Use of detention basin for flood mitigation and urban requalification in Mesquita, Brazil

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ABSTRACT

Unplanned urbanization is one of the main factors responsible for worsening flood-related problems in cities, increasing the frequency of flooding and flooding depths, consequently degrading both the natural and built environment. Considering this, the use of engineering techniques that reduce runoff and promote urban requalification are an efficient option for managing rainwater. This paper presents a case study of a flood control project using a storm water detention pond, designed to allow multiple uses of an urban space. The operation of the system is evaluated by an urban flow-cell model, known as MODCEL. This application seeks the best configuration for the layout of 'Celso Peçanha' Detention Basin, considering the local restrictions imposed by the City of Mesquita – Brazil, and optimized to damp storm flows resulting from rainfall events with return periods up to 50 years. The solution proposed considers the possibility of social urban space uses in flood control projects, revitalizing degraded areas and giving them multiple functions.

Key words | compensatory techniques, multifunctional landscapes, urban drainage

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INTRODUCTION

The increase of urbanization favours the replacement of natural surface vegetated cover by impervious surfaces, which hinder the processes of infiltration and water retention in the watersheds and cause a significant increase in surface runoff (Kibler *et al.* 1981; FISRWG 1998; Ashley *et al.* 2005; Zhu *et al.* 2007; Huong & Pathirana 2013). The combination of the increase of extreme rainfall due to climate change, additional pavement of urban expansion and decreasing spaces for water storage on the watershed overloads the urban drainage systems more frequently and shows the necessity of a more efficient utilization of public spaces (Notaro *et al.* 2013; van Dijk *et al.* 2014; Zhou *et al.* 2016).

The waters that flow over the impervious surfaces carry several types of pollutants, compromising their quality and the quality of the receiving body (Fisher *et al.* 2000; Novotny & Hill 2007; Wang *et al.* 2008; Yazdanfar & Sharma 2015; Zhou *et al.* 2016). Cities subjected to heavy storms and containing large impervious areas, preventing rainwater from infiltrating into the soil, produce a large amount of surface flows that often overload the drainage system, exposing people and properties to flooding (Fontanazza *et al.* 2012; Zhou *et al.* 2016).

In the face of an unplanned urbanization process, which is very common in developing countries, like Brazil, the occurrence of high-intensity hydrological events shows the fragility of traditional drainage systems (Andoh & Iwugo 2002; Melville-Shreeve *et al.* 2018), with frequent failures. This kind of system is usually composed of structures that accelerate flows, such as river canalization works (Novotny & Hill 2007), focusing on conveying pre-defined design discharges (Yazdanfar & Sharma 2015). These techniques can transfer the problem downstream, without controlling the related consequences. Besides that, unplanned or uncontrolled urban growth generates discharges that are greater than that for which the drainage network was designed.

doi: 10.2166/wst.2019.212

By neglecting source control, this approach implies the need for continuous interventions following flood events along the flood way.

To get out of this vicious circle, new technologies and drainage concepts emerged in North America and Europe in the 1970s. Since then, several concepts have been incorporated into urban drainage discussion, assuming different terminologies, as sustainable urban drainage systems (SUDS) in the United Kingdom, stormwater best management practices (BMPs) and low impact development (LID) in the USA, and more recently as water sensitive urban design (WSUD) in Australia, or green infrastructure worldwide (Sharma *et al.* 2016). Fletcher *et al.* (2014) present a detailed review of the history of how different concepts and related terms appeared and are used in urban storm water management. Mainly, the techniques involved in these concepts seek to minimize the effects of urbanization growth. In summary, the sustainable drainage approach seeks to increase the infiltration of rainwater into the soil by reducing and/or slowing the runoff and thus decreasing the amount of water in storm drains and rivers during heavy rains (Holman-Dodds *et al.* 2003), as well as provideing opportunities to recover storm water retention capacity. These drainage techniques, which seek to offset the negative effects of urbanization, have proved to be more sustainable, working better in the long term Dierkes *et al.* 2000; Swan *et al.* 2001; Ashley *et al.* 2005; Swan 2010).

The use of sustainable drainage techniques presents numerous advantages when compared with conventional drainage works. In general, the use of sustainable drainage technologies allows the continuity of urban development without generating excessive costs for retrofitting drainage systems or recovering from flood losses, allowing the adaptation of the discharges generated by new urbanization to couple with drainage system capacity and the combination of drainage issues with other urban opportunities, regarding leisure or landscaping, for example (Baptista *et al.* 2005). Improving biodiversity and offering retrofit opportunities to urban areas, for example, are other possibilities found in the integration of the sustainable urban drainage approach with the urban planning process.

Unlike classical drainage techniques, which make it impossible to have other uses for water in the urban environment, since the main objective is to get rid of the rainwater, sustainable drainage techniques can offer areas of multiple uses playing multiple functions, such as the use of reservoirs for skateboarding in the dry season, the use of rain gardens that can improve the local microclimate and beautify the landscape, the implementation of riverine parks that protect river banks and provide recreational environments, among others (Miguez *et al.* 2012). In this way, sustainable drainage contributes to improving the quality of life in cities with the preservation and recovery of the environment and the reduction of the loads related to diffuse pollution (Viavattene & Ellis 2013).

In the urban environment, the use is predominant of impervious surfaces instead of porous surfaces that favor infiltration, canalization of rivers instead of natural and sinuous stream courses with damping areas for flood, and concrete infrastructure rather than approaches like ponds and vegetation (Novotny & Hill 2007). Sustainable drainage aims to simulate a more natural condition for the water flow, which can provide flood mitigation, using measures like retention/detention ponds, infiltration trenches, and porous pavement.

A widespread type of measure appearing in sustainable drainage solutions is the retention/detention basin, which is an effective means of flood control (Holman-Dodds *et al.* 2003; Travis & Mays 2008). This kind of measure aims to provide temporary storage to attenuate peak flows and may remove pollutants carried by runoff, providing a water quality improvement (Ferrara & Witkowski 1983; Lawrence *et al.* 1996). However, if the detention basins also favour infiltration, they can threaten the quality of groundwater, if not used with caution (Fischer *et al.* 2003).

Retention and detention ponds contribute to the improvement of water quality, as they can help with the removal of suspended solids by the sedimentation mechanism, which consists in reducing water velocities and consequently in retaining a proportion of total suspended solids (TSS) and associated pollutants (Birch *et al.* 2006; Yazdanfar & Sharma 2015). As presented in Birch *et al.* (2006), Schueler & Helfrich (1988) found a good removal efficiency for suspended solids, variable removal of phosphorus and poor removal efficiencies for nitrogen, by reviewing a broad selection of detention pond performances. Another study presented in Birch *et al.* (2006), conducted by the Center for Watershed Protection, reported that the performance of stormwater ponds in central Texas had a high rate of total suspended solids and bacteria removal and a good reduction in nutrients and metals. The results of pollution removal can improve significantly with the use of diverse aquatic plants in the retention/detention basin (Mallin *et al.* 2002).

This article seeks to exemplify, in a practical way, the benefits of sustainable drainage with a focus on urban requalification. In this way, a detention basin is designed to temporarily store and dampen the discharges of a minor drainage system of an urban catchment, simulating a condition closer to the natural situation, decreasing the peak runoff entering drainage systems, providing retention and consequently greater infiltration of water into the soil. The term detention basin is used based on the *Urban Storm Drainage Criteria Manual: Volume 2* (UDFCD 2016), which defines these structures as storage facilities that manage stormwater quantity by attenuating peak flows during flood events. In this same Manual (UDFCD 2016), retention facilities are defined as basins with a zero release rate or a very slow release rate.

The hydrodynamic analysis of the operation of this detention basin was carried out for an enterprise in the municipality of Mesquita, located in the Metropolitan area of Rio de Janeiro, Brazil. The study area, called the watershed of Governador Celso Peçanha Avenue, drains to Sarapuí River and suffers constant flooding in the summer seasons.

METHODS

The area of interest refers to an urban watershed located in the municipality of Mesquita, one of the cities that compose the metropolitan region of Rio de Janeiro, in the southeast of Brazil. The region is part of Iguaçu–Sarapuí River Basin, located in the middle stretch of Sarapuí River, on its left bank. Flood events are common during the summer wet season and bring great losses to the local population.

The watershed of Governador Celso Peçanha Avenue storm drain is a densely urbanized area that suffers the impacts of the process of uncontrolled urbanization, with direct consequences for the drainage system, through the aggravation of floods, reduction of base flows, and deterioration of the quality of water and river ecosystems. The map shown in Figure 1 presents the location of the watershed, as well as Sarapuí River and the detention basin proposed. The watershed has an area of 0.7 km^2.

The design of local minor drainage considers the implementation of a detention basin to dampen the stormwater drained by urban catchment before discharging into Sarapuí River. This measure is able to avoid transferring floods downstream, while creating conditions to store and organize flows of the local watershed, without provoking backwater effects and overflows in the related storm drains. In this way, a rainwater detention structure was designed to be associated also with leisure uses in its

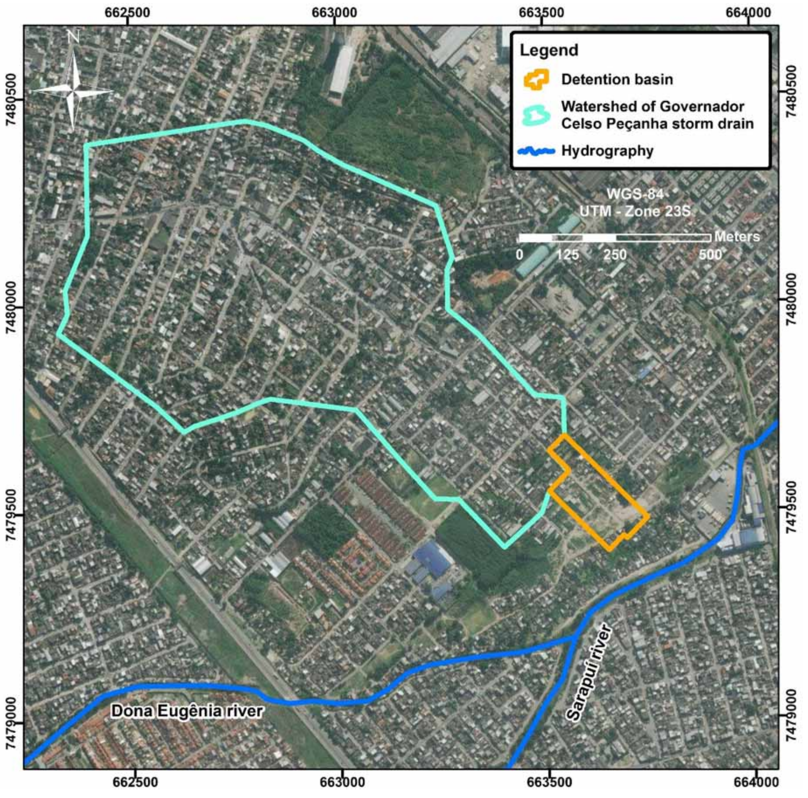

Figure 1 | Location of the watershed of Governador Celso Peçanha storm drain, Mesquita.

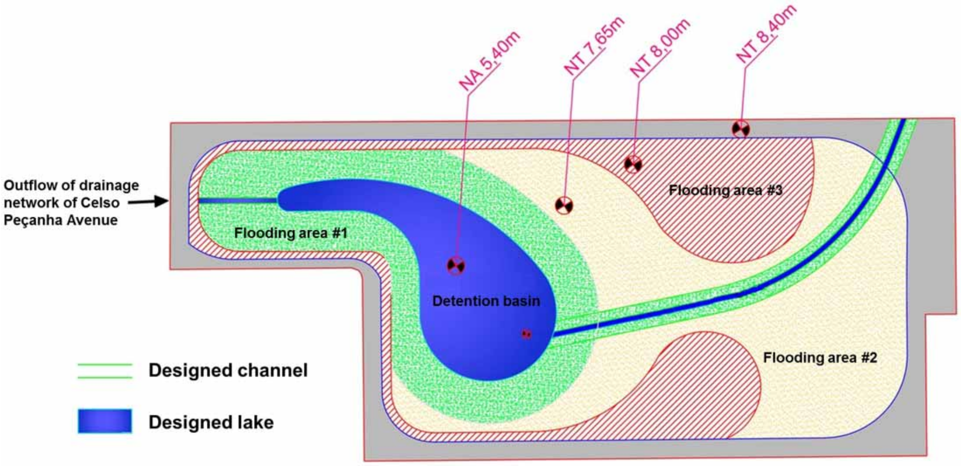

Figure 2 | Celso Peçanha Detention Basin Project.

internal area in dry weather conditions, ensuring social uses for the urban space, and the urban environment valorization of the entire neighbourhood. The final layout of the proposed square is shown in Figure 2. The inlet structure for the basin consists of a 1.5 m-diameter concrete pipe. The outlet, which connects the detention basin to Sarapuí River, has 1.5 m diameter also. The inlet and the outlet structures as well as the complete project are presented in Annex 1 (available with the online version of this paper). The damping will be done by the control of the outlet, through a one-way floodgate (FLAP type) with a diameter of 0.60 m. The use of the FLAP floodgate will prevent the waters of Sarapuí River from entering the internal area of the detention basin during large floods. The designed outlet structure consists of the installation of two floodgates in parallel, to allow possible maintenance work on one of the floodgates. The operation of the detention basin should be done with only one operating gate, with another complementary gate closed. The provision of a reserve gate also allows the opening of the two floodgates in events larger than those foreseen in the project, that is, when rainfall occurs with high return periods (RP), increasing the drainage capacity of the detention basin. The design of the floodgate structure is presented in Annex 1.

The difference between the inlet and outlet flow, related to the damping of the outflow, should be temporarily stored inside the detention basin. For this, the internal area of the pond is divided into levels, which will be flooded gradually, according to the severity of the pluviometric event. This configuration allows a hierarchizing of the use of the internal areas of the detention basin, predicting the installation of urban equipment in the levels with less frequency of flooding.

The design of the detention basin relied on defining three flood areas with different terrain elevations. Flooding Area #1 will have a permanent lake, with a water level of 5.40 m. This option aims to make it possible to use landscaping in periods without heavy storms. The water level in this lake will vary before reaching the level of and entering into Flooding Area #2. This volume is designed to contain ordinary floods, with more frequent occurrences. Therefore, urban facilities should not be installed in Flooding Area #1, reserved exclusively for flood mitigation. The water quality can be improved by introducing specific plant species, with pollutant removal abilities, into the lake environment. Flooding Area #2, designed at the terrain level of 7.65 m, will be flooded less frequently, and specific floodproof urban equipment can be installed. At this level, larger plant species can be planted, it being advisable not to concentrate them in large numbers, which could reduce the useful area for receiving water during floods. Finally, there is Flooding Area #3, to be constructed at the terrain level of 8.00 m. This area has a low probability of flooding, so it can receive more urban equipment, but it must be indicated that there is the risk of flooding in extreme hydrological events. The detention basin flooding limit is physically defined by a jogging track around the basin, to be built at the terrain level of 8.40 m. Table 1 shows the dimensions of each flooding area.

Considering the total area of the watershed Celso Peçanha, which is 0.7 km^2, and the area of the detention basin of 22,856 m^2, the ratio between the drained area and the designed pond is 3.2%. This ratio is very close to the area required for damping in detention and retention basins, on the order of 2.0% of the total basin area

Table 1 | Summary of flooding areas: levels and areas

	Levels	Areas (m^2)
Discharge channel	Lowest level = 4.40 m	1,116
Flooding Area #1	Bottom level of the lake = 4.40 m	4,226
	Permanent water level = 5.40 m	5,890
	Water level limit of the lake = 7.65 m	9,344
Flooding Area #2	7.65 m	17,326
Flooding Area #3	8.00 m	22,856
Total flooding area		22,856

considered, according to the Urban Drainage and Flood Control District (UDFCD 2008).

The evaluation of the hydraulic operation of the detention basin is carried out using mathematical modelling tools, divided into two sets. The first set is the hydrological studies, which have the objective to elaborate design rainfalls according to the pre-established risks associated with the project. The second set refers to the hydrodynamic evaluation of the behaviour of the detention basin, considering the floods resulting from the hydrological studies. This study used a hydrologic model to simulate the runoff produced in the urban catchment – HIDROFLU (Magalhães *et al.* 2005) – and a hydrodynamic model to simulate the operation of the detention basin – MODCEL (Miguez 2001; Miguez *et al.* 2017).

MODCEL is a pseudo-two-dimensional model, capable of interconnecting surface flows, storm drains and channels in one simulation tool. It works using the concept of flow-cells, which are compartments representing terrain features and their storage capacity, composing a hydraulically interconnected flow network. Therefore, the detention basin was divided into flow-cells. Each flow-cell received the respective topographic information, the type of soil cover, and the associated urbanization pattern. The types of the cell and their connections will be shown further on.

Hydrological studies

The hydrological studies were performed in order to build design rainfalls for different RP. Previous hydrological studies developed for this region were used as references. These studies were part of the 'Water Resources Master Plan of the Iguaçu/Sarapuí River Basin' developed by the Laboratory of Hydrology and Environmental Studies at UFRJ (LABHID 1996). In this study, the rainfall gauges used were Nova Iguaçu, Xerém, Bangu and São Bento.

Table 2 | Influence of each rainfall station on the Dona Eugênia River basin

		Weights (%)			
Sub-basin	Area (km^2)	São Bento	N. Iguaçu	Xerém	Bangu
Dona Eugênia River	16.84	0.136	0.474	0.039	0.351

These rainfall gauges were chosen because they represent the characteristics of the intense rainfalls in the region and because they have adequate data history for the elaboration of the intense rainfall equations.

The different design rainfall events were calculated using the following premises:

- the rainfall duration equals 76.4 minutes, referring to the calculated time of concentration for the studied watershed;
- different values of runoff coefficients were established for each cell, according to the analysis of satellite images for land-use evaluation.

The influences of each rainfall station on design rainfalls in the studied watershed receive the weights shown in Table 2.

Table 3 presents the values of the design rainfall calculated for different RP, the precipitation intensity and the peak flow hydrograph that resulted from each rainfall event, used in the simulation of the proposed detention basin operation.

Hydraulic studies

The representation of the detention basin was made by dividing its internal area into 12 flow cells, with one more cell in the external area to represent the storm drain that connects the square to Sarapuí River. From this division, a topological scheme was built for data entry in the mathematical model MODCEL. The cell division and the associated topological scheme can be seen in Figure 3.

The boundary conditions defined for the model represent: (1) the flood hydrograph entering the square, representing the outfall of the drainage network coming

Table 3 | Values of design rainfall calculated for different return periods (RP)

Return period (years)	RP5	RP10	RP20	RP50	RP100
Total height rainfall (mm)	62.5	70.7	77.6	89.2	96.81
Precipitation intensity (mm/h)	49.15	55.56	60.98	70.07	74.47
Peak flow (m^3/s)	4.95	5.91	6.73	8.13	9.06

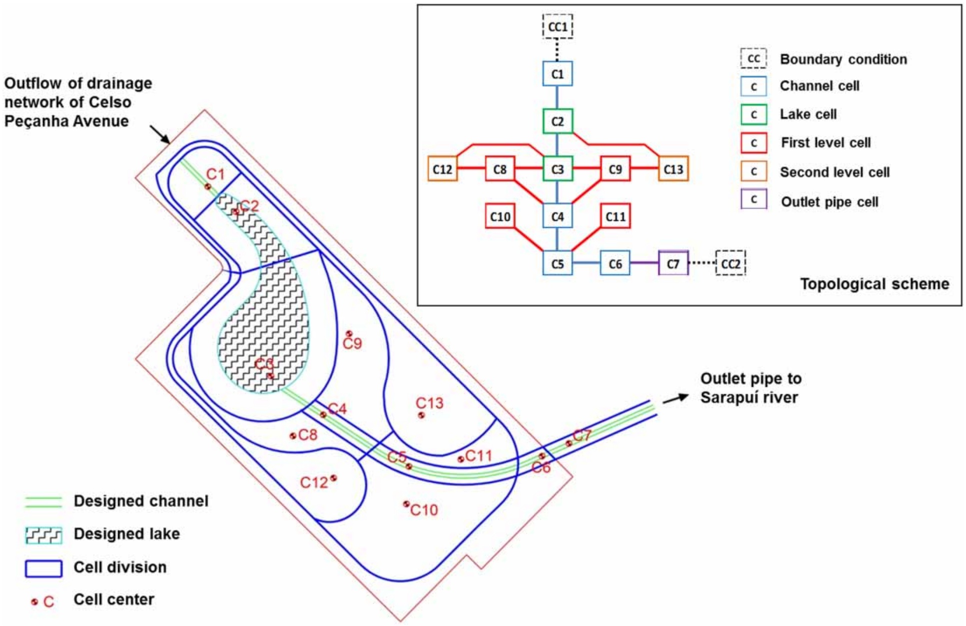

Figure 3 | Cell division and the topological scheme.

from Governador Celso Peçanha Avenue; and (2) the water level of Sarapuí River, in the outfall of the storm drain designed downstream of the detention basin, considered at the maximum water level resulting from a 20 years' storm. This configuration allows the simulation of the backwater effect on detention basin outfall.

RESULTS AND DISCUSSION

The results of the simulations allowed the analysis of the filling of the detention basin and the water levels reached for each scenario, considering the different rainfall events with different RP, as well as identifying the outflows of the

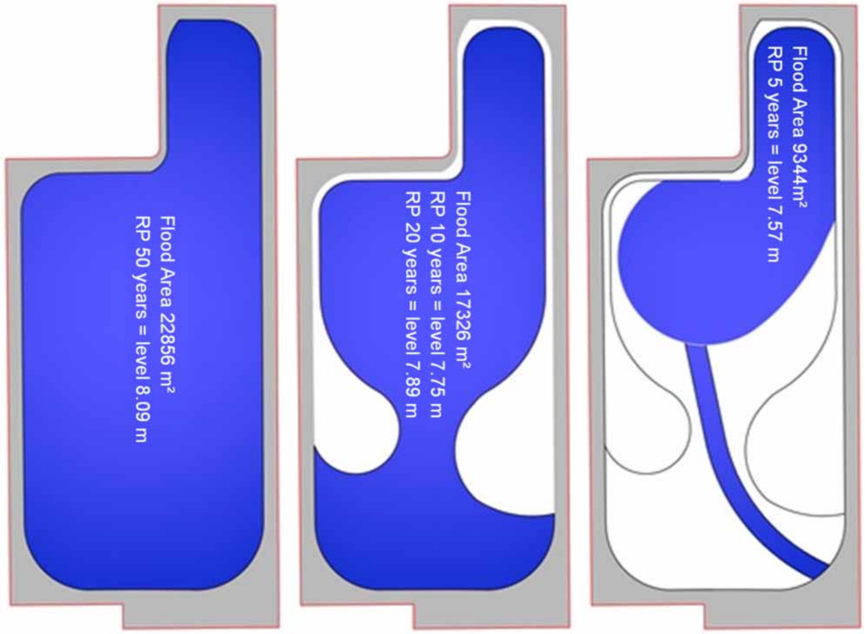

Figure 4 | Detention basin flooding scheme for each hydrological design event (return period – RP).

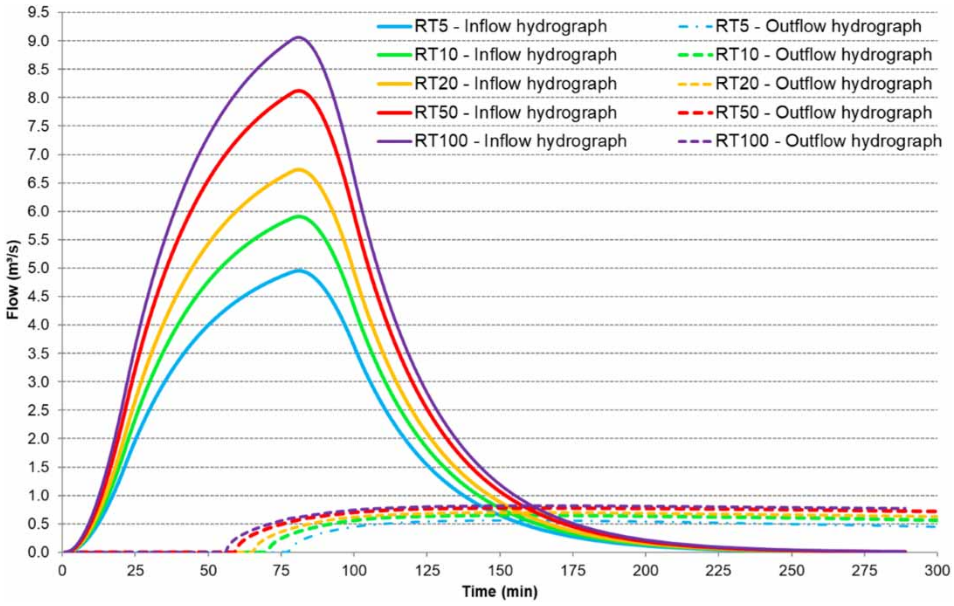

Figure 5 | Inflow and outflow hydrographs for all simulated rainfalls.

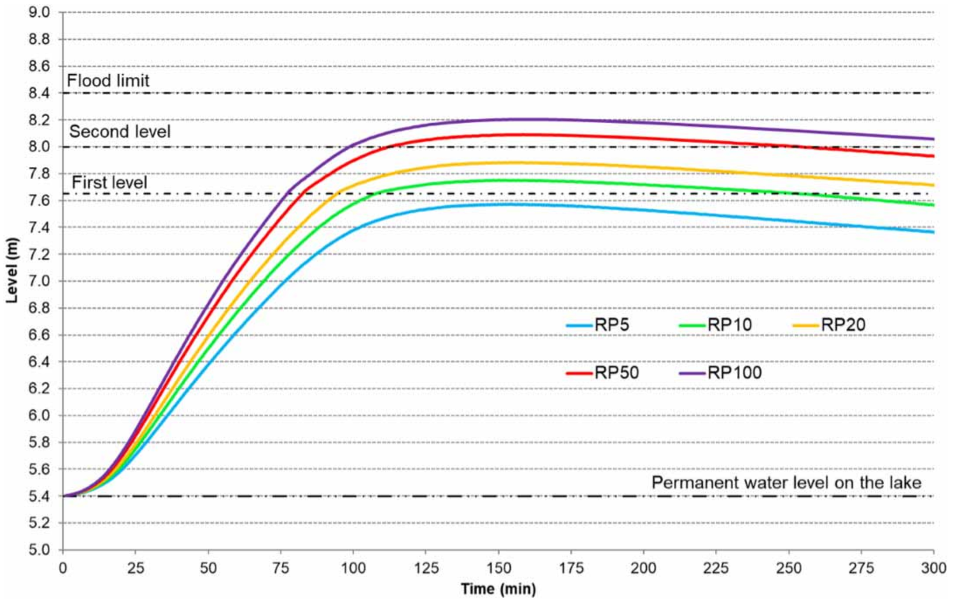

Figure 6 | Water surface elevation in the detention basin for the simulated rainfalls.

basin. In this way, it was possible to evaluate the damping efficiency of the proposed structure. The results of the hydrodynamic evaluation are presented in the form of inflow and outflow hydrographs for the detention basin and water levels. The inflow hydrographs refer to the minor drainage network contribution coming from Celso Peçanha Avenue and the outflows refer to the exit of the detention basin into Sarapuí River.

The practical result of adopting different levels of terrain can be seen in the flooding scheme of the designed detention basin, shown in Figure 4. For each design

Table 4 | Damping efficiencies for each design rainfall

Return period (years)	RP5	RP10	RP20	RP50	RP100
Efficiency	89%	89%	90%	90%	91%

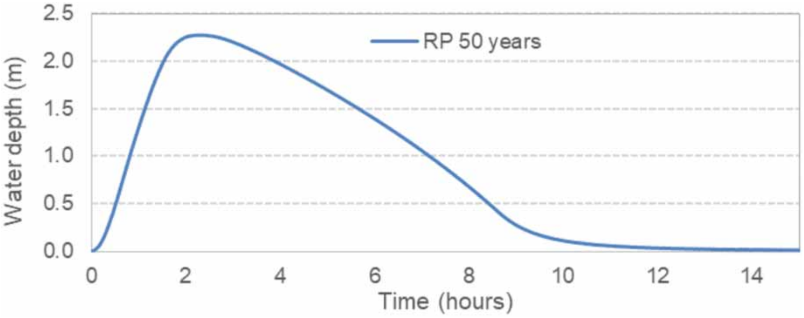

Figure 7 | Water depth variation inside the detention basin resulting from the 50 years' storm.

storm, the resulting flooded area occupies different levels.

The graph of Figure 5 shows the damping efficiencies for each design rainfall. It is observed that the detention basin provides a significant damping effect, reaching an efficiency of 91% for the design rainfall event with an RP of 100 years. The water surface elevation in the basin, presented in the graph of Figure 6, shows the detention basin filling pattern, for each design rainfall. Table 4 presents the damping efficiencies.

The detention basin has an emptying time of 12 hours, evaluated for the 50 years' storm occurring over the Celso Peçanha urban watershed and a low water level in Sarapuí River. This time has a good design security level, below 24 hours. The emptying time is shown in Figure 7.

Since the detention pond has demonstrated its functionality for storm events from 5 to 100 years of return period, one additional simulation scenario was performed to ensure the safety of its operation in the case of a great flood in Sarapuí River. This scenario aims to evaluate the filling capacity of the reservoir in the case of backwater effects in the outlet device. The result of this simulation scenario is shown in Figure 8. The reservoir volume is capable of reserving all the drained water in these conditions, a 100 years' storm and high flood water in Sarapuí River.

CONCLUSIONS

The use of a detention basin proved to be efficient for reorganizing the patterns of runoff volumes generated in a densely upstream urbanized watershed, reducing the drained peak flows to the receiving body. The results show

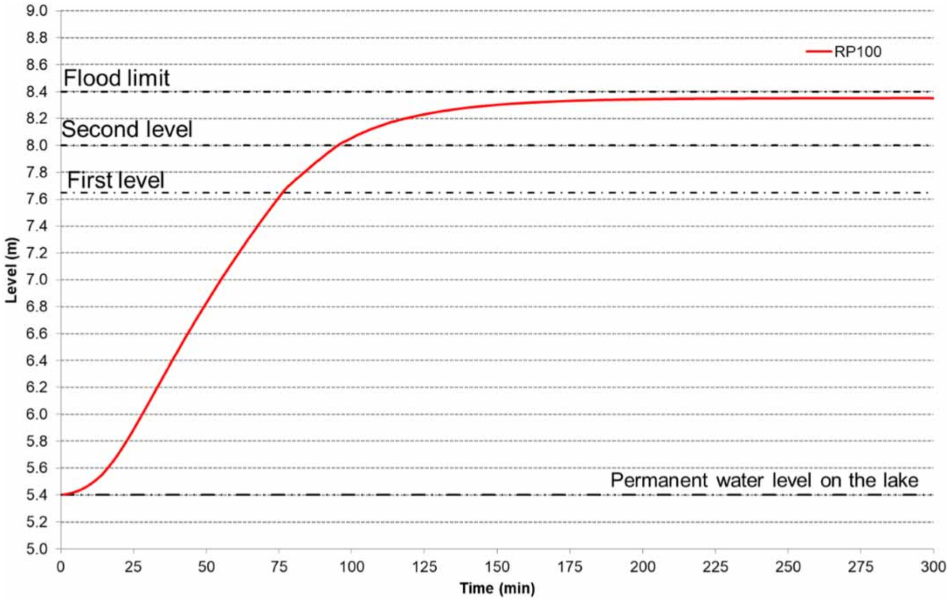

Figure 8 | Water level inside the reservoir with the occurrence of a 100 years' storm and high waters in Sarapuí River, blocking the outlet draining.

that a simple hydraulic measure can attenuate peak flows of storms of up to 50 years of return period, reaching values around 80% of peak reduction. This kind of stormwater management could be spread over other free open spaces of the city, reducing the impact of urbanization on floods, reducing their occurrence and contributing to more pleasant urban environments.

Drainage solutions integrated with urban revitalization programs can be an important alternative for flood control, due to the possibility of drawing distributed actions in the urbanized watershed and optimizing public resources, since they are directed to multipurpose activities, using the concept of multifunctional landscapes, allowing a broad range of benefits. This type of solution also adds urban, social and environmental value to the region of interest and takes advantage of the potential of integrating engineering projects with urban design, considering the social function of urban spaces.

This paper did not evaluate the improvement of the water quality that detention basins can provide to the water bodies, through the sedimentation of suspended solids and other contaminants. It would be interesting, as a next step, to assess and monitor the water quality of detention basins.

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First received 24 January 2019; accepted in revised form 11 June 2019. Available online 21 June 2019