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Evaluating the performance of on-site stormwater detention based on the technical guidelines for developing stormwater projects in Belo Horizonte (MG, Brazil)

Avaliação do desempenho de microrreservatórios dimensionados segundo a instrução técnica para projetos de drenagem urbana em Belo Horizonte (MG, Brasil)

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ABSTRACT

Standardized design criteria and performance assessment of parcel-level on-site stormwater detention (OSD) remain limited. This study evaluates the hydrological impact of OSD — designed per Belo Horizonte's (Minas Gerais, Brazil) municipal guidelines — at both parcel and catchment scales using hydrological modeling in a highly impervious, flood-prone subcatchment. Results indicate that while existing guidelines are generally effective, volume sizing could be optimized. OSD implemented across 31.8% of the catchment significantly reduced peak flows, though effectiveness varied by spatial scale. At the parcel level, outflows decreased by 72.3% for 2-year and 50.7% for 100-year return period rainfalls, with delay in peak times of 41.7%. At the catchment level, peak flow reductions reached 24.6% (2-year) and 26.4% (100-year). Flow routing at the catchment outlet revealed reductions in channel overflow volumes and maximum water heights by 75.5%, 54%, and 49% for 2-, 10-, and 50-year events, respectively.

Keywords: On-site stormwater detention systems; Low impact development; SWMM; Urban drainage assessment.

RESUMO

Critérios padronizados para o dimensionamento e a verificação de desempenho de microrreservatórios de lote ainda são pouco comuns. Este estudo avalia o impacto hidrológico de microrreservatórios projetados de acordo com as diretrizes de Belo Horizonte (Minas Gerais, Brasil), tanto em nível de lote quanto de bacia, por meio de modelagem hidrológica em uma sub-bacia altamente impermeável e suscetível a inundações. Os resultados indicam que, embora as diretrizes existentes sejam eficazes, o dimensionamento do volume do microrreservatório pode ser aprimorado. Os microrreservatórios implementados em 31,8% da área da bacia reduziram consideravelmente as vazões de pico, embora a eficiência varie conforme a escala espacial. Em nível de lote, os escoamentos foram reduzidos em 72,3% (Tempo de Retorno - TR 2 anos) e 50,7% (TR 100 anos), com atraso nos tempos de pico de 41,7%. Na escala da bacia, as reduções da vazão de pico foram de 24,6% (TR 2 anos) e 26,4% (TR 100 anos). A propagação das vazões até o exutório da bacia mostrou reduções nos volumes de extravasamento do canal e nas alturas máximas de água de 75,5% (TR 2 anos), 54% (TR 10 anos) e 49% (TR 50 anos).

Palavras-chave: Microrreservatórios de lote; Técnicas compensatórias de drenagem; SWMM; Avaliação hidrológica de bacia urbana.

INTRODUCTION

Pluvial flooding typically occurs as a result of localized, short-duration, high-intensity rainfall events that produce substantial surface runoff volumes, exceeding the capacity of the stormwater drainage system to convey the water efficiently (Cea et al., 2025; Palla et al., 2018). Urban areas are highly susceptible to pluvial flooding due to a combination of factors, including steep slopes draining into low-lying flatlands, extensive impervious surfaces, low land cover roughness, siltation of water bodies, debris accumulation in stormwater drainage systems, and the frequent inefficiency of these systems (Cea et al., 2025; Rosa et al., 2023). Rising urbanization and the increasing frequency of extreme hydroclimatic events driven by climate change are expected to intensify the impacts of urban pluvial flooding worldwide in the coming decades (Kourtis & Tsihrintzis, 2021; Yin et al., 2018).

For many years, stormwater management in urban areas focused on rapidly directing runoff downstream by straightening and channeling riverbeds. This approach helped to prevent or reduce pluvial flooding and enabled the construction of roads and avenues over the channeled waterways (Bertrand-Krajewski, 2021; Chocat et al., 2001). However, these policies have led to significant environmental impacts at the intervention sites and downstream of urban areas (Fletcher et al., 2013). Discussions on mitigating these impacts began in the 1960s, coinciding with the rise of environmental awareness in developed countries (Bertrand-Krajewski, 2021; Delleur, 2003). New technologies, known as Low Impact Development (LID) techniques —referred to by various names (see Fletcher et al., 2015 for further information) — were developed to address these issues and minimize the environmental impacts of urbanization and conventional stormwater management practices.

Among the developed techniques, near-source runoff solutions are particularly well-suited for areas with limited space for large-scale interventions. Both Brazil and other countries have reported satisfactory results in reducing the impact of surface runoff using such methods (Eckart et al., 2017; Li et al., 2019; Rosa et al., 2023). Parcel-level on-site stormwater detention (OSD), a type of low-impact development device, temporarily store runoff from impervious surfaces to help maintain peak flows at levels consistent with pre-urbanization conditions, delivering immediate local benefits (Drumond et al., 2023). These devices are highly adaptable for retrofitting, as they provide stormwater storage solutions in space-constrained areas (Walsh et al., 2014), a common condition in densely populated urban regions. Additionally, they can be installed underground to optimize space usage (Hager et al., 2019) and are considered one of the most cost-effective low-impact development options for residential areas (Liu et al., 2021; Putri et al., 2023). Devices that collect rainwater to supplement domestic water supplies, also known as rain barrels or rainwater harvesting devices, offer the added benefits of reducing the burden on water utility systems and lowering water bills (Liu et al., 2021; Molaei et al., 2019; Walsh et al., 2014). However, in many Brazilian regions with uneven rainfall distribution throughout the year, balancing the need to store water for consumption while keeping the system available to capture future rainfall presents a significant challenge and these devices have limited effectiveness in flood mitigation (Dornelles, 2012).

Key challenges related to on-site stormwater detention implementation, as identified in recent studies (Drumond et al., 2022; Drumond et al., 2020; Ronalds et al., 2019; Schellin et al., 2022) are: improve design criteria, defining the characteristics that will yield the greatest positive hydrological impact; encouraging citizens to adopt a technique that may involve high installation costs and ongoing maintenance; and developing municipal public policies, informed by scientific analysis, to guide and promote the proper use of these structures.

In Brazil, while some cities have recognized the need for new approaches to urban stormwater management to address contemporary challenges, there remains a significant gap in information, standardization, design criteria, and transfer of scientific knowledge into practice. In the city of Belo Horizonte (Minas Gerais, Brazil), the new Master Plan, Law Nº. 11,181, dated August 8, 2019 (Belo Horizonte, 2019), mandates the inclusion of permeable areas in parcels or the installation of on-site stormwater detention to mitigate the surface runoff impacts. The responsibility for defining drainage project design criteria was entrusted to the municipal Urban Water Management Department (DGAU), which commissioned the Department of Hydraulic Engineering and Water Resources at the Universidade Federal de Minas Gerais to coordinate the elaboration of the "Technical Instruction for the Development of Drainage Studies and Projects" (Belo Horizonte, 2024). This technical instruction provides guidelines for designing drainage infrastructure and various low-impact development (LID) devices, including on-site stormwater detention, based on an individual-scale evaluation of each technique.

In this context, this study aims to evaluate the performance and hydrological impact of on-site stormwater detention, designed according to Belo Horizonte's municipal guidelines (Belo Horizonte, 2022), using hydrological modeling. The assessment is conducted at both the parcel and catchment scales within a highly impervious subcatchment prone to pluvial flooding in Belo Horizonte. As far as the authors are aware, this is the first study to evaluate the efficiency of Belo Horizonte's new municipal guidelines in controlling surface runoff across different spatial scales (parcel and catchment). We provide a detailed and critical assessment of the procedures required to adapt the design of on-site stormwater detention to the available tools in the hydrological model. Additionally, this study promotes the dissemination of design guidelines for on-site stormwater detention, supporting the broader adoption of low-impact development practices within the Brazilian context.

ON-SITE STORMWATER DETENTION DESIGN CRITERIA IN BELO HORIZONTE CITY

According to Belo Horizonte's new Master Plan, on-site stormwater detention is required to capture surface runoff from the impervious areas of each parcel within the municipal territory, with few exceptions. The total volume of on-site stormwater detention is determined based on a rate of 30 $L.m^{-2}$ of impervious area, with 80% of the total calculated volume allocated to a 1st chamber and the remaining 20% to a 2nd chamber (Belo Horizonte, 2022), as illustrated in Figure 1.

Figure 1. On-site stormwater detention schematic.

The first chamber is designed to attenuate the peak flow of the post-urbanization hydrograph to match the pre-urbanization peak flow, based on a design storm with a 2-year return period and a 120-minute duration. The 2-year return period is used to represent flow rates that closely resemble the natural peak flows resulting from more frequent rainfall events.

The second chamber must attenuate at least 50% of the peak flow from the post-urbanization hydrograph for a design storm with a 100-year return period and a 120-minute duration. The 100-year return period is used to attenuate the peak flows from extreme rainfall events which typically cause the most severe disruptions to the city's drainage system.

The PBH design criteria adopt a 120-minute design storm duration, aligning with the concentration time of the municipality's largest catchment. This selection was further validated by parcel-scale hydrological simulation results and monitoring data from two experimental on-site stormwater detention systems in Belo Horizonte, which confirm the adequacy of this duration for effective sizing of on-site stormwater detention devices (Belo Horizonte, 2022).

The two chambers are connected by the overflow of excess water from the first to the second chamber.

Design rainfall intensity and its temporal distribution are obtained from an intense rainfall equation developed for the Metropolitan Region of Belo Horizonte by Pinheiro & Naghettini (1998). A recent study by Rodrigues (2020) confirmed that this equation remains valid for the region. The pre- and post-urbanization inflow into on-site stormwater detention are calculated using the Modified Rational Unit Hydrograph Method – HUMRM (Smith & Lee, 1984). PBH (Belo Horizonte, 2022) recommended adopting a surface runoff coefficient of 0.25 for pre-urbanization hydrographs and 0.90 for post-urbanization hydrographs.

The diameter of the outlet orifice of the first chamber is determined using the design storm with a 2-year return period and a 120-minute duration, combined with the height of the detention device, and the general orifice equation, Equation 1 (Azevedo Netto, 2015).

$$Q = Cd * A * \sqrt{2 * g * h} \quad (1)$$

Where: Cd is the discharge coefficient; A is the cross-sectional area of the bottom orifice; g is acceleration due to gravity; and h is the hydraulic head over the center of the orifice.

The discharge coefficient is determined based on the ratio of the pipe's diameter to its length, according to the classification proposed by Azevedo Netto (2015), who suggests the following values: 0.61 for orifices, 0.82 for nozzles, and 0.90 for short pipes. PBH (Belo Horizonte, 2022) recommends the use of orifices as flow outlet devices, and adopting for the second chamber, an outlet orifice diameter equal to that calculated for the first chamber.

The overflow pipe must have a diameter greater than or equal to the diameter of the inlet pipe. PBH (Belo Horizonte, 2022) advises against directly connecting the overflow pipe and the public drainage network. This ensures that any overflow remains visible on-site, thereby facilitating the detection of potential clogs or obstructions in the outlet orifices. The discharge from the on-site stormwater detention must occur by gravity (Belo Horizonte, 2022). As such, the design must account for the elevation of both the bottom of the proposed device and the discharge point in the public drainage network—whether into a street gutter or an existing stormwater manhole.

The final sizing of the on-site stormwater detention must be performed using the Puls routing method, based on the established post-urbanization hydrographs. If the required restricted flow rates are not achieved in the first simulation, the geometry must be adjusted until the target performance is reached.

MATERIAL AND METHODS

Study area

The Luxemburgo subcatchment was selected as a case study. The catchment is located in the central-south region of Belo Horizonte city, covering an area of 92.4 hectares. It is predominantly urban, with residential and commercial buildings occupying most of the territory (Figure 2). Notably, only 6.9% of the parcels within the catchment consist of permeable areas.

The main channel of the Luxemburgo subcatchment flows through a channelized section beneath Guaicuí Street and discharges into the Leitão stream at Prudente de Morais Avenue. A large portion of Leitão stream's main channel is enclosed, and the downstream areas of its catchment frequently experience flooding (Rosa et al., 2020). The Luxemburgo subcatchment is situated just upstream of the most critical area of the Leitão creek catchment. Attenuating surface runoff in Luxemburgo subcatchment directly helps to reduce the flooding impacts in the central area of Belo Horizonte.

Hydrological model

The Storm Water Management Model (SWMM) is the hydrological model used in this study. It was developed by the United States Environmental Protection Agency (EPA) to perform numerical simulations of runoff in urban drainage systems (Rossman & Huber, 2016). SWMM performs calculations based on the conservation equations of mass, energy, and momentum. The user can choose between the Curve Number (CN), Green-Ampt, or Horton methods to account for effective rainfall. Surface runoff is calculated by treating each subcatchment as a nonlinear reservoir, with modifications to Manning's equation. Flood routing in the system's channels and conduits follows the principles of mass and momentum conservation for gradually varied and unsteady flow, using the one-dimensional Saint-Venant equations (Rossman, 2017).

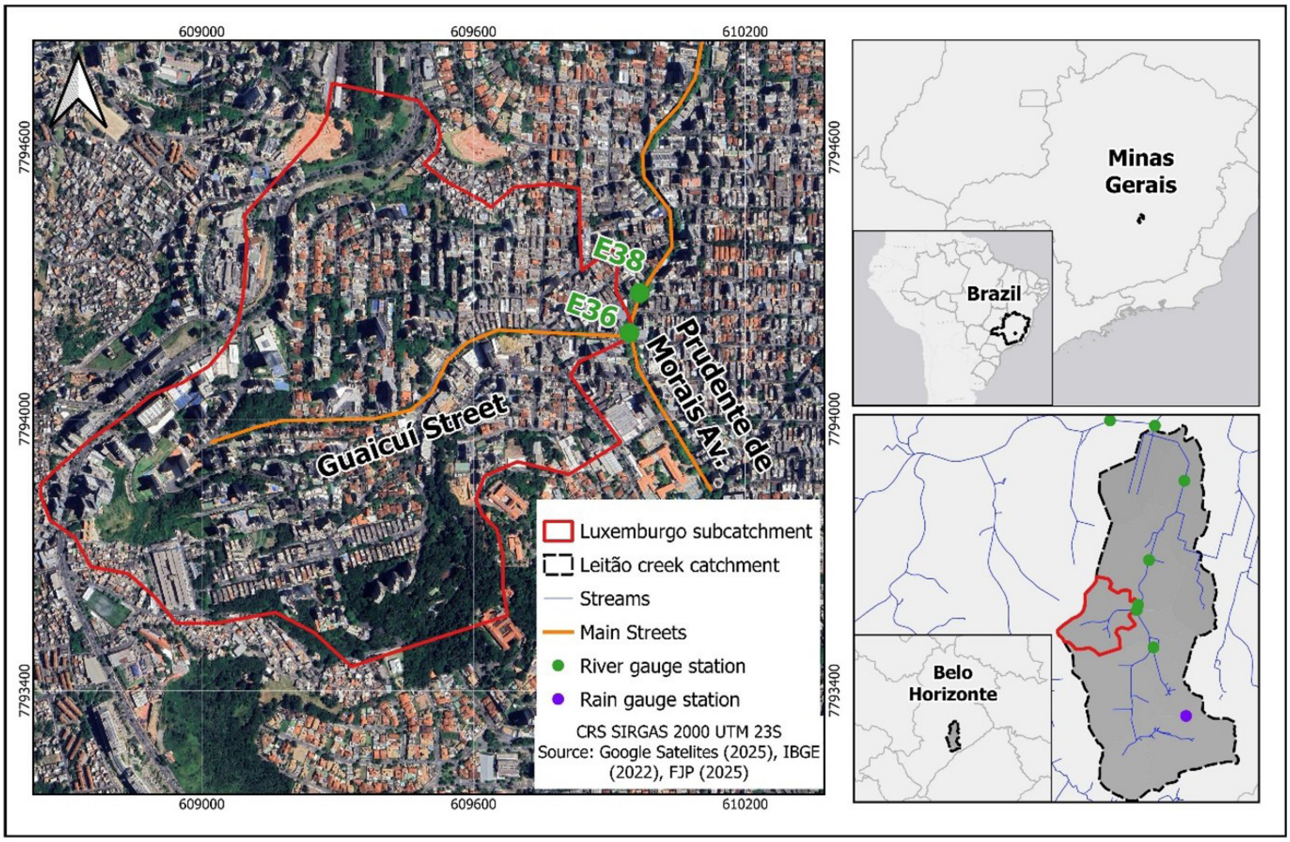

Figure 2. Location of Luxemburgo subcatchment and monitoring stations within Leitão creek catchment, in Belo Horizonte, Minas Gerais, Brazil.

In SWMM, the rainfall-runoff process is modeled using *rain gauges* and *subcatchments*, while the drainage system is represented as a network of *nodes* and *links*. Nodes serve as junctions, flow dividers, storage units, or outfalls, and links connect these nodes through conduits (pipes and channels), pumps, or flow regulators such as orifices, weirs, or outlets (Rossman & Huber, 2016). To represent on-site stormwater detention on parcels, the software offers two distinct options. The first, a *storage unit*, is integrated into the drainage system as a node structure that stores runoff water until its full capacity is reached. Water may exit the unit through surface evaporation, overflow, infiltration through the bottom and/or sides, or via a bottom drainage structure. The main input parameters for simulating the storage unit are the maximum water height capacity; the initial water level within the structure at the start of the simulation; the evaporation factor; the soil characteristics of the sides and bottom; and the storage curve, which represents the water level heights and their corresponding surface areas inside the storage unit (Rossman, 2017). The volume of the storage unit is calculated at each time step using the water balance equation (Equation 2). The water level inside the unit is computed by interpolating the volume data from the storage curve.

$$V^{t+\Delta t} = V^t + 0.5*\left(Q_e^t + Q_e^{t+\Delta t}\right)*\Delta t - 0.5*\left(Q_s^t + Q_s^{t+\Delta t}\right)*\Delta t \quad (2)$$

Where: $V^{t+\Delta t}$ is the storage unit volume at time step $t+\Delta t$; V^t is the storage unit volume at time step t; Q_e is the inflow; and Q_s is the outflow.

Outflow from the storage unit through a bottom orifice is calculated using the general orifice equation as described in Equation 1.

Overflow from the storage unit is determined using Equation 3 (Rossman, 2017).

$$Q = Cw * L * \left(H - Z\right)^{1.5} \quad (3)$$

Where: Cw is the discharge coefficient, L is the length of the spillway crest; H is the water level from the unit bottom; and Z is the orifice height from the unit bottom. SWMM estimates both Cw and L.

The second SWMM option for representing an on-site stormwater detention is through the Low Impact Development (LID) module. The *rain barrel* is a rainwater storage unit with an integrated drainage device. In SWMM, the rain barrel is treated as a property of the subcatchment, with inflow originating from both permeable and impervious areas, as well as other LID structures. Outflow from the rain barrel can occur through surface overflow or a bottom drain (Rossman & Huber, 2016).

Rain barrel input parameters include: the maximum water level height, cross-sectional area, drain offset height relative to the bottom, drain delay (the time before the drain opens after rainfall stops), drain coefficient, and drain exponent. Bottom drain outflow is computed using Equation 4.

$$q = Ch^n \quad (4)$$

Where q is the outflow ($mm.h^{-1}$); C is the drain coefficient ($mm.h^{-1}$); h is the water level above the drain (mm); and n is the drain exponent, typically 0.5 for orifices (Rossman & Huber, 2016). The drain coefficient is calculated by Equation 5.

$$C = 0.6 * \sqrt{2 * g} * \frac{Ao}{Arb} \tag{5}$$

Where C is the drain coefficient; g is acceleration due to gravity; Ao is the cross-sectional area of the drain orifice; and Arb is the cross-sectional area of the rain barrel (Rossman & Huber, 2016).

Modeling Luxemburgo catchment

The model of the Luxemburgo subcatchment used in this study was developed, calibrated, and validated by Rosa et al. (2020). The constructed model estimates infiltration using the Curve Number (CN) method, transforms rainfall into runoff by treating the subcatchment as a nonlinear reservoir, and maintains a base flow of 0.17 m^3/s in the main closed channel. Flow routing is carried out using the dynamic wave method to account for backwater effects, with a processing time step of 1.0 second. Numerical continuity errors for flow and total runoff volume were kept below 3%.

Rosa et al. (2020) used 20 monitored rainfall events between 2011 and 2015 to manually calibrate the model (seven events) and validate it (13 events).

The calibration and validation processes accounted for the hydrological behavior of the entire Leitão stream catchment. However, the parameters were individually calibrated for each subcatchment, ensuring they were specifically tailored to accurately reflect the specific hydrological characteristics of each area. The Luxemburgo subcatchment was calibrated and validated using data from the river gauge E36 (Figure 2) (Rosa et al., 2020).

On-site stormwater detention design following the municipal criteria

To determine the impervious areas contributing to on-site stormwater detention in the parcels of the Luxemburgo subcatchment, a vector file created from an aerial image, containing polygons representing each building, was used (Prodabel, 2015). A manual correction was carried out to include paved yards, balconies, and parking lots as impervious areas using a 2021 Google® Satellite image in the QGIS geoprocessing software (version 3.16).

A total of 923 impervious areas were delineated, accounting for 31.8% of the total catchment area. These areas were categorized into nine classes to facilitate the implementation of nine different types of on-site stormwater detention in the SWMM model. Figure 3 shows the location of the impervious areas, and the corresponding area ranges applied to each class. A representative impervious area value for each area class was calculated as the arithmetic mean of all identified impervious surfaces within a class (Table 1).

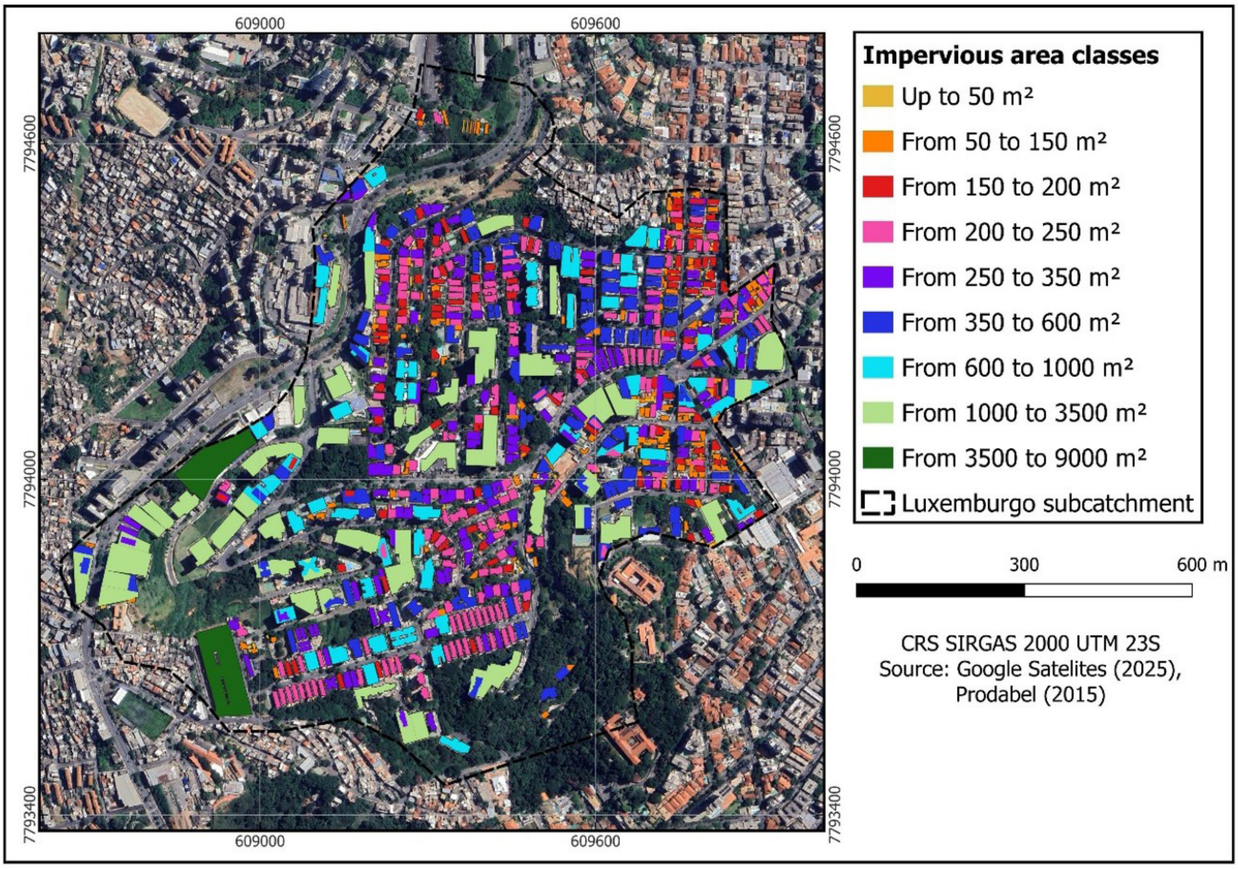

Figure 3. Location of the impervious areas and the corresponding area range applied to each class.

Table 1. On-site stormwater detention sizing according to the impervious area class.

Class	Adopted contributing area (m^2)	Total volume (m^3)	1st chamber volume (m^3)	2nd chamber volume (m^3)	Drain diameter (mm)
Up to 50 m^2	22	0.66	0.528	0.132	6.5
From 50 to 150 m^2	96	2.88	2.304	0.576	13.4
From 150 to 200 m^2	180	5.4	4.320	1.080	18.4
From 200 to 250 m^2	225	6.75	5.400	1.350	20.6
From 250 to 350 m^2	298	8.94	7.152	1.788	23.7
From 350 to 600 m^2	421	12.63	10.104	2.526	28.1
From 600 to 1000 m^2	755	22.65	18.12	4.53	37.7
From 1000 to 3500 m^2	1,657	49.71	39.768	9.942	55.9
From 3500 to 9000 m^2	8,252	247.56	198.048	49.512	124.7

The design storms were determined using the IDF curve for the Belo Horizonte Metropolitan Region proposed by Pinheiro & Naghettini (1998), applying a 12-minute time discretization, following the municipal design guidelines which recommend a temporal resolution corresponding to 10% of the total rainfall duration (Belo Horizonte, 2022).

The total volume of on-site stormwater detention was calculated considering 30 L $\cdot m^{-2}$ of impervious area (Belo Horizonte, 2022), with 80% allocated to the 1st chamber and 20% to the 2nd chamber (see Table 1 for on-site stormwater detention volumes by impervious area class). The drain diameter of the 1st chamber was calculated using Equation 6.

$$D = \sqrt{\frac{4\,.\,Q}{\pi\,.\,Cd\sqrt{2gh}}} \tag{6}$$

Where: D is the diameter; Cd is the discharge coefficient; Q is the outflow; g is acceleration due to gravity; and h is the hydraulic head over the center of the orifice.

The maximum water level height for on-site stormwater detention across all classes was set at 1.0 m, and the discharge coefficient was set to 0.61, as recommended by Azevedo Netto (2015) for orifices. Initially, the drain of the 2nd chamber was designed to be identical to that of the 1st chamber. Additionally, an overflow pipe with a defined diameter was incorporated into the 2nd chamber to manage overflow, which activates once the water level surpasses 1.0 m. The overflow pipe diameters for contributing areas up to 421 m^2 were set to 100 mm, for areas of 755 and 1657 m^2, they were set to 200 mm, and for the contributing area of 8,252 m^2, the diameter was set to 400 mm. The initial design characteristics of on-site stormwater detention for each of the nine classes are presented in Table 1.

The sizing verification of on-site stormwater detention's 1st chamber in SWMM was performed as follows:

- The parcel widths were calculated according to Equation 7 and 8 (Garcia & Paiva, 2006), with the perimeter being the perimeter arithmetic mean of each class:

$$W = \frac{Kc\sqrt{A}}{1.12}\left[1-\sqrt{1-\frac{1.128}{kc}^{2}}\right] \tag{7}$$

$$Kc = 0.282\frac{P}{\sqrt{A}} \tag{8}$$

Where: A is the impervious area; P is the perimeter; and Kc is the compactness coefficient.

- The percentage of the parcel's impervious area (Ai) was set to 100%, implying that no infiltration losses were considered;
- The rain barrel tool from the LID module was used to represent the 1st on-site stormwater detention chamber in the subcatchments.

After setting the input parameters, the design storm with a 2-year return period and a 120-minute duration was simulated. The effective rainfall was calculated by multiplying the total rainfall by the surface runoff coefficient for post-urbanization conditions (0.90). This effective rainfall was then input into the SWMM model as a time series in the rain gage, ensuring that the generated hydrograph closely resembled that produced by the HUMRM method, as recommended by PBH (Belo Horizonte, 2022). The rain barrel volumes were adjusted until the peak outflows from the subcatchments matched or remained below the peak flows of the pre-urbanization hydrographs for the same design storm.

The sizing verification of on-site stormwater detention's 2nd chamber in SWMM was conducted as follows:

- For the already designed 1st chamber, the effective design storm with a 100-year return period and a 120-minute duration was simulated;
- The overflow from each rain barrel was used as the inflow for the storage unit, which represented the on-site stormwater detention's 2nd chamber;
- Storage unit outflows (both drained and overflowed) were added to the total outflow from the rain barrels in the LID module.

The volumes of the 2nd chambers and the drain diameters were adjusted until the peak outflows were reduced to 50% or less of the peak flows from the post-urbanization hydrographs for the 100-year return period storm with a 120-minute duration.

Assessing critical rainfall duration in the catchment before and after on-site stormwater detention implementation

To evaluate the impact of implementing parcel-level on-site stormwater detention - designed according to Belo Horizonte's guidelines - on the critical rainfall duration for the Luxemburgo subcatchment, synthetic rainfall intensities were calculated using

Table 2. Simulated scenarios.

Scenario	Assessment target	Rainfall return period (years)	Rainfall duration (minutes)	On-site stormwater detention?
Sub2-NoSD	Subcatchment runoff	2	120	No
Sub2-YesSD	Subcatchment runoff	2	120	Yes
Sub100-NoSD	Subcatchment runoff	100	120	No
Sub100-YesSD	Subcatchment runoff	100	120	Yes
Chan2-NoSD	Channel flow routing	2	Critical	No
Chan2-YesSD	Channel flow routing	2	Critical	Yes
Chan10-NoSD	Channel flow routing	10	Critical	No
Chan10-YesSD	Channel flow routing	10	Critical	Yes
Chan50-NoSD	Channel flow routing	50	Critical	No
Chan50-YesSD	Channel flow routing	50	Critical	Yes

the IDF curve proposed by Pinheiro & Naghettini (1998) for Belo Horizonte Metropolitan Region. The return periods considered for this study were 2 and 100 years, and the assessed durations were 10, 15, 30, 45, 60, 120, and 180 minutes. The design hyetographs were derived from the temporal rainfall distribution graphs (Pinheiro & Naghettini, 1998), utilizing the 50% exceedance probability curve.

Impact of on-site stormwater detention implementation at the catchment scale

To assess the impact of parcel-level on-site stormwater detention on the outflow of the Luxemburgo subcatchment, four scenarios were defined, varying the design storm characteristics and the presence (or absence) of on-site stormwater detention (from scenario Sub2-NoSD to scenario Sub100-YesSD in Table 2). To assess the impact of using the LID technique on main channel discharges, six scenarios varying the design storm characteristics and the presence (or absence) of on-site stormwater detention (from scenario Chan2-NoSD to scenario Chan50-YesSD in Table 2) were defined. The 2-year return period was used to represent channel response under frequent rainfall events, while the 10 and 50-year return periods were selected to reflect the system behavior under more severe storm conditions, as recommended by PBH (Belo Horizonte, 2022). The critical rainfall duration was adopted to evaluate the worst-case hydrological response on the main drainage network.

The impact on channel discharges was assessed by analyzing changes in the total overflow volume and the maximum overflow height along 14 junctions between sections of Guaicuí Street (Figure 4), beneath which the catchment's main channel flows. The minor drainage system of the Luxemburgo subcatchment was not considered in this study.

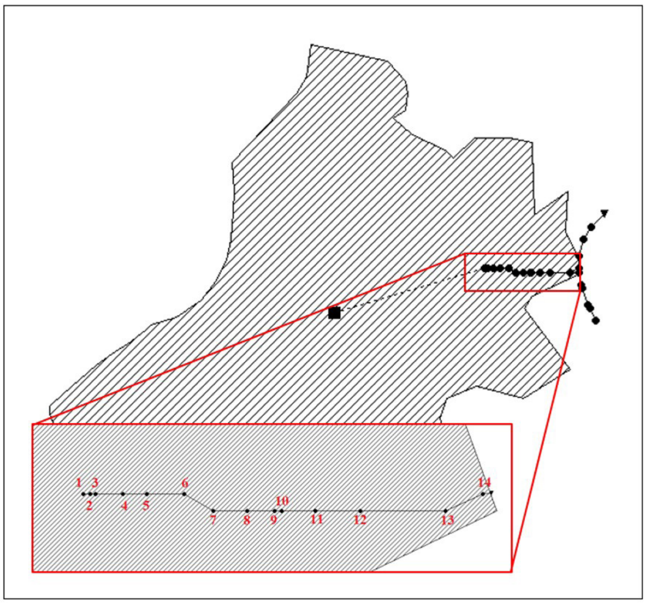

Figure 4. Junctions of the channel beneath Guaicuí Street represented in the SWMM model.

RESULTS AND DISCUSSIONS

On-site stormwater detention redesign

After verifying the initial sizing of on-site stormwater detention in SWMM, the updated dimensions (Table 3) showed an average volume increase of 5.8% for the 1st chamber and 54.1% for the 2nd chamber (excluding the first impervious area class). Additionally, the drain diameters of the 2nd chambers increased by an average of 32.7%.

The sizing of the on-site stormwater detention's 1st chamber, designed to store 80% of the total volume as per PBH (Belo Horizonte, 2022), was sufficient to meet the municipality's criteria for reducing outflow peaks. The 1st chamber effectively attenuated the post-urbanization peak flow to align with the pre-urbanization peak flow, based on a design storm with a 2-year return period and a 120-minute duration.

However, the initial volumes allocated to the 2nd chambers (20% of the total on-site stormwater detention volume) were inadequate to attenuate at least 50% of the post-urbanization peak flow for a design storm with a 100-year return period and a 120-minute duration. Both the 2nd chamber volumes and drain diameters needed to be increased to meet this requirement.

Comparing the calculation methods underlying the guidelines for on-site stormwater detention sizing recommended by PBH (Belo Horizonte, 2022) with the modeling conducted in this study, it was found that the outflows drained by the 1st chambers in the

Table 3. On-site stormwater detention updated sizing according to the impervious area class.

Class	Adopted contributing area (m²)	1st chamber volume (m³)	Increase in 1st chamber volume	2nd chamber volume (m³)	Increase in 2nd chamber volume	Drain diameter in 2nd chamber (mm)	Increase in Drain diameter in 2nd chamber
Up to 50 m²	22	0.55	4.2%	0.132	0%	6.5	0%
From 50 to 150 m²	96	2.43	5.5%	1.35	57.3%	21.0	36.3%
From 150 to 200 m²	180	4.60	6.5%	2.60	58.5%	28.0	34.2%
From 200 to 250 m²	225	5.75	6.5%	3.25	58.5%	30.0	31.4%
From 250 to 350 m²	298	7.63	6.7%	4.40	59.4%	33.0	28.2%
From 350 to 600 m²	421	10.74	6.3%	5.60	54.9%	42.0	33.0%
From 600 to 1000 m²	755	19.20	6.0%	10.20	55.6%	55.0	31.4%
From 1000 to 3500 m²	1,657	42.03	5.7%	21.20	53.1%	85.0	34.3%
From 3500 to 9000 m²	8,252	207.03	4.5%	77.00	35.7%	124.0	0%

Table 4. Updated storage rate and volume distribution between chambers.

Class	Adopted contributing area (m²)	Total volume (m³)	Storage rate (L. m⁻²)	1st chamber volume	2nd chamber volume
Up to 50 m²	22	0.68	31.0	80.7%	19.3%
From 50 to 150 m²	96	3.78	39.4	64.3%	35.7%
From 150 to 200 m²	180	7.20	40.0	63.9%	36.1%
From 200 to 250 m²	225	9.00	40.0	63.9%	36.1%
From 250 to 350 m²	298	12.03	40.4	63.4%	36.6%
From 350 to 600 m²	421	16.34	38.8	65.7%	34.3%
From 600 to 1000 m²	755	29.40	38.9	65.3%	34.7%
From 1000 to 3500 m²	1,657	63.23	38.2	66.5%	33.5%
From 3500 to 9000 m²	8,252	284.03	34.4	72.9%	27.1%

PBH sizing were, on average, 7.9% higher than those obtained in the SWMM simulations. As a result, the undrained portion was necessarily transferred to the 2nd chamber in SWMM, requiring larger storage volumes. This difference is likely due to the distinct flow routing methods used, with PBH (Belo Horizonte, 2022) employing the Puls method, while SWMM uses the water balance equation in the LID module. Additionally, the calculation time step adopted in this study was 1-minute, while 12 minutes time step was employed by PBH (Belo Horizonte, 2022). A test simulation in SWMM for a contributing area of 96 m² using a 12-minute time step demonstrated that the time step had an impact, with on-site stormwater detention's outflow hydrograph showing a peak flow 8.2% lower compared to the simulation with a 1-minute time step.

Based on the updated volumes and drain diameters obtained from the SWMM simulation, the actual storage rates for each impervious area and the percentages allocated to each chamber were calculated. The results are shown in Table 4.

For impervious areas of 50 m² or smaller, the PBH (Belo Horizonte, 2022) on-site stormwater detention sizing guidelines (30 L.m^{-2} of impervious area, with 80% of the volume allocated to the 1st chamber and 20% to the 2nd chamber) proved adequate. However, for larger impervious areas, the average storage rate was 39.4 L.m^{-2}, with 65.7% allocated to the 1st chamber and 35.3% to the 2nd chamber. Based on these results, we recommend a storage rate of 40 L.m^{-2} of impervious area, distributed as 65% and 35% for the 1st and 2nd chambers, respectively, to meet the outflow restrictions for both design storms. However, the adoption of these values should be confirmed through comparison with monitored data from full-scale on-site stormwater detention, as this will help determine the most realistic guidelines.

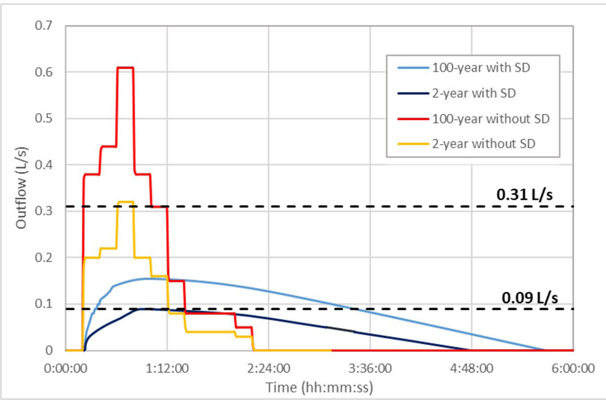

Figure 5. Outflow hydrographs from an impervious area of 22 m², with and without on-site stormwater detention (SD), for design storms with return periods of 2 and 100 years. Peak flow thresholds: 0.09 L/s (pre-urbanization flow for a design storm with a 2-year return period and 120-minute duration) and 0.31 L/s (50% of the post-urbanization flow for a design storm with a 100-year return period and 120-minute duration).

Outflow hydrographs of impervious areas with and without on-site stormwater detention were compared. Figures 5 and 6 illustrate the hydrographs for contributing impervious areas of 22 m² and 421 m², respectively.

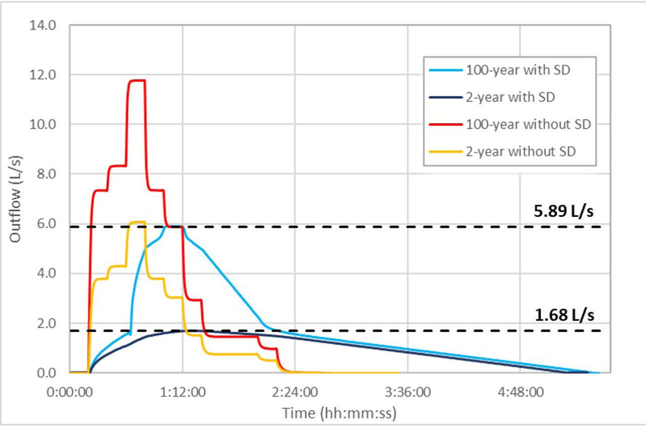

Figure 6. Outflow hydrographs from an impervious area of 421 m², with and without on-site stormwater detention (SD), for design storms with return periods of 2 and 100 years. Peak flow thresholds: 1.68 L/s (pre-urbanization flow for a design storm with a 2-year return period and 120-minute duration) and 5.89 L/s (50% of the post-urbanization flow for a design storm with a 100-year return period and 120-minute duration).

For on-site stormwater detention with a contributing impervious area of 22 m², the peak flow from the 2-year return period storm reached but did not exceed the flow threshold, indicating that the 1st chamber effectively controlled the outflow. For the 100-year return period storm, both chambers attenuated the peak flow, keeping it below the required threshold and eliminating the need for additional storage in the 2nd chamber.

The outflow hydrographs from the on-site stormwater detention in Figure 6 (contributing impervious area of 421 m²) are similar to those designed for other impervious area classes. The outflow from the 1st chamber meets the threshold for the 2-year return period storm, while the combined outflow – both drained and overflow – from both chambers meet the threshold for the 100-year return period storm. In all cases, the adopted volumes and drain diameters were selected to ensure that their combined minimum values kept peak flows below the required thresholds.

In the outflow hydrograph for the 100-year return period precipitation (Figure 6), once the flow threshold for the 1st chamber is reached, the hydrograph shape shifts as the 2nd chamber starts draining part of the runoff. The cessation of the 2nd chamber's operation is also evident when the flow threshold for the 2-year return period storm is reached during the hydrograph recession.

The 'step-like' shape of the hydrographs without on-site stormwater detention can be attributed to the discrepancy between the 12-minute timestep of the design hyetographs input into SWMM and the 1-minute calculation time step. To address this difference, SWMM divides each rainfall depth into 12 equal parts, resulting in uniform outputs over each 12-minute interval during the rainfall-runoff transformation. Since all parcels are impervious, all hydrological losses are disregarded except for initial abstractions. To assess the impact of this time discretization difference, a simulation with a 12-minute calculation timestep was run, producing smoothed hydrographs with no significant changes in runoff volumes, peak flows, or peak times.

Reductions in peak flows averaged 72.3% for the 2-year return period storm and 50.7% for the 100-year return period storm. Additionally, peak times increased by 41.7%, and hydrograph durations grew by 54.4%. These variations are expected, as the devices temporarily store the runoff from impervious areas and subsequently release it into the stormwater network, leading to extended flood hydrographs. The high efficiency of the designed on-site stormwater detention in attenuating and delaying the outflow hydrographs at the parcel scale suggests that the sizing guidelines provided by PBH (Belo Horizonte, 2022) have the potential to effectively reduce the impacts of surface runoff in urban areas.

Catchment critical rainfall duration before and after on-site stormwater detention implementation

The outflow hydrographs of the Luxemburgo catchment before on-site stormwater detention implementation, for design rainfalls with return periods of 2 and 100 years, are shown in Figures 7 and 8, respectively, with each curve representing a rainfall duration. The outflow hydrographs after on-site stormwater detention implementation, for design rainfalls with return periods of 2 and 100 years, are shown in Figures 9 and 10, respectively.

In the simulations without on-site stormwater detention, the critical rainfall duration was 10 minutes, as it produced the highest peak flows, with values of 21.94 m³/s and 52.37 m³/s for the 2-year and 100-year return periods, respectively. After implementing on-site stormwater detention, the critical duration remained 10 minutes, with peak flows of 15.41 m³/s and 36.22 m³/s for the 2-year and 100-year return periods, respectively.

The Luxemburgo catchment has a steep average slope of 35.27% and a small area (92.4 ha), resulting in short time of concentration, high runoff velocities, and short critical rainfall durations. Additionally, on-site stormwater detention attenuate runoff from only one-third of the total catchment area, which may not be enough to alter the critical rainfall duration for the two studied return periods.

The adopted methodology for simulating on-site stormwater detention (representing 1st chambers as an internal subcatchment characteristic using the LID module) combines runoff routing from all 923 impervious areas simultaneously through their respective on-site stormwater detention at the outlet, after accounting for surface runoff across the entire subcatchment while maintaining the original time of concentration. As a result, in this study, SWMM did not capture spatial variation effects related to device placement. However, a semi-distributed modeling approach can be adopted in SWMM, which may influence hydrograph peaks timing (Helfer, 2019; Tassi, 2002). Future research could investigate the impact of rain barrel implementation on critical rainfall duration by using a semi-distributed model of the Luxemburgo catchment, representing the minor drainage network and incorporating LID devices at the parcel scale.

A comparison of Figures 7 to 10 reveals the attenuation of peak flows after on-site stormwater detention implementation, with average reductions of 27.9% and 29.2% for rainfall events with return periods of 2 and 100 years, respectively. Table 5 summarizes the changes in peak flows, peak times, and base times following on-site stormwater detention implementation.

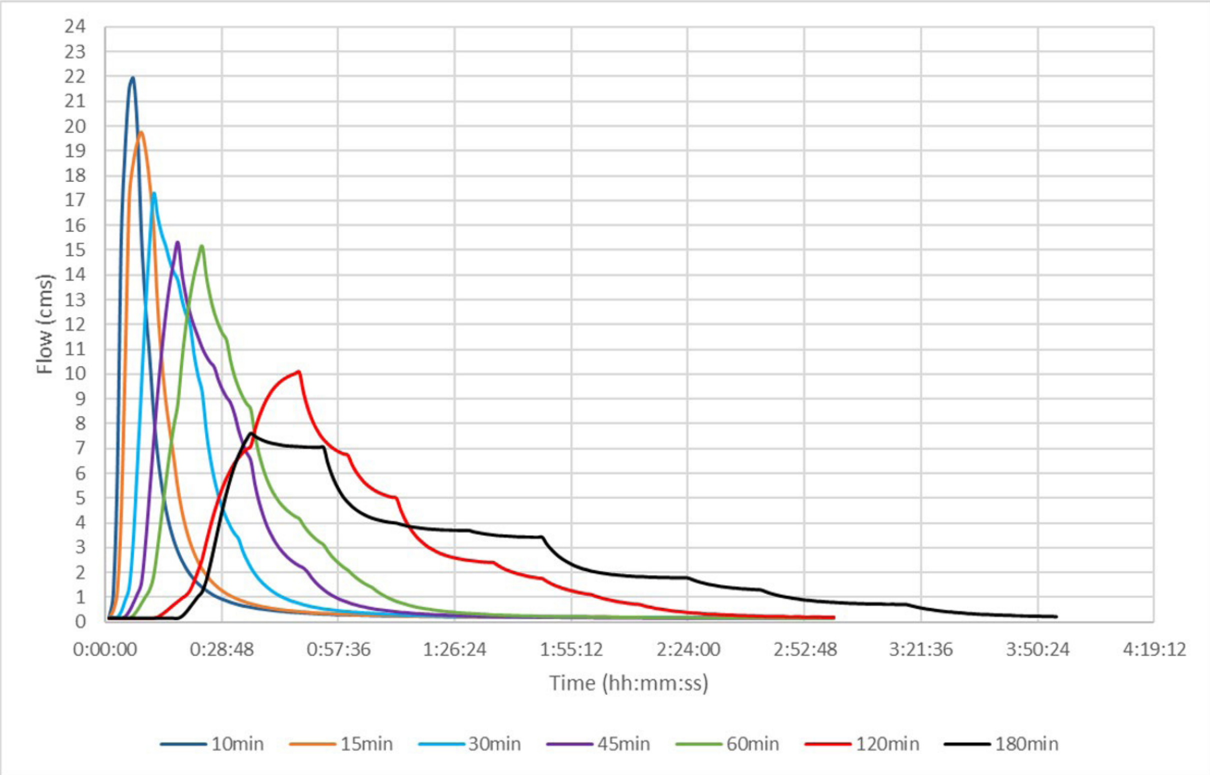

Figure 7. Outflow hydropgraphs of the Luxemburgo catchment before on-site stormwater detention implementation for design rainfalls with a 2-year return period and different durations.

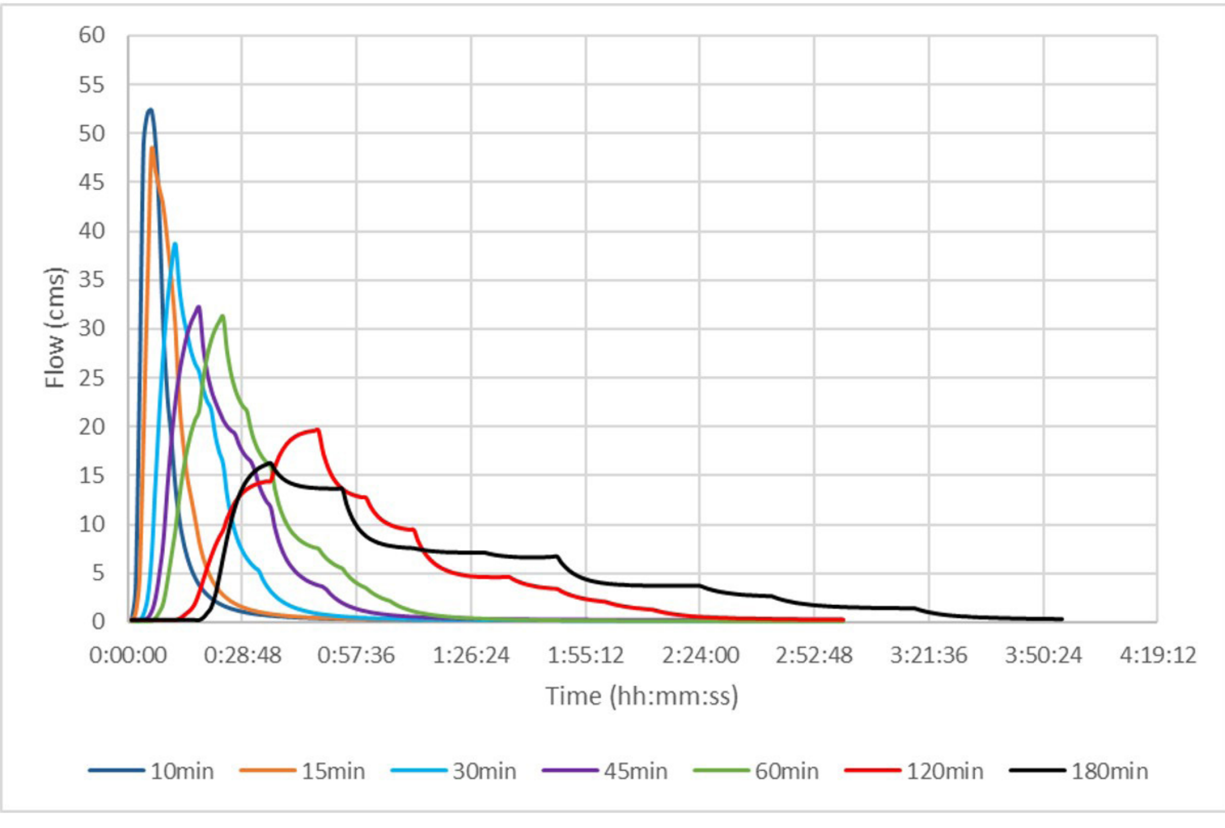

Figure 8. Outflow hydropgraphs of the Luxemburgo catchment before on-site stormwater detention implementation for design rainfalls with a 100-year return period and different durations.

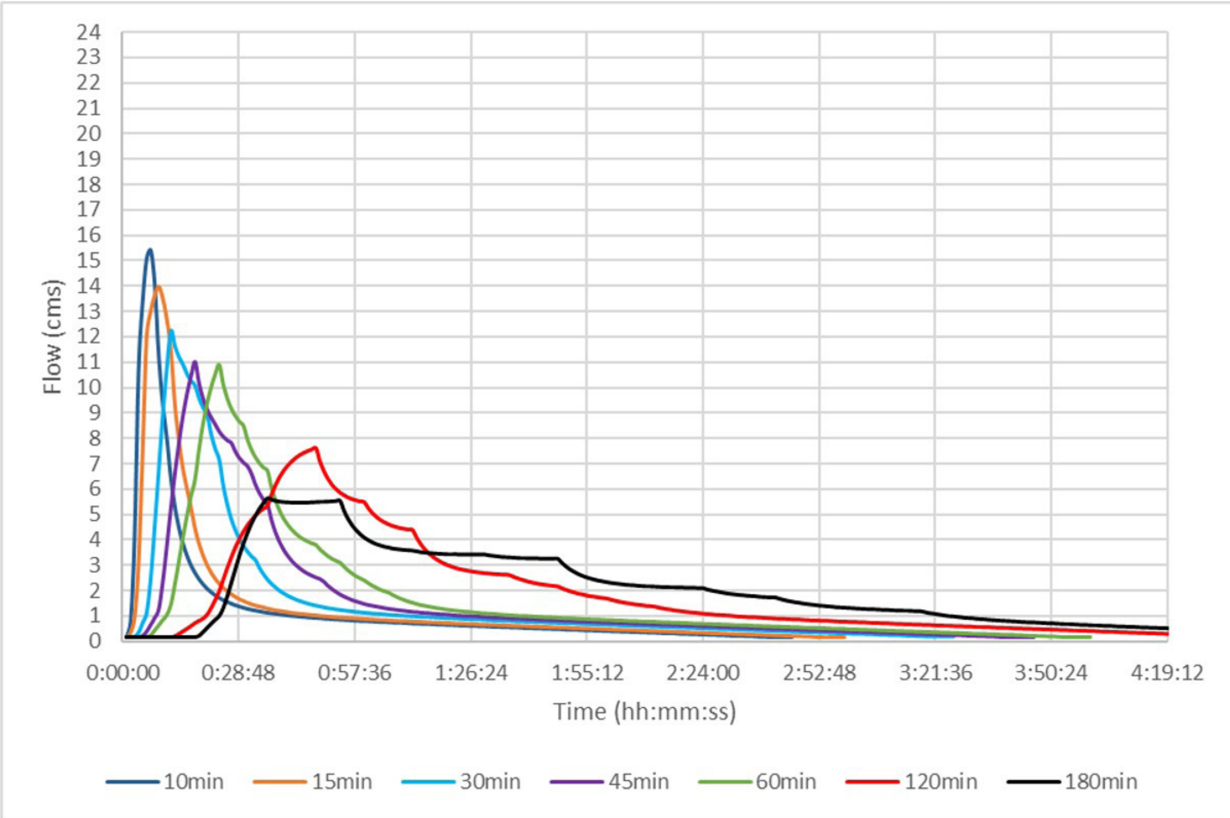

Figure 9. Outflow hydropgraphs of the Luxemburgo catchment after on-site stormwater detention implementation for design rainfalls with a 2-year return period and different durations.

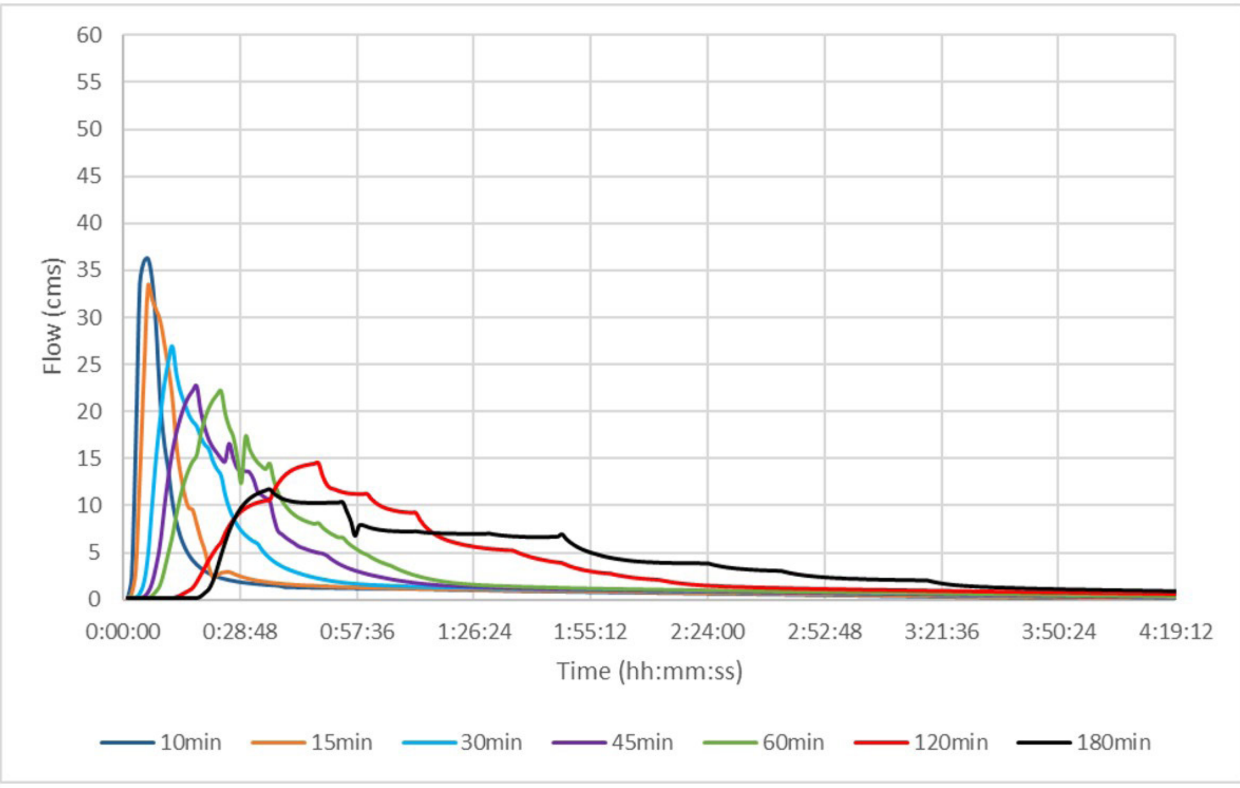

Figure 10. Outflow hydropgraphs of the Luxemburgo catchment after on-site stormwater detention implementation for design rainfalls with a 100-year return period and different durations.

Table 5. Changes in peak flows, peak times, and base times in the Luxemburgo catchment after on-site stormwater detention implementation for rainfall events with return periods of 2 and 100 years and rainfall duration ranging from 10 to 180 minutes.

Return period (years)	Rainfall duration (minutes)	Peak flow change	Peak time change	Base time change
2	10	-29.8%	0%	29.5%
	15	-29.3%		36.8%
	30	-29.3%		43.4%
	45	-29.3%		44.2%
	60	-28.0%		42.1%
	120	-24.6%		26.5%
	180	-26.0%		9.6%
100	10	-30.8%		81.5%
	15	-31.1%		84.4%
	30	-30.3%		81.2%
	45	-29.4%		73.7%
	60	-29.1%		78.4%
	120	-26.4%		74.7%
	180	-27.5%		30.9%

The greatest reductions in peak flows were observed for rainfall durations close to the critical duration, whereas longer precipitation durations reduced on-site stormwater detention efficiency. The adoption of a 120-minute design rainfall duration, as recommended by PBH (Belo Horizonte, 2022), allowed the devices to perform with high efficiency for short-duration events. No changes were observed in peak times, likely due to the same factors that explain the stability of the critical rainfall duration, namely the modeling approach for on-site stormwater detention on SWMM in this study which did not capture spatial variation effects related to device placement, and the installation of devices in only one-third of the catchment area.

Regarding hydrographs base times, on-site stormwater detention implementation increased their durations by approximately 37.1% and 72.1% for rainfall return periods of 2 and 100 years, respectively. The more pronounced increase in base time for 100-year return period rainfall events is likely due to the larger runoff volumes stored and retained in on-site stormwater detention.

On-site stormwater detention hydrological impact

Catchment impact

To assess the effect of implementing parcel-scale on-site stormwater detention at the outlet of the Luxemburgo subcatchment (prior to flow routing), four scenarios were simulated, and outflow hydrographs were generated both before and after the implementation of the devices (Figure 11). Scenarios Sub2-NoSD and Sub2-YesSD correspond to a design rainfall with a 2-year return period and a 120-minute duration, representing conditions before and after the implementation of on-site stormwater detention, respectively. Similarly, Scenarios Sub100-NoSD and Sub100-YesSD correspond to the design rainfall with a 100-year return period and a 120-minute duration, also analyzed before and after the implementation of on-site stormwater detention.

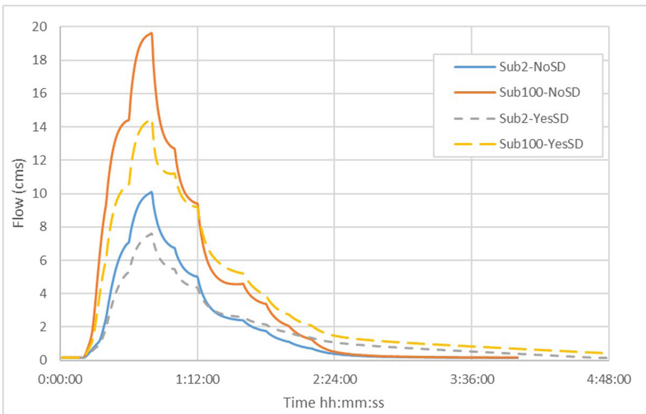

Figure 11. Outflow hydrographs from the Luxemburgo catchment for the four scenarios developed in SWMM.

The addition of on-site stormwater detention resulted in peak flow attenuation and an increase in base time. The peak flows, peak times, base times, and their percentage differences at the catchment outlet are presented in Table 6.

Compared to the average peak flow reductions observed at the parcel scale (72.3% and 50.7% for 2- and 100-year return periods, respectively), the reductions at the catchment scale were considerably lower. However, since on-site stormwater detention receive contributions from only 31.8% of the total Luxemburgo catchment area, the attenuation of peak flows can still be considered significant.

Once again, no changes were observed in the hydrograph peak times after the implementation of on-site stormwater detention.

Stormwater drainage network impact

To evaluate the impact of on-site stormwater detention implementation on the stormwater drainage network, particularly at the stream channel beneath Guaicuí Street (the catchment outlet), six scenarios were simulated using SWMM, and their respective outflow hydrographs were compared with the maximum channel capacity (4.8 $m^3.s^{-1}$) obtained after performing simulations using varying input flows rates, until identifying the maximum flow conveyable by the channel without causing overflow in the system (Figure 12).

Scenarios Chan2-YesSD and Chan2-NoSD refer to the design rainfall with a 2-year return period and a 10-minute duration, with and without on-site stormwater detention, respectively. Similarly, scenarios Chan10-YesSD and Chan10-NoSD pertain to the design rainfall with a 10-year return period and a 10-minute duration, while scenarios Chan50-YesSD and Chan50-NoSD correspond to the design rainfall with a 50-year return period and a 10-minute duration, both with and without on-site stormwater detention, respectively.

In all scenarios, channel overflows were observed as the peak flow exceeded the threshold of 4.8 $m^3.s^{-1}$. Given the high recurrence of 2-year return period rainfall events and considering that drainage channels in Belo Horizonte are designed for higher return periods, the results suggest that the stormwater drainage network of the Luxemburgo catchment lacks the capacity to manage runoff as originally designed.

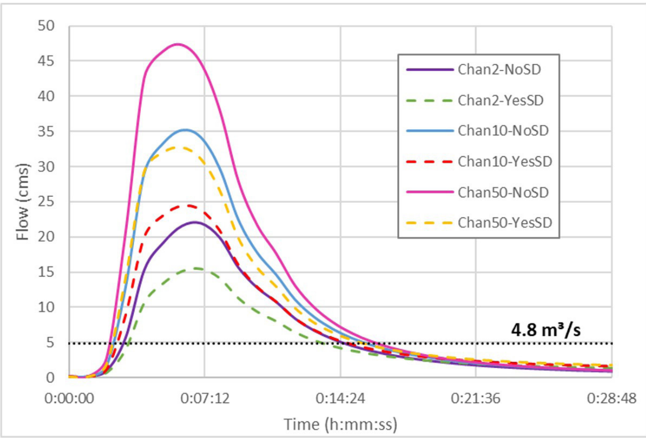

Figure 12. Outflow hydrographs of the Guaicuí Street channel in the six scenarios with and without on-site stormwater detention.

The peak flows, peak times, base times, and their percentage differences, with and without on-site stormwater detention, are detailed in Table 7.

In all three pairs of scenarios, peak flows were reduced by an average of 30.4% with the implementation of on-site stormwater detention. For the scenarios involving the 2-year return period design rainfall (Chan2-NoSD and Chan2-YesSD), this reduction was expected, as it was considered during the assessment of the critical rainfall duration, even though the hydrographs were obtained at the catchment outlet prior to flow routing through the stormwater network. Additionally, in the scenarios related to the 10 and 50-year return period rainfall (Chan10-NoSD, Chan10-YesSD, Chan50-NoSD and Chan50-YesSD) the observed peak flow reductions were slightly higher than those obtained with 2-year return period. This suggests that on-site stormwater detention perform consistently across rainfall events with return periods ranging from 2 to 100 years, demonstrating reliable effectiveness over a wide range of conditions.

As previously observed with the hydrographs obtained at the catchment outlet, there were no changes in the peak times after flow routing, which remained at 6 minutes across all scenarios. In contrast, the base times increased by an average of 32.6%, with a more pronounced increase in scenario Chan10-YesSD.

The total overflow volume and the maximum water overflow height at each junction (Figure 4) along the stormwater drainage network of Guaicuí Street were obtained during SWMM simulations (Table 8) with and without on-site stormwater detention.

All junctions experienced a significant reduction in overflow volumes (close to or exceeding 50%). The only exception was junction 13, which showed no overflow for the 2-year return period rainfall. The reductions were nearly identical for both observed variables and diminished as the return period increased.

Despite the observed reductions, overflows still occurred in the channel across all simulated scenarios. Therefore, the implementation of on-site stormwater detention across all impervious areas in the Luxemburgo catchment was not enough to fully mitigate flooding. A potential solution could be the adoption of additional LID techniques.

Table 6. Peak flow, peak time, and base time of the outflow hydrographs from the Luxemburgo catchment.

Scenarios	Peak flow ($m^3.s^{-1}$)	Peak flow change	Peak time (minute)	Base time (minute)	Base time change
Sub2-NoSD	10.07	-24.6%	48	212	20.9%
Sub2-YesSD	7.59		48	268	
Sub100-NoSD	19.63	-26.4%	48	218	31.7%
Sub100-YesSD	14.45		48	319	

Table 7. Peak flow, peak time and base time of the outflow hydrographs from the Luxemburgo catchment in the six scenarios.

Scenarios	Peak flow ($m^3.s^{-1}$)	Peak flow change	Peak time (minute)	Base time (minute)	Base time change
Chan2-NoSD	21.94	-29.8%	6	124	21.5%
Chan2-YesSD	15.41		6	158	
Chan10-NoSD	35.22	-30.8%	6	126	41.9%
Chan10-YesSD	24.46		6	192	
Chan50-NoSD	47.26	-30.6%	6	126	34.4%
Chan50-YesSD	32.72		6	217	

Table 8. Variation in the overflow volumes and the maximum water overflow height along the stormwater drainage network of Guaicuí Street.

Junction	2-year return period		10-year return period		50-year return period	
	Overflow volume change	Maximum water overflow height change	Overflow volume change	Maximum water overflow height change	Overflow volume change	Maximum water overflow height change
1	-67%	-66%	-51%	-50%	-44%	-46%
2	-81%	-81%	-52%	-53%	-46%	-47%
3	-65%	-65%	-50%	-50%	-45%	-45%
4	-58%	-59%	-48%	-48%	-44%	-44%
5	-53%	-53%	-46%	-46%	-44%	-43%
6	-100%	-100%	-59%	-59%	-51%	-51%
7	-100%	-100%	-58%	-59%	-51%	-51%
8	-100%	-100%	-59%	-59%	-50%	-51%
9	-83%	-83%	-55%	-55%	-48%	-48%
10	-78%	-76%	-53%	-53%	-47%	-47%
11	-71%	-70%	-51%	-52%	-46%	-46%
12	-100%	-100%	-100%	-100%	-68%	-68%
13	0%	0%	-58%	-59%	-52%	-51%
14	-99%	-99%	-59%	-59%	-51%	-51%
Average	-76%	-75%	-54%	-54%	-49%	-49%

Adapted from Belo Horizonte (2022).

CONCLUSIONS

This study examined the hydrological impacts of on-site stormwater detention, sized according to Belo Horizonte municipality guidelines, for a highly impervious, flood-prone urban catchment using SWMM. The model was adapted to represent two-chamber on-site stormwater detention, as specified in the guidelines, and their hydrological impact was assessed at both the parcel level and the catchment outlet before and after flow routing.

The modeling results suggest that on-site stormwater detention design should allocate 40 $L.m^{-2}$ of impervious area, with 65% of the volume stored in the first chamber and 35% in the second. To validate this recommendation, real-scale monitoring of on-site stormwater detention is advised.

On-site stormwater detention implementation across 31.8% of the catchment effectively reduced peak flows, though the magnitude of reduction varied with spatial scale. At the parcel level, outflows were reduced by an average of 72.3% (2-year return period rainfall) and 50.7% (100-year return period rainfall), with peak times delayed by 41.7%. At the catchment scale (prior to flow routing), on-site stormwater detention reduced peak flows, especially for durations close to the critical one. However, it did not delay peak times, likely due to the modeling approach applied for on-site stormwater detention placement in SWMM in this study which did not account for spatial variation effects. Additionally, the implementation of devices in only one-third of the catchment area may have limited the overall impact. Reductions in peak flows for the 2- and 100-year return period rainfall were 24.6% and 26.4%, respectively. The catchment critical rainfall duration was 10 minutes, for both with and without on-site stormwater detention scenarios.

Flow routing at the catchment outlet led to reductions in channel overflow volumes and maximum water heights by 75.5%, 54%, and 49% for 2-, 10-, and 50-year return period rainfall events, respectively. While these results are promising, flooding still occurred along Guaicuí Street during these events, indicating that additional interventions are necessary for effective flood mitigation.

Overall, the proposed SWMM model was effective in evaluating the impact of on-site stormwater detention at the parcel-level, producing results that were consistent with the methodology proposed by PBH (Belo Horizonte, 2002). At the catchment level, the model was also able to provide satisfactory responses in peak flow attenuation. However, the lack of representativeness of the device's spatial variation in Luxemburgo subcatchment prevented the evaluation of peak time delays and potentially impacted the observed peak flows. Therefore, adopting a modelling approach that incorporates catchment discretization, the minor drainage system and, the spatial distribution of LIDs would be better suited for analysis at the catchment level. Additionally, the model robustness would benefit from a more refined temporal resolution for rainfall input.

This study underscores the importance of parcel-scale on-site stormwater detention in reducing surface runoff impacts in highly impervious catchments and demonstrates the effectiveness of hydrological modeling in evaluating such methods. It also highlights the benefits of using individual LID techniques in stormwater management, demonstrating their potential for application in urban planning and sanitation in Brazil.

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DATA AVAILABILITY STATEMENT

Research data is only available upon request

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