Science of the Total Environment 647 (2019) 923–931

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Stormwater volume reduction and water quality improvement by bioretention: Potentials and challenges for water security in a subtropical catchment

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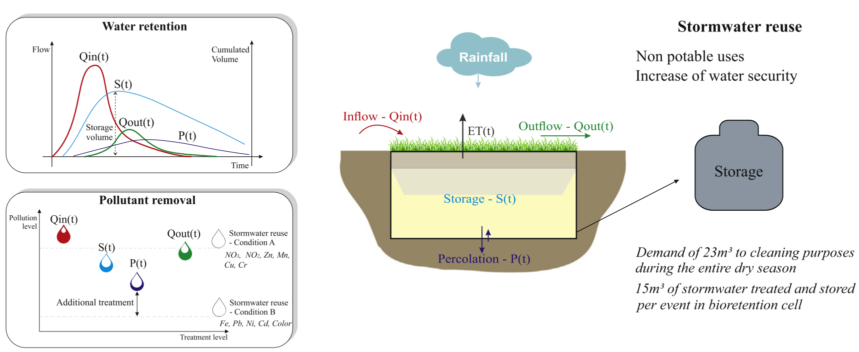
HIGHLIGHTS

- Bioretention presents a good runoff reduction capacity (mean efficiency of 70%).
- The results suggest that groundwater replenishment occurs mainly after the event.
- Stormwater reuse directly from the bioretention can be compromised by its quality.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 March 2018
Received in revised form 23 July 2018
Accepted 1 August 2018
Available online 04 August 2018

Editor: G. Ashantha Goonetilleke

Keywords:
Bioretention
Stormwater reuse
Water security
Stormwater harvesting
Pollutant removal

ABSTRACT

Climate change scenarios tend to intensify extreme rainfall events and drought in Brazil threatening urban water security. Low Impact Development (LID) practices are decentralized alternatives for flood mitigation and prevention. Recently, their potential has increasingly been studied in terms of stormwater harvesting. However, there is still a lack of knowledge about their potentialities in subtropical climate regions. Therefore, this study evaluated the behavior of a bioretention cell in a Brazilian city, during the dry period, which is critical in terms of pollutant accumulation and water availability. In addition to the runoff reduction and pollutant removal efficiency, this paper analyzed the potential for water reuse in terms of the stored volume and water quality guidelines. The results obtained show an average runoff retention efficiency of 70%. Considering only the water availability aspects, the potential stored runoff could be reused for non-potable purposes, reducing the water demand in the catchment by at least half during the dry season. On the other hand, the bioretention presented two different conditions for pollutant removal: Condition A – the concentration values are within the recommended limits for water reuse. The parameters found in this condition were NO_3, NO_2, Zn, Mn, Cu, Cr; Condition B – the pollutant concentrations are above the guideline limits for water reuse and cannot be directly used for different purposes. The parameters found in this condition were Fe, Pb, Ni, Cd and color. Considering water reuse, an additional treatment is required for parameters in this second condition. Further studies should evaluate the design aspects that can allow collection of LIDs effluent, additional treatment if necessary, and reuse in the catchment.

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https://doi.org/10.1016/j.scitotenv.2018.08.002
0048-9697/

1. Introduction

Rapid urbanization has caused structural and environmental changes in urban basins, increasing paving, reducing soil infiltration and increasing pollutant deposition (Konrad and Booth, 2005; Leopold, 1968; Stovin et al., 2012; Wong and Eadie, 2000). It has also changed social conditions making the population more vulnerable to risks. As a consequence of these changes, there is an important increase in surface runoff, turning natural hydrological cycle risks into urban problems. Extreme rainfall events are precursors of risks to the population (Santos, 2007; Young et al., 2015), who are more vulnerable to floods and landslides. These can be made worse by climate change (Debortoli et al., 2017; Marengo et al., 2010).

Concerning the Brazilian scenario, research carried out by the Brazilian Institute of Geography and Statistics (IBGE) found that more than half of the municipalities in Brazil experienced floods between 2008 and 2012. Among these, the metropolitan region of Sao Paulo was the third city with the highest number of occurrences with a total of 704 floods (IBGE, 2013). During this period, there were deaths in 25% of the flood events in the southeast region. From 2014 to 2016, an extreme drought affected southeast Brazil and the rainfall from January to March was 54% lower than the 1961–1990 reference period (Cemaden, 2015), which caused an unprecedented water crisis in Sao Paulo state. The main supply system in the Sao Paulo metropolitan area, Cantareira, operated at the levels of its dead volume affecting the water security of about 8.8 million people (Escobar, 2015; Tafarello et al., 2016). These extreme droughts also led to other water-related impacts, such as increases in the price of electricity and food (Richards et al., 2015).

Due to the fact that cities are facing these environmental problems and knowing that they tend to become worse with climate change scenarios, the largest cities in the world created the C40 group to discuss and exchange public management actions and policies aimed at reducing the impacts generated and felt by them. In 2014, this group released a diagnostic report and evaluation of its proposed actions. In this report (C40, 2014), 90% of the cities that comprise the group indicated that climate change presents significant risks to their cities; the main ones related to floods and water stress. In addition, they also point to urban drainage as a key to flood risk management, where alternative techniques and systems rank in third place in the group's most accomplished actions. Therefore, the importance of urban drainage can be observed as an adaptation measure to make cities more resilient (Carter et al., 2015). Considering that water stress will become increasingly frequent in these scenarios, alternative drainage techniques that reuse stormwater as a form of urban harvesting (Agudelo et al., 2012) contributes to increasing urban resilience, as well as water, food and energy security.

These alternative techniques have various nomenclatures which are used worldwide, depending on the region and country where they are used. The most used is Low Impact Development (LID) practices, Stormwater Control Measures (SCM) and Best Management Practices (BMP) in the USA, Water Sensitive Urban Design (WSUD) in Australia and Sustainable Urban Drainage Systems (SUDS) in Europe (Eckart et al., 2017; Fletcher et al., 2013). In this study, we will adopt the LID terminology. LID practices aim to reestablish the natural hydrological cycle of pre-urbanization, focusing on water infiltration and integrated efficiency in the runoff amount and pollutant control (Council, 2007; Fletcher et al., 2013; Prince George's County, 2007). Research centers in Melbourne (Australia) and Santa Monica (USA) are pioneers in integrating LID practices in stormwater reuse from stormwater harvesting.

Many studies further evaluate the benefits of separate water retention and flood attenuation (Davis, 2008; Winston et al., 2016) from pollutant treatment and water quality improvement (Bratieres et al., 2008; Davis, 2007), making it difficult to integrate assessments for stormwater harvesting (Lucke and Nichols, 2015; Hatt et al., 2009). This gap is even larger in subtropical regions as most of the studies are conducted in temperate regions, where geoclimatic, sanitary and social conditions are very different from those in subtropical climate areas. Therefore, studying adaptations and monitoring LID practices for tropical and subtropical regions is still a shortcoming, and some questions still remain:

1. Does using stormwater harvesting techniques increase water security in cities?
2. Does only the direct reuse of stored stormwater contribute to the increase in water security?
3. Does the effluent of the LIDs systems have the appropriate quality standard for water reuse?

Aiming to answer these questions, in this study we evaluated the performance of an LID practice of bioretention already installed in an urban subtropical climate basin, designed for flood mitigation purposes. Based on runoff monitoring (volume, flow and pollution), we considered the potential of adapting these techniques to stormwater harvesting, concerning the direct reuse of water and its contribution to increasing water safety.

2. Methodology

2.1. Study site

The bioretention analyzed in this study was created and has been in operation since 2015 at the University of Sao Paulo (USP/SC campus 2) in the city of Sao Carlos. This area is representative of other cities with medium to fast urbanization rates and is classified as Cfa in the Köppen climate classification having a total annual rainfall of 1361.6 mm and an average daily temperature of 21.5 °C. The rainy season occurs from November to April and January has the most rainfall (274.7 mm and average daily temperature of 23.4 °C). The dry season occurs from May to October and July has the least rainfall (28.3 mm and an average daily temperature of 18.5 °C) (EMBRAPA, 2017).

USP/SC Campus 2 is located in the Mineirinho river basin. It was inaugurated in 2005 and is still in an expansion process (in 2015 only 15% of its total area was occupied). Therefore, the influence of land use and occupation changes on the long-term bioretention performance can be evaluated. Moreover, the area is a development axis of Sao Carlos city, mainly with a population of low income and popular housing. The Mineirinho basin presents environmental fragility, with points of irregular sewage deposition (Benini, 2005).

The bioretention catchment has a total area of 2.3 ha representing an urban drainage system on a neighbourhood level scale (terminology from Marsalek and Schreier (2009)) with runoff reaching the Mineirinho river directly. The main contribution to runoff comes from pedestrian paths, roads and classroom buildings (Fig. 1), totalizing 25% of the catchment. The other 75% is mostly grassland.

As for the bioretention device, it has a total surface area of 60.63 m^2 and is 3.2 m deep. Its interior has a filter media composition divided into three layers - soil, gravel and sand - with an average porosity of 35% (Fig. 1). The top layer is composed of natural soil from the region, which is characterized as dark brown with organic matter and a main composition of medium sized sand (40%), 25% fine sand and 16% clay, and it has a hydraulic conductivity of 5.83 $mm \cdot h^{-1}$. This layer has a depth of 50 cm and is covered by four different plant types (*Brachiaria* sp., *Sorghum sudanense*, *Sansevieria trifasciata* and *Cyperus papyrus*) responsible for landscape integration, soil fixation and helps to improve pollutant removal (Hunt et al., 2015).

The intermediate layer is a 70 cm gravel layer, with a diameter of 5 cm and porosity of 40%. The bottom layer is 2 m deep comprising coarse sand, with 1 mm diameter and porosity of 30%. The gravel and sand layers together are responsible for the greater retention of surface runoff volume and qualitative treatment, totaling a volume of approximately 58 m^3. The configuration presented was chosen to achieve the qualitative treatment of sedimentary solids.