Singapore’s ABC Waters Program. Journal of Hydrology, 538, 842-862.

Liu, J., Sample, D. J., Owen, J. S., Li, J., & Evanylo, G. (2014). Assessment of selected bioretention blends for nutrient retention using mesocosm experiments. *Journal of environmental quality*, *43*(5), 1754-1763. doi:10.2134/jeq2014.01.0017

Lucas, A., H.(2011) *Monitoramento e modelagem de um sistema filtro-vala-trincheira de infiltração em escala real*. Thesis Universidade Federal de São Carlos. (in Portuguese).

Lucas, A., H.; Sobrinha, L. A.; Moruzzi, R. B.; Barbassa, A. P. (2015) *Avaliação da construção e operação de técnicas compensatórias de drenagem urbana:* o transporte de finos, a capacidade de infiltração, a taxa de infiltração real do solo e a permeabilidade da manta geotêxtil. Engenharia Sanitaria e Ambiental, p. 17-28 (in Portuguese).

Lucke, T., & Nichols, P. W. (2015). The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation. *Science of the Total Environment*, *536*, 784-792. doi: http://dx.doi.org/10.1016/j.scitotenv.2015.07.142

Luell, S. K., Hunt, W. F., & Winston, R. J. (2011). Evaluation of undersized bioretention stormwater control measures for treatment of highway bridge deck runoff. *Water Science and Technology*, *64*(4), 974-979. doi: 10.2166/wst.2011.736

Macedo, M., B., Rosa, A., Mendiondo, E. M., de Souza, V. C., B. (2015). Otimização da eficiência de técnicas compensatórias de bioretenção em clima subtropical. *XXI Simpósio Brasileiro de Recursos Hídricos*, Brasília (in Portuguese).

Macedo, M. B.; Rosa, A.; Lago, C.; SOUZA, V. C.; Mendiondo, E. M. *Subtropical climate issues for bioretention: learnings from the operation pathologies and maintenance to optimize LID practices*. Journal of Environmental Engineering, (submitted)

Mangangka, I. R., Liu, A., Egodawatta, P., & Goonetilleke, A. (2015). Performance characterisation of a stormwater treatment bioretention basin. *Journal of environmental management*, *150*, 173-178. doi: Performance characterisation of a stormwater treatment bioretention basin

McAuley, A. (2009). *Technical Design Guidelines*. Nothern Territpty Department of Planning and Infrasctructure.

Ohnuma JR, A. A.(2008*). Medidas não convencionais de reservação d'água e controle da poluição hídrica em lotes domiciliares*. Thesis Universidade de São Paulo. (in Portuguese).

Richards, P. J., Farrell, C., Tom, M., Williams, N. S., & Fletcher, T. D. (2015). Vegetable raingardens can produce food and reduce stormwater runoff. *Urban Forestry & Urban Greening*, *14*(3), 646-654. doi: http://dx.doi.org/10.1016/j.ufug.2015.06.007

Rosa, A.; Macedo, M. B., D.; Souza, V. C.; Mendiondo, E. M. (2016). *New insights for sizing stormwater treatment practices using a computational model as applied to a case study design in Sao Carlos, Brazil*. Journal of Hydrology – Special Issue. (submitted)

Santos, R., F. (2007). Vulnerabilidade ambiental: desastres naturais ou fenômenos induzidos? *MMA* (in Portuguese).

Silveira, A. D., & Goldenfum, J. A. (2007). Metodologia generalizada para prédimensionamento de dispositivos de controle pluvial na fonte. *Revista Brasileira de Recursos Hídricos*, *12*(2), 157-168 (in Portuguese). doi: 10.21168/rbrh.v12n2.p157-168

Su, Y., & Mitchell, G. F. (2003). Using first order modeling to describe first flush effects of storm water runoff. *StormCon 2003*.

Wang, J., Zhang, P., Yang, L., & Huang, T. (2015). Adsorption characteristics of construction waste for heavy metals from urban stormwater runoff. *Chinese Journal of Chemical Engineering*, *23*(9), 1542-1550. doi: http://dx.doi.org/10.1016/j.cjche.2015.06.009

Wang, J., Zhang, P., Yang, L., & Huang, T. (2016). Cadmium removal from urban stormwater runoff via bioretention technology and effluent risk assessment for discharge to surface water. *Journal of contaminant hydrology*, *185*, 42-50. doi: http://dx.doi.org/10.1016/j.jconhyd.2016.01.002

Winston, R. J., Dorsey, J. D., & Hunt, W. F. (2016). Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. *Science of the Total Environment*, *553*, 83-95. doi: http://dx.doi.org/10.1016/j.scitotenv.2016.02.081

Young, C. E. F.; Aguiar, C.; Souza, E. (2015). Valorando empestades: custo econômico dos eventos climáticos extremos no Brasil nos anos de 2002 – 2012. *Observatório do clima*. São Paulo. (in Portuguese).

5 EFFICIENCY OF STORMWATER CONTROL PRACTICES AND WATER QUALITY IMPROVEMENT THROUGH CONTROLLED EXPERIMENTS OF BIORETENTION IN LABORATORY AND FIELD SCALE

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Abstract

With the aim to minimize the increasing impacts of soil sealing, the Low Impact Development (LID) practices raise as a technology capable of reducing the runoff and promoting a greater infiltration of the water into the ground. Most of the LID studies involving bioretention are focused on temperate climate regions and laboratory scale, with few covering the field scale, mainly in subtropical and tropical regions. Therefore, this study compares the performance of a bioretention device in laboratory scale (useful volume of $0.46m^3$) and a device applied at real scale (useful volume of $62m^3$) in the city of São Carlos-SP, Brazil, under subtropical condition. In both scales it was used the same application rate, obtaining a water retention efficiency of 100%. The percolation rate in laboratory scale ranged from 32% to 76%, while the percolated percentage in the field was about 95%. For the qualitative analysis, in the laboratory scale, the pollutant removal efficiency was low, comparing to other studies, and vary significantly among the pollutants. Export was observed for NO3 and NH3. On the other hand, in field scale the pollutant removal efficiency was high, ranging from 87% to 100%. Applying the same rainfall intensity in both scales, only the water retention values were similar, demonstrating that the method of inlet volume extrapolation to field scale was not representative for percolation and removal pollutants analyses. Further research is recommended, testing different inlet volume and rainfall intensities, to help in a better comprehension of storage and treatment capacity.

Key-words: Urban drainage; Quantitative efficiency; Pollutant removal; Controlled experiments.

5.1 Introduction

With the rapid growth of cities and the lack of urban and territorial planning, there is an increase in soil sealing and, consequently, an increase in runoff. Soon, the classic urban drainage systems are overloaded, leading many times to urban flooding. The extreme precipitation events are already a major cause of natural disasters in Brazil (SANTOS, 2007; YOUNG et al., 2015), causing floods, landslides, among others. In addition, according to the projections of climate change, this scenario must get even worse (VALVERDE & MARENGO, 2010; MARENGO et al., 2010). Thereby, low impact development (LID) practices emerge as alternative and sustainable urban drainage systems, capable of reducing the runoff at the source, reestablishing the percolation into the ground, reducing socioenvironmental impacts.

Within the concept of LID practices, there are different approaches, ranging from participative planning, environmental education, and devices to reduce runoff (FLETCHER et al., 2012). These devices can be applied in many scales, such as source control, micro and macro drainage (MARSALEK & SCHEREIER, 2009). Examples would be green roofs, infiltration trenches, permeable pavements, wetponds, bioretention cells ERICKSON et al., 2013; BAPTISTA et al., 2005; URBONAS & STAHRE, 1993). In Brazil, recent studies address these devices application, focusing mainly on infiltration trenches and wells (LUCAS, 2011; GUTIERREZ, 2011; LUCAS et al., 2015). However, to increase the knowledge on a greater number of devices and the particularities in subtropical climate regions, this paper outline the operation of a bioretention system. Macedo et al. (submitted a and b) have started studies enumerating and investigating maintenance needs and proper operation of bioretention cells in field scales, under subtropical conditions.

The bioretention system has the quali-quantitative treatment as a dual function, once it retains/detains the runoff while removes pollutant load. According to Erickson et al. (2013) and Laurenson et al. (2013) the qualitative treatment occurs through the physical-chemical process of filtration, sedimentation and sorption, and biological process of microbiological degradation and phytoremediation.

Considerable research efforts have been invested in evaluating the bioretention system performance, prevailing studies in laboratory scale. Wang et al. (2015) and Wang et al. (2016) investigated metals removal (Cd, Cu, Pb), testing different filtering media with experiments conducted in bioretention columns. They found a removal rate above 90%, in the percolation outlet. Rycewicz-Borecki et al. (2017) also evaluated the removal of metals Cu, Pb, and Zn, with experiments in laboratory scale. Their results reported metal removal above 92% and demonstrate accumulation in the macrophytes used to assist the treatment. Nevertheless, the studies conducted in the laboratory are not limited to metals. Chahal et al. (2016), Liu et al. (2014) and Bratieres et al. (2008) are some authors who evaluated the nutrient removal in bioretention system and report removal efficiency ranging from 80 to 99%.

Some studies with field application have also begun to be developed. In their paper, Manganka et al. (2015) have focused on how hydraulic and hydrologic factors affect the pollutant removal in field conditions, under dry and rainy seasons. Petterson et al. (2016) and Lucke & Nichols (2015) have investigated the removal of pathogens, nutrients, and metals. Davis (2007), Hatt et al. (2009), Winston et al. (2011) and Brown & Hunt (2012) found nutrient removal rate varying from 3.2 to 64% - for some studies, there was even nitrogen exportation – and removal rates from 57 to 83% for metals.

Laboratory scale studies have some advantages: the environmental conditions can be controlled to conduct a deeper investigation of the treatment processes; it is possible to test the different factors that take a role in the treatment mechanisms, allowing identify the key-factors. In addition, there is no temporal dependence on the occurrence of storms and a greater amount of analyses can be done in a shorter time. However, what occurs in the laboratory not necessarily will occur in the field. In many times the results cannot be extrapolated without further analyzes. When comparing laboratory and field studies it is possible to observe that lab experiments reported higher pollutant removal than field experiments (around 90% and 60% respectively).

Therefore, it is important to evaluate these systems together, operating under the same conditions in laboratory and field, in order to develop a comparison between these two scales of analysis. Only a few studies address to this comparison, until the moment. One example is Hsieh & Davis (2005) study, which investigate the removal rates in column experiments and in bioretentions operating in the field. Their results demonstrate higher efficiencies for the field systems when analyzing parameters of minerals contamination (Pb and TSS) and higher efficiencies for the columns to parameters that indicate nutrient contamination (TP, NH_4, and $NO_{2,3}$).

Despite the importance of these studies, only a few have addressed the two scales of analysis in an integrated way. Additionally, it should be noted that a great amount of the studies report results from temperate climates, where the climate, environmental and socio-economic conditions differ widely from tropical and subtropical regions. Therefore, the primary objective of this research is to compare two analysis scale (laboratory and field), conducting controlled experiments were conducted in two analysis scale, allowing a comparison. Further, the study provides a better comprehension of bioretention systems performance under subtropical climate.

5.2 Methodology

Two experimental scales – laboratory and field – was studied in order to compare their performance results. The water and pollutant mass balance quantification, the study area characterization and how we determinate the rain intensity to ensure similarity between the two scales are presented in the next sections.

5.2.1 Quali-quantitative data collection

To determine the system performance and efficiency, it is necessary to determine numerically the variables of the water and pollutant mass balance. In this study, the relevant variables to determine the balances was inflow, outflow, stored volume, precipitated volume and percolation flow (as represented in the diagram shown in Figure 5.1). The equation 5.1 and 5.2 (adapted from Erickson et al., 2013) were used to quantify the water balance and mass balance, respectively.

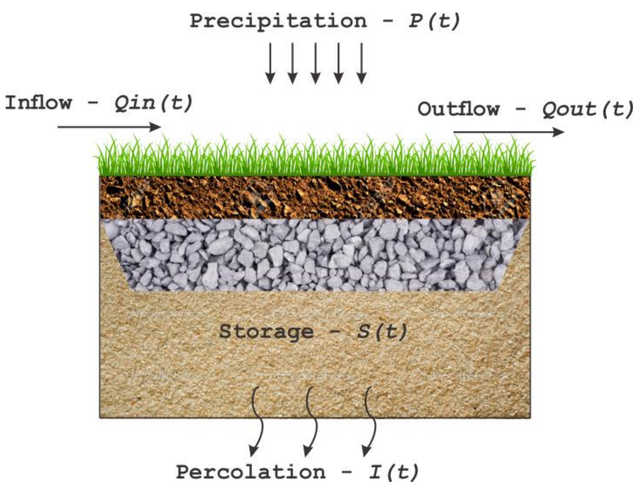

Figure 5.1 – Bioretention diagram representing the laboratory and field scale and the variables of water balance.

$$S(t) = V_{in}(t) - V_{out}(t) = (Q_{in}(t)t + P(t)A_w) - (Q_{out}(t)t + I(t)t) \quad (5.1)$$

$$M_s(t) = (M_{in} + M_P) - (M_{out}(t) + M_I(t)) \quad (5.2)$$

where:

A_w = Catchment surface [m²];

$I(t)$ = Percolated flow into the ground [L/min];

$M_I(t)$ = Infiltrated/treated pollutant mass by the LID practice [g];

$M_{in}(t)$ = Pollutant mass in the inflow runoff [g];

$M_{out}(t)$ = Pollutant mass in the outflow [g];

$M_s(t)$ = Stored pollutant mass, including positive or negative reactions due to internal processes, i.e. sorption, degradation, etc., in the bioretention basin [g];

$M_P(t)$ = Pollutant mass in the precipitation, directly over the bioretention basin [g];

$P(t)$ = Direct precipitation over the bioretention basin [mm]

$Q_{in}(t)$ = Inflow discharge [L/min];

$Q_{out}(t)$ = Outflow discharge [L/min];

$S(t)$ = Storage volume in the bioretention basin [L];

t = Analyzed time interval [min]

$V_{in}(t)$ = Inlet volume [L];

$V_{out}(t)$ = Outlet volume [L].

In the laboratory scale, the collection of quantitative data and qualitative samples was made each 5min, manually for inflow, outflow, and percolation, and automatically to the storage, using the humidity sensor TDR CS616. On the other hand, in the field scale, the collection of quantitative data was made automatically, using level sensor HOBO-WATER U20L-02. For the qualitative sample collection it was used an automatic sampler with a time interval of 5min in the inflow, and for the storage and outflow, the samples were collected manually in a time interval of 10min.

The water quality parameters analyzed was selected to represent organic matter contamination - chemical organic demand (COD) and total organic carbon (TOC) – nutrient contamination - nitrite (NO2), nitrate (NO3), ammonia (NH3) e phosphate (PO4) – solid contamination - sedimentable solids (SS) – and metals contamination - iron (Fe), zinc (Zn) and cadmium (Cd). The analysis follows the methods proposed on the Standard Methods for Examination of Water and Wastewater (APHA et al., 1915). For each variable of the pollutant mass balance, the total load was quantified according to equation 5.3, integrating for the total time of the analyzed hydrographs.

$$Load = \int C(t)Q(t)\,dt = \sum C(t)Q(t)\,\Delta t \qquad (5.3)$$

where:

C(t) = Concentration, at time t [mg/L];

Q(t) = Water flow at time t [L/min];

Δt = Considered time interval [min].

5.2.2 Study area and experimental scales

The two experiments are situated at São Carlos, SP, Brazil, in the University of Sao Paulo campus (USP campus 1 and 2) (Figure 5.2). For each one of the scales, it was delimitated the catchment and, consequently, the contribution area for the diffuse pollution. Table 5.1 presents the specific characteristics for both scales.

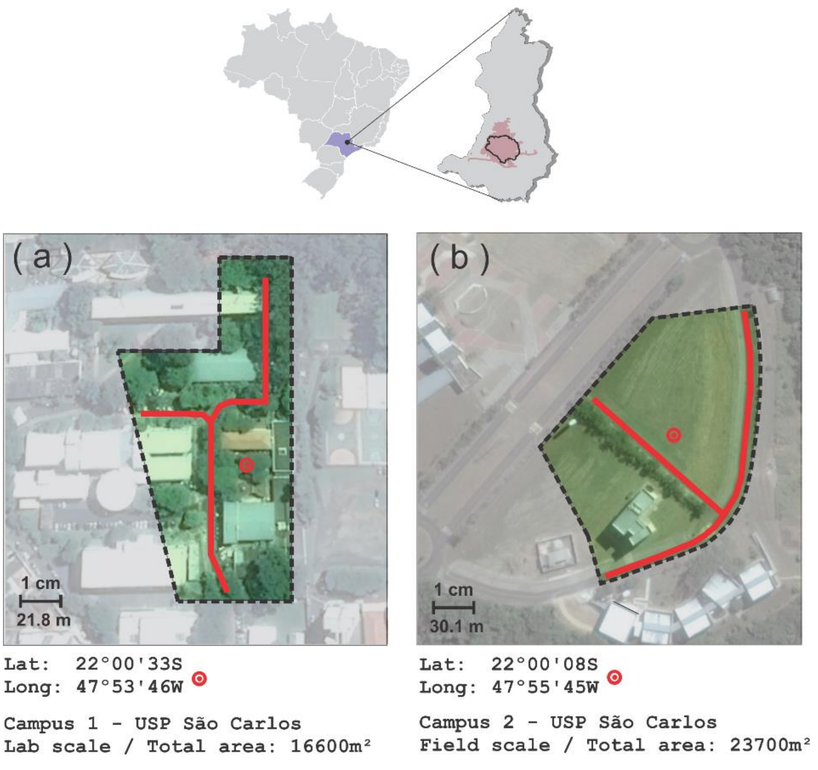

Figure 5.2 – Study areas for laboratory scale (a) and field scale (b). The diffuse pollution was collected in the pathways represented by the red lines.

Table 5.1 – Specifications of the experimental scales analyzed

	H soil (m)	**H gravel (m)**	**H sand (m)**	**$H_{equivalent}$ = Storage/area (m^3/m^2)**	**Water balance variables monitored**
Lab scale	0.2	0.3	0.5	0.32	*Qin(t), Qout(t), I(t)*
Field scale	0.5	0.7	2	1.02	*Qin(t), Qout(t), S(t), P(t)*

Also, in this characterization stage, we defined the parameter *equivalent useful depth* ($H_{equivalent}$), obtained by a ratio of useful storage volume per surface area. Considering its definition, the $H_{equivalent}$ is a parameter that can be applied to any bioretention, of different sizes and scales. From this value, it is possible to compare two or more devices as to their actual treatment zone per unit area. Higher values represent larger zones and, consequently, greater treatment capacity.

For the laboratory scale, a prototype with small dimensions (1m x 1m x 1.45m) was built to better evaluate the key-factors that play an important role in the efficiency of a bioretention practice. In this scale, the $H_{equivalent}$ calculated is 0.32m, as observed in Table 5.1. The laboratory device is composed of three layers, the first of which is a natural soil - predominantly sandy -, serving as a medium for vegetation fixation (garden grass, *Axonopus compressus*), followed by gravel and sand, according to the arrangement shown in Figure 5.1. This filtering media was chosen to achieve the double function of water retention and water qualitative treatment. The diffuse pollution was collected manually along a contribution area of 1.6ha, in USP campus 1 (Figure 5.2a), as proposed by Maglionico (2007). This area is completed urbanized, with a high level of surface paving. The runoff was simulated using a tank-pump-dispenser flow system, operating at constant flow and adjusted to simulate selected rainfall intensity. The water balance variables monitored were: inflow (Q_{in}(t)), outflow (Q_{out}(t)) and percolation I(t).

As for the field scale, the bioretention device is applied in USP campus 2. In this scale, the device receives runoff of a catchment with a total area of 2.3 ha, then considered a micro drainage scale (Figure 5.2b). The area is still characterized in the most part as crawling vegetation, having only a few pathways. Therefore, the main contributions to the runoff are the automobile and pedestrian ways and the waterproof area relative to the laboratory building. The bioretention device has a surface area of 60.63m² and 3.2m depth (Table 5.1). From the ratio of useful volume and surface area, a $H_{equivalent}$ of 1.02m was determined. This device has the same filtering media composition as the laboratory scale (gravel follow by sand, as shown in Figure 5.1) covered by local natural soil, with sandy-loamy feature. The superficial layer was vegetated with *Brachiaria sp*., selected to maintain the landscape integration and to soil stabilization. In this scale, the water balance variables monitored were: precipitation (P(t), inflow (Q_{in}(t)), outflow (Q_{out}(t)) and storage (S(t)).

5.2.3 Comparing the scales of analysis

Comparing the two experimental scales requires establishing an equivalence relation between them. Therefore, a unique value of rainfall intensity was determined for both scales, in order to accomplish the relations expressed in Figure 5.3. This value was calculated by averaging the rainfall intensities used in laboratory scale, according to equation 5.4.

$$I_{med\ lab} = \frac{\sum_{i=1}^{n} V_{i,total}/(A_{lab} x\ t_i)}{n} \tag{5.4}$$

where:

$I_{med\ lab}$ = Mean rainfall intesity [mm/h];

A_{lab} = Bioretention surfasse area in laboratory [m²];

n = Total number of campaigns;

$V_{i,total}$ = Total inlet volume, considering campaign *i* [L];

t_i = Duration of campaign *i* [h];

$\mathbf{V_{lab}(t)}$ [L] ≡ $\mathbf{P(t)}$ [mm] $\mathbf{V_{field}(t)}$ [L] ≡ $\mathbf{P(t)}$ [mm] + $\mathbf{Q(t)}$ [L]

$V_{lab}(t)$, t_{lab} $V_{field}(t)$, t_{field}

$\mathbf{I_{lab}}$ [mm] = $\mathbf{V_{lab}(t)}$ [L] /($\mathbf{A_{lab}}$ [m²] x $\mathbf{t_{lab}}$ [min])

$\mathbf{I_{field}}$ [mm] = $\mathbf{V_{field}(t)}$ [L] /($\mathbf{A_{field}}$ [m²] x $\mathbf{t_{field}}$ [min])

$\mathbf{I_{lab} = I_{field}}$

Figure 5.3 – Representative scheme of the equivalence relation between the laboratory and field scale. For laboratory scale, the control volume only amounts to directly incident precipitation over the device, which is simulated in the experiments. For the field scale the control volume simulates the precipitation and inflow, in a conjugated way.

The total duration and mean inflow necessary to obtain the same rainfall intensity in field scale was calculated according to the equation 5.5 and 5.6, adopting the $I_{med\ lab}$ value previously determined and with a control volume limited by the maximum capacity of the water tank truck.

$$t_{field} = \frac{V_{control}}{A_{field}\ x\ I_{med\ lab}} \tag{5.5}$$

$$Q_{med\ field} = \frac{V_{control}}{60\ x\ t_{field}} \tag{5.6}$$

where:

$Q_{med\ field}$ = Mean inflow, in field [L/min];

A_{field} = Bioretention surfasse area in field [m^2];

$V_{control}$ = Control volume, equivalente with total inlet volume [L];

t_{field} = Duration of the event in field [h];

5.2.4 Campaigns

For the laboratory scale, six campaigns were made to evaluate the bioretention quali-quantitative efficiency. The inflow ranged from 691 L/h to 2667 L/h (equivalent to an I_{lab} of 475 mm/h to 1839 mm/h), as presented in Table 5.2. For the first four campaigns, only the water balance variables were monitored, having sample collection to qualitative analysis only for the campaigns 5 and 6. The samples were collected manually, in the weir outlet (outflow) and percolation. The total number of samples collected per campaigns is specified in Table 5.2.

Different conditions of initial humidity in the filtering media were also tested, varying the time interval between the campaigns from one day to two months (Table 5.2). During the experiments, the room temperature was 25ºC.

Table 5.2 – Summary of campaigns in laboratory scale

	Dry time between campaigns	Q in med (L/h)	Duration (min)	Qualitative Nro. samples
Campaign 1	-	1016	30	-
Campaign 2	2 months	2667	12	-
Campaign 3	8 days	1469	18	-
Campaign 4	1 day	691	27	-
Campaign 5	7 days	1702	14	10
Campaign 6	1 month	962	27	10

For the field scale study, the inflow was simulated in order to correspond with the $I_{med\ lab}$, previously determined. Then, a controlled event was conducted using a water tank truck serving as a reservoir. The total control volume was 10.12m³, corresponding to a water depth of 0.43mm and a mean inflow of 31578m³/h, or 520mm/h.

To analyze the qualitative parameters in this scale, it was collected a total of nine samples, with six collected in the inlet, representing the $M_{in}(t)$, and three collected inside the storage, representing the $M_S(t)$. As the inflow simulation is done with a control volume relative to P(t) and Qin(t) in a conjugate way, the incoming water quality represents the diffuse pollution found in the runoff and in the directly incident rainfall, even if this last one has a small contribution. In this system, the percolation into the ground is not collected, and consequently, it is not quantified.

5.3 Results and discussion

5.3.1 Laboratory scale

Table 5.3 shows the water balance results to the bioretention in laboratory scale. Except to the campaign 2, the rainfall intensity and the total volume applied was not enough to saturate completely the filtering media and generate outflow in the weir. Only for campaign 2, there was a small outflow, not representing neither 1% of the total inlet volume. Therefore, considering all the surveys, the mean water retention efficiency was 99.9% ± 0.2.

It was also found high percolation rates, generally higher than 60%, achieving values of 73.7%. However, for the campaign 1 and 6, this rate was less significant, achieving only 31.2% and 39.8%, respectively. These two lower values occurred for the campaigns that toke place after a long dry period (≥ 1 month), so that the filtering media was completely dry and, therefore, with a higher retention capability. As for the campaign 2, even if it also occurred after a long dry period (2 months), the mean inflow (Table 5.2) and total inlet volume (Table 5.3) were the greatest of all campaigns, leading even to outflow. Then, it is possible that the filtering media has saturated more quickly, promoting the percolation.

Table 5.3 – Concentrated water balance, percolation rate and water retention efficiency for laboratory-scale campaigns

	Total volume (L) / Equivalent depth(mm)				Percolation rate (%)	Eff ret hid. (%)
	In	**Out**	**Percolated**	**Storage**		
Campaign 1	508.22 / 350,5	0 / 0	163.00 / 112,4	345.22 / 238,1	32,1	100,0
Campaign 2	533.33 / 367,8	2 / 1,38	357.02 / 246,2	176.31 / 121,6	66,9	99,6
Campaign 3	421.91 / 291,0	0 / 0	303.20 / 209,1	118.71 / 81,9	71,9	100,0
Campaign 4	310.74 / 214,3	0 / 0	229.10 / 158,0	81.64 / 56,3	73,7	100,0
Campaign 5	397.05 / 273,8	0 / 0	257.40 / 177,5	139.65 / 96,3	64,8	100,0
Campaign 6	435.73 / 300,5	0 / 0	173.48 / 119,6	262.25 / 180,9	39,8	100,0
				Media	58,2	99,9
				Standard Deviation	17.7	0.2

To complement the water balance analysis, Figure 5.4 shows the variation in time for each of the variables, in all campaigns. Considering the bioretention dimensions and a filtering media porosity of 37%, the total useful volume of storage is around 500 L. However, the highest peak was found to the campaign 2, with a value close to 400 L, which means that in any of the experiments the storage peak achieved its maximum. Nevertheless, the percolation hydrographs present considerable peaks (25 L/min) and mean percolation rates for all the experiments. This result indicates that the water retention capability of the system is affected not only by the useful volume but also by the hydraulic conductivity of the ground. Therefore, to calculate the system's amortization capacity these two factors must be considered in the projects.

Still for campaign 2, for the Figure 5.4, we can observe an outflow even if the inlet volume did not reach the maximum storage capacity. This can occur because the inflow exceeds the infiltration velocity into the bioretetion cell, leading to a runoff in the technique itself.

The percolation hydrographs and the temporal variation of storage (Figure 5.4) indicates a similar behavior between then, with the percolation peak occurring right after the storage peak. From these results, it is also observed that the filtering media maintains the water storage even after the most significant percolation has ceased, remaining almost constant after 120 min. The ensemble of results shows that the bioretention can help reestablishing the water balance prior urbanization (increasing water percolation rates into the ground).

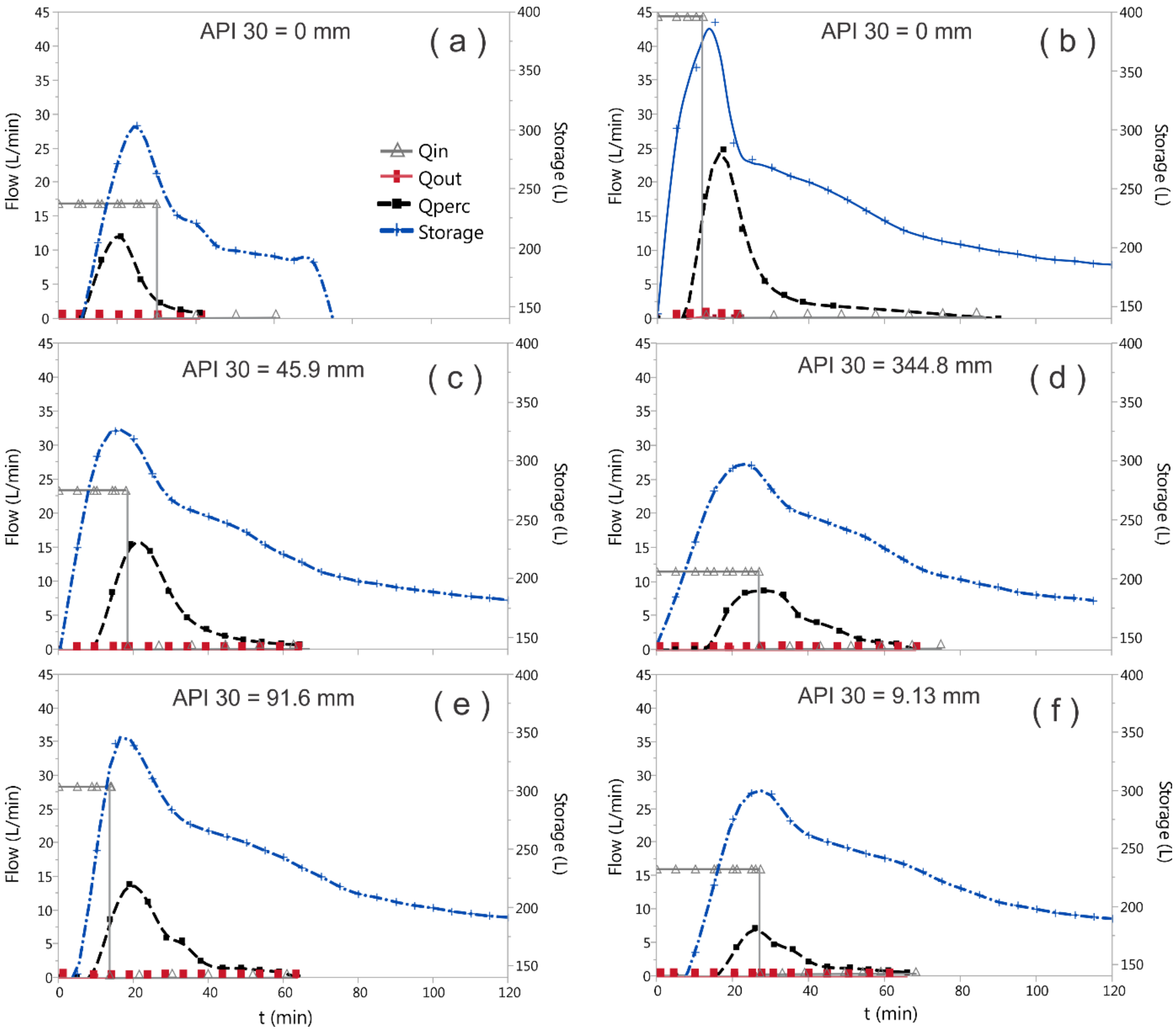

Figure 5.4 –Temporal behavior of the variables inflow, outflow, storage and percolation, in the laboratory scale experiment, for: (a) campaign 1; (b) campaign 2; (c) campaign 3; (d) campaign 4; (e) campaign 5 and (f) campaign 6.

To better evaluating the water storage process, Figure 5.5 was elaborated with the storage areas divided between the soil and sand layer, where the humidity sensors were installed. The soil layer responds more quickly (storage peaks slightly before the sand layer) since it is the first contact of the incoming flow. The sand layer, however, has a greater storage capacity in total volume and with a longer retention time.

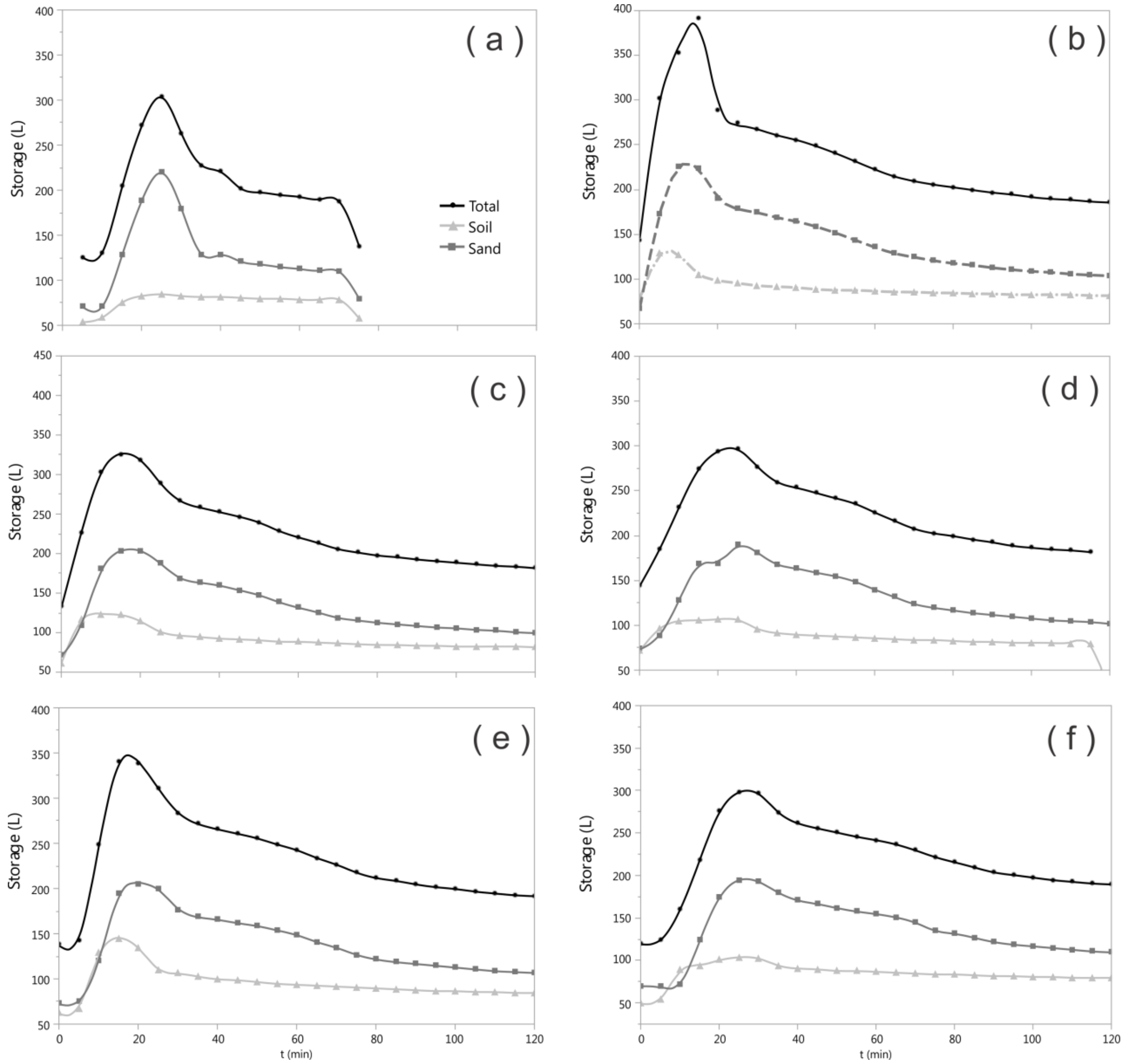

Figure 5.5 – Storage capacity by layers of the bioretention for: (a) campaign 1; (b) campaign 2; (c) campaign 3; (d) campaign 4; (e) campaign 5 and (f) campaign 6.

For the campaigns 5 and 6, in addition to the water balance analysis of the system, samples were collected to analyze the water quality, raising the system mass balance and the efficiency in the removal of pollutants, for the percolation (Table 5.4).

The campaign 5 show lower efficiency in removing TOC and higher efficiency to SS, follow by Zn. Regarding all pollutants, it is possible to observe an average range of removal efficiency, varying from 20% to almost 50%. This range is low when comparing to others studies that also evaluate laboratory performance and obtained removal rates in order of 90% (RYCEWICZ-BORECKI et al., 2017; CHAHAL et al., 2016; WANG et al., 2016; WANG et al., 2015; LIU et al., 2014 e BRATIERES et al., 2008). Finally, exportation of pollutants was found to NO3, Fe, and Cd. Fe exportation probably occurred due to the local soils characteristics, which belong to the oxisols group (characterized by high Fe content). The pollutograph of each pollutant is shown in Figure 5.6.

Table 5.4 – Mass balance and pollutant removal efficiency for laboratory scale

			COD	TOC	PO_4	NO_2	NO_3	NH_3	SS	Fe	Zn	Pb	Cu	Cd
Campaign 5	Load (g)	$M_{in}(t)$	8,537	3,925	0,23	0,004	0,147	0,079	0,199	2,342	0,044	0,036	0	0,002
		$M_I(t)$	4,647	3,558	0,185	0,002	0,618	0,06	0,004	5,465	0,023	0,02	0	0,002
		$M_{out}(t)$	0	0	0	0	0	0	0	0	0	0	0	0
	EMC (mg/L)	$M_{in}(t)$	21,5	9.88	0.58	0,009	0.37	0.2	0.5	5.89	0.11	0.09	0	0.0045
		$M_I(t)$	18.08	13.84	0.71	0.007	2.40	0.23	0.016	21.26	0.08	0.079	0	0.008
		$M_{out}(t)$	0	0	0	0	0	0	0	0	0	0	0	0
	Eff $_{\text{pollution retention}}$ (%)		45,6	9,4	19,8	44,5	-320,6	24,8	97,8	-133,3	47,7	42,9	-	-26,6
Campaign 6	Load	$M_{in}(t)$	1,09	5,28	0,42	0	0,27	0,01	0,62	4,26	0,14	0,04	0	0,01
		$M_I(t)$	2,56	2,84	0,08	0	0,77	0,07	0,01	1,51	0,02	0	0	0
		$M_{out}(t)$	0	0	0	0	0	0	0	0	0	0	0	0
	EMC (mg/L)	$M_{in}(t)$	2.5	6.854	0.545	0.005	0.355	0.015	0.8	5.53	0.185	0.055	0	0.015
		$M_I(t)$	64.08	50.15	1.58	0.02	14.76	1.42	1.53	29.42	0.425	0.03	0	0.003
		$M_{out}(t)$	0	0	0	0	0	0	0	0	0	0	0	0
	Eff $_{\text{pollution retention}}$ (%)		-135,1	46,3	81,6	73,5	-180,5	-543,2	97,9	64,5	83,4	97,6	-	98,2
Media (%)			-45	28	51	59	-251	-259	98	-34	66	70	-	36
SD (%)			128	26	44	20	99	402	0	140	25	39	-	88

When analyzing the results for campaign 6, the lowest removal efficiency was also for TOC, with 46.3%. However, this value is about 5x greater than for Campaign 5. Similar behavior occurs for the other pollutants, except for those that we observe exportation. Despite the increase in removal efficiency when compared to campaign 5, when compared to the others laboratory scale studies - already cited - the value of nutrient removal is still low, not exceeding 82%. For metals, the efficiency reaches values of 98.2%, close to the results observed in other studies. The pollutograph of each pollutant is shown in Figure 5.7.

Still regarding the campaign 6, exportation was found to the parameters COD, NO_3, and NH_3. Manganka et al. (2015) have better analyzed the nitrogen series. They observe that the previously dry period have a primordial role in treatment, especially for the nitrogen compounds. Long periods of drought contribute to reducing nitrite and ammonia at the device outlet, while increase the nitrate load, confirming the occurrence of the nitrification process inside the bioretention. This behavior is partially noted in the campaign 6, which occurred after 1 month of drought. Table 5.4 shows an increase in nitrite removal, while the amount of nitrate in the outlet (exportation) also increases, what may be explained by the nitrification process. However, there was also an increase in the amount of ammonia in the outlet.

For the other pollutants, the difference between the results obtained from the two campaigns can also be explained by the different dry periods prior to the experiment. The campaign 5 toke place after 7 days of drought, while for the campaign 6 this period was of one month. Therefore, it may have occurred a pollutant storage with no degradation in the small period between campaign 4 and 5, which were then washed away by the percolation during campaign 5. Due to the greater drought time, this did not happen for the campaign 6, justifying the greater removal efficiencies.

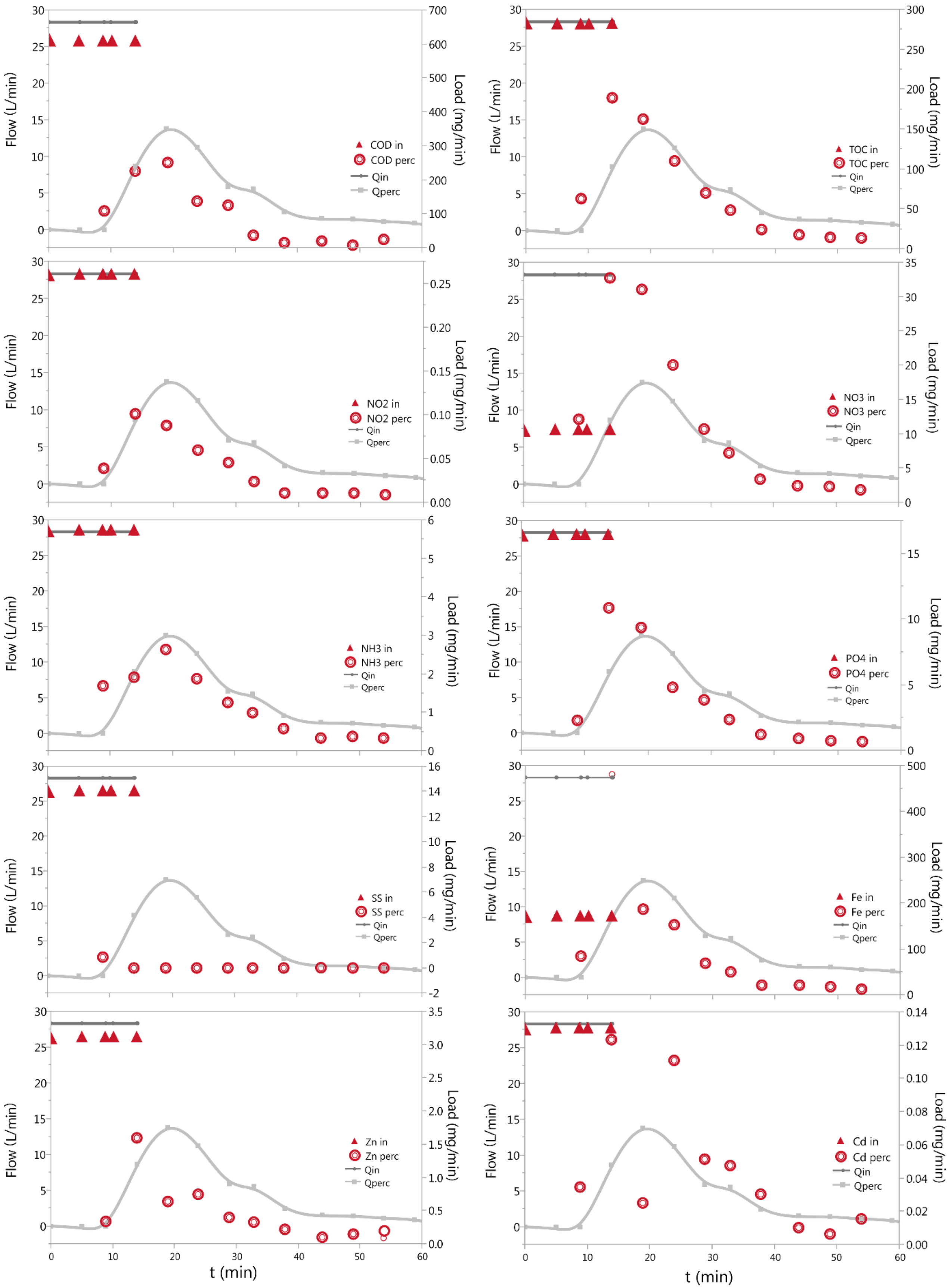

Figure 5.6 – Instant mass balance (pollutographs and hydrographs) for campaign 5.

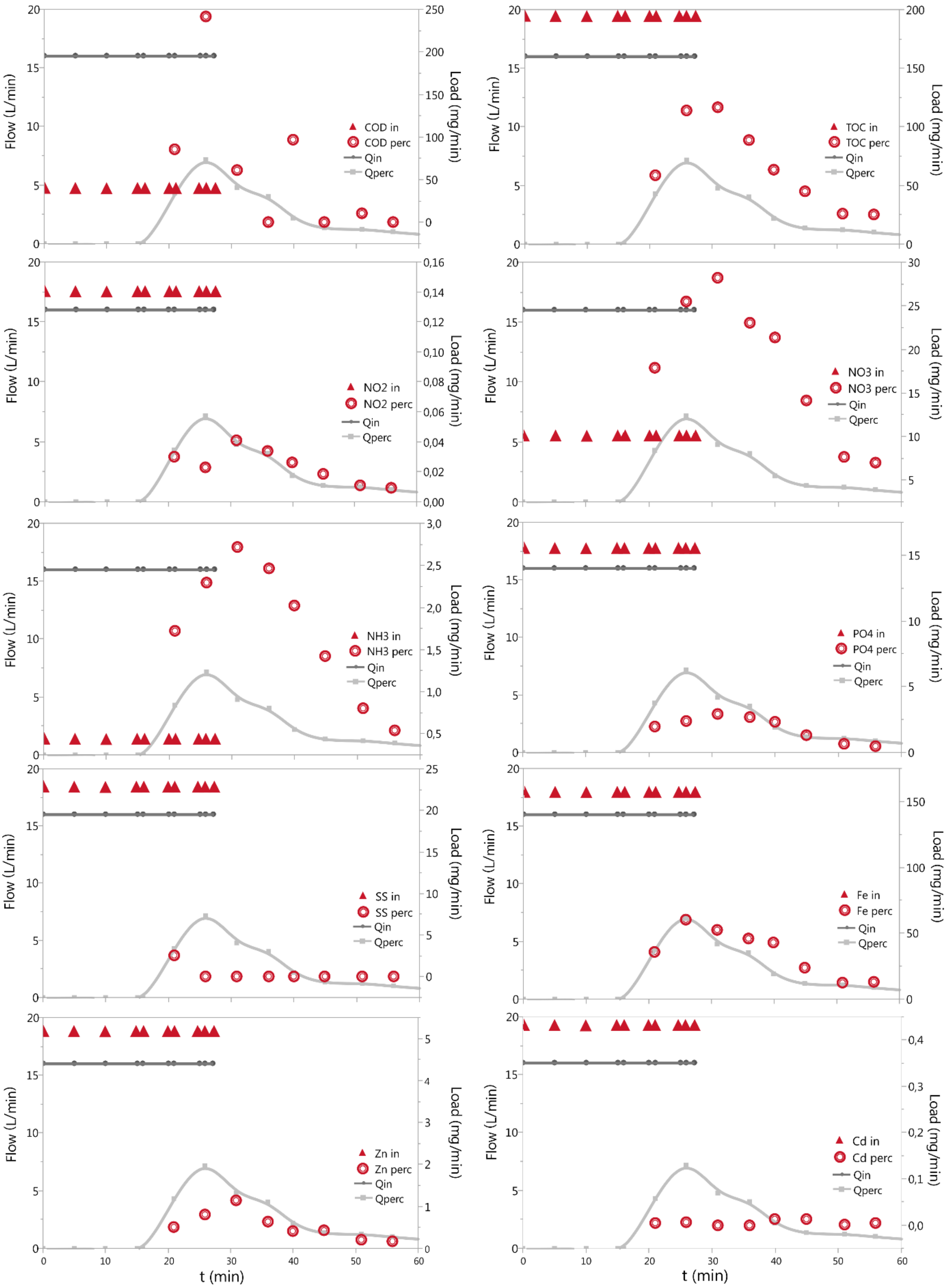

Figure 5.7 – Instant mass balance (pollutographs and hydrographs) for campaign 6.

5.3.2 Field scale

The Table 5.5 and Figure 5.8 present the water balance results for the bioretention application in field scale. The results demonstrate that there was no outflow, representing a water retention efficiency of 100%.

Since the bioretention device in the field has known dimensions, with a surface area of 60.63 m^2, total depth of 3.2 m and average porosity of 37%, the storage capacity totalizes a volume of 62 m^3. Considering the control volume used in the experiment (only 16% of the total useful volume), the storage data shows a negligible volume, not reaching even 0.12% of the total capacity. On the basis of this result, the great part of the inlet volume appears to percolates into the ground (percolation rate of 95.3%), with almost the same speed and flow. Figure 5.8 shows this behavior clearly since the curves Q_{in} and Q_{perc} overlaps almost entirely.

However, the storage data were collected by level sensors inside visit pipes distributed all along the bioretention basin, dividing it into four equal parts. This form of data collection considers as volume stored only the net level within the bioretention basin. Nonetheless, for low inlet volumes, as in this case, a part of the volume is possibly stored as moisture in the sand layer, which does not generate a net level. Based on this observation, we raise the hypothesis that the first portion of the bioretention basin retains almost all of this volume, failing to reach the first visit pipe.

Moreover, the expected behavior for the storage was a smooth and increasing curve while there was an increment of water in the device, reaching a peak when there was no further increase (as occurred for the laboratory scale). Contrarily, Figure 5.8 shows a storage behavior with great peak variations in few minutes. This erratic behavior throughout the experiment is probably due to the representative time scale of each sampled value, which has an intrinsic measurement error.

Table 5.5 – Concentrated water balance, percolation rate and water retention efficiency for field-scale event.

	Total volume (L) / Equivalent depth(mm)				**Percolation rate (%)**	**Eff ret hid. (%)**
	In	**Out**	**Percolated**	**Storage**		
Controlled event	10.1 / 0,4	0 / 0	9.6 / 0,4	0.08 / 0,0035	95,3	100,0

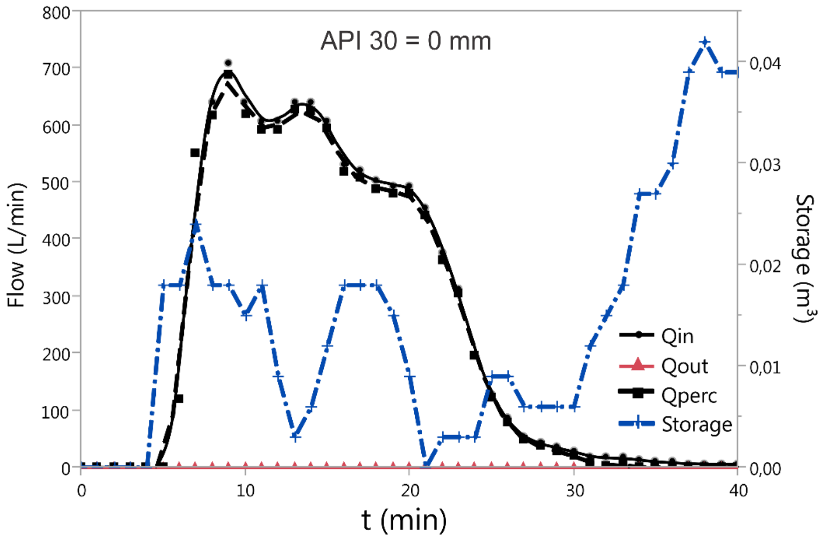

Figure 5.8 – Temporal behavior of the variables inflow, outflow, storage, and percolation, in field scale event.

The study in the field also assessed the evaluation of pollutant retention efficiency. Water quality samples were collected and analyzed for the inlet ($M_{in}(t)$), which represents the pollution in runoff, and for the storage ($M_S(t)$). There was no outflow during the experiment and, consequently, samples of $M_{out}(t)$ were not collected.

Table 5.6 – Mass balance and pollutant removal efficiency for field scale. These are the results for the controlled event with $I_{med\ lab}$ of 520 mm/h, six samples for $M_{in}(t)$ and three for $M_S(t)$.

		DQO	COT	PO_4	NO_2	NO_3	NH_3	SS	Fe	Zn	Pb	Cu	Cd
$M_{in}(t)$	Load (g)	321.12	133.56	3.14	0.055	10.12	2.93	5.03	125.91	1.42	0	0	0.114
	EMC (mg/L)	32.02	13.32	0.31	0.005	1.009	0.29	0.50	12.55	0.14	0	0	0.011
$M_S(t)$	Load (g)	2.46	3.67	0.13	0.003	0.953	0.24	0	1.71	0.04	0	0	0.014
	EMC (mg/L)	4	5.96	0.21	0.005	1.54	0.39	0	2.77	0.07	0	0	0.024
$M_{out}(t)$	Load (g)	0	0	0	0	0	0	0	0	0	0	0	0
	EMC (mg/L)	0	0	0	0	0	0	0	0	0	0	0	0
$Eff_{ret\ pollution}$		99%	97%	96%	94%	91%	92%	100%	99%	97%	-	-	87%

Table 5.6 presents a summary of the pollutant mass balance results, including pollutant removal efficiency for the stored water. Despite the higher concentration values for the pollutants in the storage, the total load was low due to the low stored volume. Therefore, we found good results in the removal efficiency, with the lowest value of 87% for Cd. When regarding the stored water ($M_S(t)$), most of the treatment process have already occurred, such as absorption by plant tissues, soil sorption, filtration through the sand and gravel layers and degradation. Therefore, it is common the removal of some pollutants at this stage. In addition, the water stored over time will percolate with equal quality or better. However, there was no data monitored for $M_I(t)$.

5.3.3 Comparing the scales of analysis

Comparing the two scales of analysis, the results indicate that the $I_{med\ lab}$ selected for the experiments were inferior to infiltration rate and insufficient to saturate completely the filtering media, leading to no outflow. Although the laboratory scale did not reach fully the storage capability, the storage achieved values around 80%. On the other hand, for the field scale, the results indicate negligible storage and total volume percolated achieving almost same values that the inlet volume. However, it is raised the hypothesis that the water is stored as sand moisture, not generating water level, yet retaining volume. Therefore, to evaluate better the water dynamic in bioretention applied in field new experiments with a larger control volume and different rainfall intensities are required.

For the percolation rate, the laboratory scale has lower values when compared to the field scale (58.2% vs 95.3%). The different application rate (ratio between the inlet volume and total storage capacity) for each scale may explain this result. The application rates range from 62.1% to 106.6% for laboratory scale, and it has a value of 16.3% for field scale, as shown in Table 5.7. Finally, the both cases underline the competence of a bioretention practice in reestablishing the water balance prior urbanization.

Table 5.7 - Comparison between the inlet volumes, useful volumes and application rate in the laboratory and field scales.

Scale	**Useful volume (m^3)**	**Inlet volume (m^3)**	**Application rate (in % of useful volume)**	**Eff quanti med (%)**	**Eff quali med (%)**
Laboratory	0.5	0.31 - 0.53	62.1 - 106.6	99.9	-17.0
Field	62.0	10.12	16.3	100.0	95.1

Regarding the qualitative aspects of the runoff, before and after treatment, the sampling points in the two scales were different. For the laboratory scale, the samples were collected in the percolation outlet, while for the field scale the samples were collected on the visit pipes. Although this difference in sampling, both scales can be compared for treatment efficiency, since the stored water will percolate at some point, with an equal or high quality.

Higher removal rates were found to the device in the field, indicating better treatment than the laboratory scale. However, in the literature review, the studies found lower rates of pollutant removal in real-scale applications. The application rate and $H_{equivalent}$ explain the difference in the results found in this paper and in literature. Although the Imed lab was the same for the two scales to ensure hydrological similarity, the application rate for field scale was at least 3x less than for laboratory scale. Proportionally, in the application field, the volume to be treated in the same unit of filtering media is lower, leading to a greater treatment capacity.

Moreover, the ratio between useful volume and surface area (shown in Table 5.1 and represented by the variable $H_{equivalent}$) is higher for the field scale than for the laboratory scale, with values of 1.02m and 0.32m respectively. In other words, even at equal application rates in both scenarios, the field scale will still have greater $H_{equivalent}$ due to its dimensions, corroborating for a better treatment, in this case studied.

5.4 Conclusion

For the laboratory scale, we found a water retention efficiency of 99.9% and percolations rate ranging from 32% to 76%. Even if the sand layer was not completely saturated, the percolation process occurred. This result indicates the importance of considering the percolation in the retention and detention capacity of bioretention practices. The qualitative analysis demonstrates low pollutant removal efficiency and export for NO_3 and NH_3.

For the field scale, the results demonstrate water retention efficiency of 100%, but with low stored volume when compared with it total capacity (less than 0.12%). Additionally, it was achieved high rates for pollutant removal, with an efficiency range of 87% to 100%.

Comparing the two scales of analysis, the water retention efficiencies are similar. However, in both cases, the application rates were not enough to saturate the filtering media and generate outflow.

Further trials will be required to test a wider range of control volumes and rainfall intensity, which can be able to fill completely the device useful volume. In the field scale, it should be incorporated methods to measure the sand humidity, in order to better analyze the storage, even for small volumes. It is recommended the survey using telemetry and availability of online data. These systems allow the identification of measurement failures, erratic behavior, and real-time monitoring, preventing loss of important information and increasing the accuracy of monitoring.

References

Baptista, M. B., de Oliveira Nascimento, N., & Barraud, S. (2005). *Técnicas compensatórias em drenagem urbana*. Porto Alegre, ABRH. 266p. (in Portuguese)

Bratieres, K., Fletcher, T. D., Deletic, A., & Zinger, Y. (2008). Nutrient and sediment removal by stormwater biofilters: A large-scale design optimisation study. *Water research*, *42*(14), 3930-3940. doi: http://dx.doi.org/10.1016/j.watres.2008.06.009

Brown, R. A., & Hunt, W. F. (2012). Improving bioretention/biofiltration performance with restorative maintenance. *Water Science and Technology*, *65*(2), 361-367. doi: 10.2166/wst.2012.860

Chahal, M. K., Shi, Z., & Flury, M. (2016). Nutrient leaching and copper speciation in compost-amended bioretention systems. *Science of The Total Environment*, 556, 302-309. doi: http://dx.doi.org/10.1016/j.scitotenv.2016.02.125

Davis, A. P. (2007). Field performance of bioretention: Water quality. *Environmental Engineering Science*, *24*(8), 1048-1064. doi:10.1089/ees.2006.0190

Erickson, A. J., Weiss, P. T., & Gulliver, J. S. (2013). Optimizing stormwater treatment practices. New York, Springer Science & Business Media, 330p.

Fletcher, T. D., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources*, *51*, 261-279. doi: http://dx.doi.org/10.1016/j.advwatres.2012.09.001

Gutierrez, L. A. R. (2011) *Avaliação da qualidade da água de chuva e de um sistema filtro-vala-trincheira de infiltração no tratamento do escoamento superficial direto predial em escala real em São Carlos SP*. Thesis. Universidade Federal de São Carlos. (in Portuguese).

Hatt, B. E., Fletcher, T. D., & Deletic, A. (2009). Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. *Journal of Hydrology*, *365*(3), 310-321. doi: http://dx.doi.org/10.1016/j.jhydrol.2008.12.001

Hsieh, C. H., & Davis, A. P. (2005). Evaluation and optimization of bioretention media for treatment of urban storm water runoff. *Journal of Environmental Engineering*, 131(11), 1521-1531. doi: http://dx.doi.org/10.1061/(ASCE)0733-9372(2005)131:11(1521)

Laurenson, G., Laurenson, S., Bolan, N., Beecham, S., & Clark, I. (2013). Role of Bioretention Systems in the Treatment of Stormwater. *Advances in agronomy*.

Liu, J., Sample, D. J., Owen, J. S., Li, J., & Evanylo, G. (2014). Assessment of selected bioretention blends for nutrient retention using mesocosm experiments. *Journal of environmental quality*, *43*(5), 1754-1763. doi:10.2134/jeq2014.01.0017

Lucas, A., H. (2011). *Monitoramento e modelagem de um sistema filtro-vala-trincheira de infiltração em escala real*. Thesis. Universidade Federal de São Carlos. (in Portuguese).

Lucas, A., H.; Sobrinha, L. A.; Moruzzi, R. B.; Barbassa, A. P. (2015). Avaliação da construção e operação de técnicas compensatórias de drenagem urbana: o transporte de finos, a capacidade de infiltração, a taxa de infiltração real do solo e a permeabilidade da manta geotêxtil. *Engenharia Sanitaria e Ambiental*, 20(1), 17-28. doi: http://dx.doi.org/10.1590/S1413-41522015020000079923. (in Portuguese).

Lucke, T., & Nichols, P. W. (2015). The pollution removal and stormwater reduction performance of street-side bioretention basins after ten years in operation. *Science of the Total Environment*, *536*, 784-792. doi: http://dx.doi.org/10.1016/j.scitotenv.2015.07.142

Macedo, M. B.; Rosa, A.; Lado, C.; Souza, V. C.; Mendiondo, E. M. Subtropical climate issues for bioretention: Learnings from the operation pathologies and maintenance to optimize LID practices. *Journal of Environmental Engineering*, submitted a.

Macedo, M. B.; Rosa, A.; Lado, C.; Souza, V. C.; Mendiondo, E. M. Stormwater runoff control and water quality improvement through bioretention in Brazilian subtropical climate: A case study in São Carlos – SP. *Journal of Environmental Management*, submitted b.

Maglionico, M. (1998). *Indagine sperimentale e simulazione numerica degli aspetti qualitativi dei deflussi nelle reti di drenaggio urbano.* Thesis. Università di Bologna. (in Italian)

Mangangka, I. R., Liu, A., Egodawatta, P., & Goonetilleke, A. (2015). Performance characterisation of a stormwater treatment bioretention basin. *Journal of environmental management*, *150*, 173-178. doi: Performance characterisation of a stormwater treatment bioretention basin

Marengo, J. A.; Schaeffer, R.; Zee, D.; Pinto, H. S. (2010). Mudanças climáticas e eventos extremos no Brasil. Available in: http://www. fbds. org. br/cop15/FBDS_MudancasClimaticas. pdf. Accessed in October, 2010. (in Portuguese)

Marsalek, J., & Schreier, H. (2009). *Innovation in stormwater management in Canada: The way forward*. Water Quality Resources Journal of Canada, 44(1), v-x.

Petterson, S. R., Mitchell, V. G., Davies, C. M., O'Connor, J., Kaucner, C., Roser, D., & Ashbolt, N. (2016). Evaluation of three full-scale stormwater treatment systems with respect to water yield, pathogen removal efficacy and human health risk from faecal pathogens. *Science of the Total Environment*, 543, 691-702. doi: http://dx.doi.org/10.1016/j.scitotenv.2015.11.056

Rycewicz-Borecki, M., McLean, J. E., & Dupont, R. R. (2017). Nitrogen and phosphorus mass balance, retention and uptake in six plant species grown in stormwater bioretention microcosms. *Ecological Engineering*, 99, 409-416. doi: http://dx.doi.org/10.1016/j.ecoleng.2016.11.020

Santos, R., F. (2007). Vulnerabilidade ambiental: desastres naturais ou fenômenos induzidos? *MMA* (in Portuguese).

Urbonas, B.; Stahre, P. (1993). Stormwater: best management practices and detention for water quality, drainage, and CSO management. New Jersey, PTR PH, 449p.

Valverde, M. C.; Marengo, J. A. (2010). Mudanças na circulação atmosférica sobre a América do Sul para cenários futuros de clima projetados pelos modelos globais do IPCC AR4. *Revista Brasileira de Meteorologia*, 25(1), 125-145. doi: https://dx.doi.org/10.1590/S0102-77862010000100011

Wang, J., Zhang, P., Yang, L., & Huang, T. (2015). Adsorption characteristics of construction waste for heavy metals from urban stormwater runoff. *Chinese Journal of Chemical Engineering*, *23*(9), 1542-1550. doi: http://dx.doi.org/10.1016/j.cjche.2015.06.009

Wang, J., Zhang, P., Yang, L., & Huang, T. (2016). Cadmium removal from urban stormwater runoff via bioretention technology and effluent risk assessment for discharge to surface water. *Journal of contaminant hydrology*, *185*, 42-50. doi: http://dx.doi.org/10.1016/j.jconhyd.2016.01.002

Winston, R. J.; Luell, S. K.; Hunt, W. F. (2011). Evaluation of Undersized Bioretention for Treatment of Highway Bridge Deck Runoff. In *Proceedings* 12th International Conference on Urban Drainage, Porto Alegre, Brazil.

Young, C. E. F.; Aguiar, C.; Souza, E. (2015). Valorando empestades: custo econômico dos eventos climáticos extremos no Brasil nos anos de 2002 – 2012. *Observatório do clima*. São Paulo. (in Portuguese).

6 GENERAL CONCLUSION

The conclusion will be presented in the form of answers to the proposed objectives and, subsequently, a section of recommendations for future works.

6.1 Conclusions

The research objective is "*Evaluate the integrate efficiency (quali-quantitative) of LID practices in mitigating exceedance risks of urban drainage, by controlled and non-controlled experiments in bioretention systems under subtropical climate, aiming the optimization of the operation and maintenance*".

In general, conducting this research it was possible to observe that the bioretention applied in micro drainage scale contributed to increasing the sustainability and reduce the risks in the catchment. This was possible because, in one hand, the technique demonstrated a good ability in reducing the peak flows transferred to downstream, increasing the percolation to groundwater and helping to reestablish the pre-urbanization water balance. On the other hand, the treatment occurring in the filtering media is capable of amortizing the pollution load transferred to the urban river.

Typical conditions and characteristics of subtropical regions have been shown to have main interference in the quali-quantitative treatment capacity of the device. Maintenance and adaptations were proposed to mitigate these effects. However, for all systems to be implemented in subtropical regions, these specificities must be taken into account.

One specific objective is "*Evaluate the water and pollution mass balance in stormwater, by controlled and non-controlled experiments under subtropical climate*".

The results obtained through field and laboratory surveys under controlled and non-controlled conditions indicate a good capacity to reduce the peak flows and pollutant loads transferred to downstream. Values up to 70% of peak flow reduction were obtained for non-controlled field events, ranging from low to high total precipitated depth (2.6 to 39 mm). These same events, when evaluated by the qualitative aspects, presented a reduction in the pollutant load of the order of 67%.

However, some adversities were observed. The total retention volume did not reach half of the bioretention total capacity, indicating problems of infiltration into the soil. As for the qualitative analysis, some pollutants, such as Fe and NO_3, were exported during rainfall events. These adversities indicate problems related mainly to specific characteristics of subtropical climate, such as soil characteristics (highly weathering and high amounts of Fe).

Therefore, given the second specific purpose "*Optimize, physically and economically, the operation and maintenance of the bioretention system applied in field under subtropical climate, quantifying the efficiency variation after the maintenance actions*" and attempting that the technique work properly and closer to its design efficiency, it is necessary to propose maintenance and adjustments in the implementation and operation stage. In this study, we proposed and evaluated as maintenance measures the runoff semi-direct injection, physical barrier and establishment of fast fixation vegetation. These measures showed good results in reestablishing the storage capacity, increasing the retained volume to almost double, comparing to the pre-maintenance events. In addition, the erosion of the vegetated layer was no longer observed after maintenance.

These results are important because they extend the practical knowledge in real scale for the use of LID practices, with a focus on Brazil. Only with the practical and detailed knowledge, it is possible to increase the application of these systems as public policies actions by the managers.

6.1 Recommendations for future studies

- Although the results obtained in this research shows good performance, further studies should be conducted with a larger number of monitored events, ranging from dry to rainy season.
- The evapotranspiration is an important variable in the water balance, for the decay in the hydrograph in subtropical conditions. Therefore, means of measure this variable should be adopted.
- We recommend more experiments in laboratory scale, varying factors such as soil type, vegetation, filtering media and layers layout. This variation will allow identifying the key factors to the system performance. The main factors to be tested must be co-related with the subtropical conditions.

- A maintenance schedule and evaluation plan, considering preventive and corrective actions, should be done at the beginning of the studies and reassessed whenever possible.
- It is recommended the use of telemetry for monitoring. Thus, a larger and more accurate number of data can be obtained.
- The results of this research indicate good perspectives to the water reuse and nutrients cycling in bioretention systems. This alternative should be better investigated.