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Adaptability of the city of Belo Horizonte to changes in rainfall patterns – a case study of the Ressaca Stream Basin

Adaptabilidade da cidade de Belo Horizonte frente às mudanças nos padrões de chuva – estudo de caso para a Bacia do Córrego Ressaca

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ABSTRACT

With the impermeabilization of urban soils and the increase in the frequency of heavy rains, conventional drainage systems have become obsolete, resulting in the occurrence of floods. In this sense, the aim of this study was to evaluate the impact of implementing urban drainage compensatory techniques in Ressaca stream basin - Belo Horizonte - MG. For this, scenarios were proposed that contemplate the current condition of occupation of the basin, verifying the possible techniques to be adopted, and a future situation, which envisages a new pattern of urban development and an equation IDF that incorporates non-stationarity conditions. The increase in peak flow rates observed when comparing the scenarios that contemplate the different perspectives of IDF, although quite expressive, could be attenuated with the implementation of techniques that contribute to reducing runoff volume. This study findings evidence the hydrological benefits that compensatory techniques could promote in the face of a scenario of changes in rainfall patterns.

Keywords: Urban resilience; Compensatory techniques; Municipal management; Climate change.

RESUMO

Com a impermeabilização dos solos urbanos e o aumento da frequência de chuvas intensas, os sistemas convencionais de drenagem tornaram-se obsoletos, resultando na ocorrência de enchentes. Nesse sentido, o objetivo deste estudo foi avaliar o impacto da implantação de técnicas compensatórias de drenagem urbana na bacia do córrego Ressaca - Belo Horizonte - MG. Para isso, foram propostos cenários que contemplam a condição atual de ocupação da bacia, verificando as possíveis técnicas a serem adotadas, e uma situação futura, que contempla um novo padrão de desenvolvimento urbano e uma equação IDF que incorpora condições de não estacionariedade. O aumento das vazões de pico observadas na comparação dos cenários que contemplam as diferentes perspectivas do IDF, embora bastante expressivo, poderia ser atenuado com a implantação de técnicas que contribuam para a redução do volume de escoamento. Os achados deste estudo evidenciam os benefícios hidrológicos que as técnicas compensatórias podem promover diante de um cenário de mudanças nos padrões de chuva.

Palavras-chave: Resiliência urbana; Técnicas compensatórias; Gestão municipal; Alterações climáticas.

INTRODUCTION

Among the leading challenges currently faced by cities, extreme events and urban floods resulting from poorly planned urbanization processes deserve mention (Battemarco et al., 2018; Oliveira et al., 2021). As the complexity of urban drainage problems increases, more comprehensive and integrated analyses become necessary, considering the interrelationships between the physical environment and human interventions.

Urban drainage should comprise a set of measures aimed at mitigating the risks and losses resulting from floods, not being restricted to aspects imposed by engineering alone. According to Tavares et al. (2019) and Battemarco et al. (2018), conventional urban drainage techniques do not cover all the problems associated with the hydrological cycle. Thus, the search for more efficient methods for planning and managing drainage has become essential.

In this sense, the implementation of physical and technical measures associated with the concepts of "Best Management Practices" in the U.S. and Canada, "Techniques Alternatives" in France, and Compensatory Techniques in some countries and Brazil, among others, has been a great inspiration (Garrido Neto et al., 2019). These techniques aim to reduce runoff volumes, peak flow rates, the vulnerability of urban areas to flooding and, to a lesser extent, protect the quality of the environments receiving the generated runoff through increased infiltration and retention of rainwater (Lopes et al., 2020; Nunes et al., 2017).

Several studies have been carried out addressing the positive impact of implementing compensatory techniques, infrastructures widely used in several countries, specifically in urban drainage in urbanized basins (Cândido, 2015; Mao et al., 2017; Rosa, 2017; Woods Ballard et al., 2015). However, in Brazil, these techniques are not widespread, with hygienist practices largely predominating (Garrido Neto et al., 2019). Moreover, it is noteworthy that the implementation of such techniques is favorable to the environment, acting in the control of flooding and erosion, in addition to assisting in the adaptability to climate change (Santos et al., 2020).

According to Ramalho et al. (2022), to address climate change and the consequences that derive from it, various authors have produced the concept of climate change adaptation, varying in their approach to the concept, which has resulted in various definitions. In fact, climate change adaptation has more success when applied at a local scale. As such, climate change policies, including adaptation strategies, must be local, mainly because of the different contexts provided by a variety of community stakeholders, which contribute to the proximity to the challenges and an understanding of bigger problems at a local scale.

In the context of the city of Belo Horizonte, some efforts have been made by the government to promote the use of compensatory techniques. An example is the implementation of individual reservoirs, foreseen in the municipality in some cases since 1996 (Belo Horizonte, 1996). The new Master Plan currently in force establishes goals for the increase in green areas and enforces a fee for building constructions above municipal limits. It also determines the creation of green connections, promoting increased soil permeability rates and incentives for this rate to be met. In addition, the Plan also establishes the creation of connections between valleys, with afforestation and an end to the channeling of water sources, and green areas in public places, such as parks and environmental preservation areas (Belo Horizonte, 2019). In this context, we highlight draft bill Nº. 963/2014, which proposes the mandatory installation of green roofs in new developments with more than three floors; the bill is currently under consideration by the City Council (Belo Horizonte, 2014).

Associated with the climate change scenario, according to Nunes et al. (2021), trends were detected in the series of daily and subdaily precipitation in the city of Belo Horizonte, which justify the need to change the intense rainfall equation (IDF) for the municipality. This fact highlights the importance of obtaining continuous and quality data to have long-term hydrological observations that help in the evaluation of how the change in the atmosphere is altering the hydrological processes. In this context, Global Climate Models (GCMs) are principally utilized to simulate and project climate on a global scale (Ahmed et al., 2019; Khan et al., 2018).

In this sense, the present study aimed to evaluate the implementation of Compensatory Techniques in Urban Drainage in the city of Belo Horizonte in a scenario of urban renewal, *i.e.*, it intended to assess the potential of implementing green roofs, as required by Belo Horizonte's City Hall, in real estate properties undergoing stages of licensing and regularization and, also, of permeable pavements, which would be an initiative of managing agencies. To this end, scenarios contemplating the current conditions of occupation of a basin located in the municipality were presented, analyzing the possible techniques to be adopted, and a future situation, envisioning a new pattern of urban development and an IDF equation, which incorporates conditions of non-stationarity.

MATERIAL AND METHODS

Characterization of the study area

The Ressaca stream sub-basin is a direct tributary of Lake Pampulha and forms a sub-basin pertaining to the Onça river basin. Figure 1 shows the location of the sub-basin selected for the study. This stream, together with the Sarandi, are the main tributaries of the lake and, according to the Geological Survey of Brazil (Companhia de Pesquisa de Recursos Minerais, 2001), they contribute approximately 70% of the water volume and represent 63% of the total drainage area.

According to CPRM (Companhia de Pesquisa de Recursos Minerais, 2001), the Ressaca stream emerges in Belo Horizonte at an altitude of 920 m and has a length of 8.8 km, from its spring, near Belo Horizonte's old landfill, to its confluence with the Sarandi stream; its drainage area measures 20.6 km^2.

Regarding lithology, the Ressaca basin is located under the Domain of the Belo Horizonte Complex, corresponding to the Geomorphological Domain of the Belo Horizonte Depression, in which gneiss-migmatitic rocks predominate. In its surface formations, there is soil with varying thickness and pedological evolution, in addition to alluvial deposits associated with the main watercourses (Gomes, 1998). The distribution of soil types can also be related to the rock layer that originated the upper soil layers (Costa, 2002). The hydraulic conductivity of the Belo Horizonte Complex (gneisses and migmatites) is approximately 1.1x10^{-6} m/s.

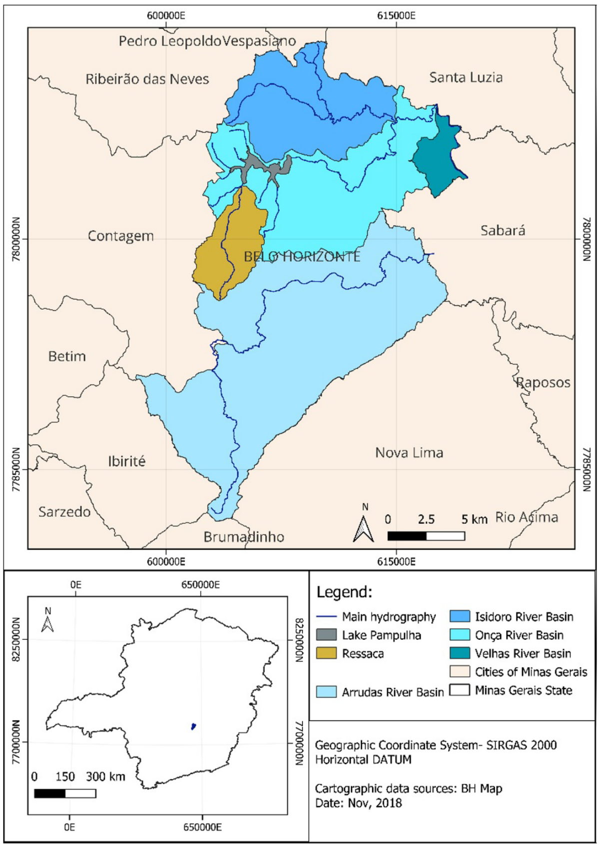


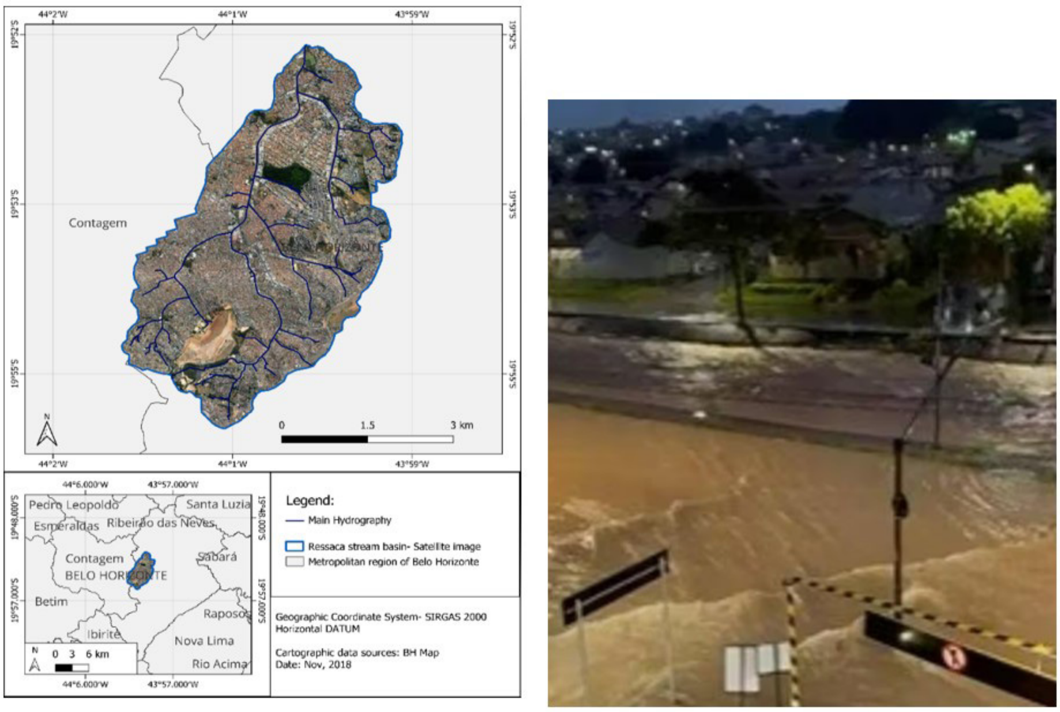
Figure 1. Location of the Ressaca stream sub-basin.

According to Cajazeiro (2012), the Belo Horizonte Depression has a lowered morphology and is delimited to the south by the Serra do Curral mountain range, corresponding to the northern limit of the Iron Quadrangle of Minas Gerais. It is characterized by the predominance of a relief of smooth hills, with concave and convex slopes, reaching average altitudes ranging between 800 and 900 meters and average slopes of 0 to 12%.

The use and occupation of the soil in the Ressaca stream basin is predominantly urban (Figure 2a), with few unoccupied areas, mainly represented by green areas, which are mostly parks and vacant lots. Thus, the basin is characterized by significantly altered areas, with considerable soil impermeabilization and changes in natural hydrological behavior (Cajazeiro, 2012).

The aforementioned characteristics have contributed to cases of flooding (Figure 2b), in addition to silting and eutrophication both in the watercourses belonging to the basin and in the downstream watercourses. The Municipality of Belo Horizonte has carried out some works with the aim of mitigating the floods that occur in the area (Belo Horizonte, 2020a). The Ressaca basin is located in areas susceptible to flooding, as stated in the Flood Chart (Belo Horizonte, 2019) and the Mapping of Main Flood Points (Belo Horizonte, 2020b).

Thus, the hydrological and hydraulic study of the region is extremely necessary, in order to establish the risks related to water quality and flooding, foreseeing preventive measures against floods and aiming at improving the quality of the water courses in the basin.



(a) (b)

Figure 2. Satellite image of the Ressaca basin (use and occupation of the soil) (a) and flooding on Avenida Heráclito Mourão de Miranda, around Ressaca stream (b). Source: O Tempo (2023).

Characteristics of the hydrological model for hydrological phenomena modeling

The EPA Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model that computes runoff quantity and quality. It is a nonlinear reservoir runoff model based on the continuity and momentum equations. The runoff component of SWMM operates on a collection of subcatchment areas that receive precipitation and generate runoff. SWMM treats each subcatchment area as a non-linear reservoir and calculates surface runoff using a method of planes in which it applies a water balance equation over the subcatchment for each time step. The subcatchment is broken down into pervious and impervious planes, based on the parameters input (Fry & Maxwell, 2018).

The first step of hydrological modeling using SWMM, version 5.1.012, consists of the construction of a topological model indicating all sub-basins, conduits, nodes, junctions, outlets, and storage units. The model developed and calibrated by Cândido (2015) was used, whose performance was evaluated by comparing the simulated flow rate data with those observed at a fluviometric station installed at a point further downstream in the basin (Figure 3). The validated model, also considering the precipitation data from the stations identified in Figure 3, generated a Nash coefficient of 0.77. In this model, a total of 23 sub-basins were identified (Figure 3).

The infiltration model selected by Cândido (2015) was that of the Natural Resources Conservation Service (NRCS), which enabled the determination of the Curve Number (CN) of each sub-basin. To this end, the land use map of the municipality of Belo Horizonte, elaborated by Teixeira et al. (2014), was used. According to Cândido (2015), the "% Impermeable" parameter, required for sub-basins in the SWMM, was calculated by dividing the area of the "urban spot" class, defined in the land use map, by the total area of the sub-basin.

Still according to Cândido (2015), the input parameters for the sub-basins were width, area, slope (calculated using the Quantum Geographic Information System - QGIS), and, also, the Manning coefficient (n-Manning), storage depth (SD) in depression, and drying time, which refers to the time for a completely saturated soil to become completely dry. The initial values adopted for these parameters were obtained by Silva (2014). In order to calculate the actual rainfall rate, the Curve Number model was also used. For the conduits, the main input parameters were shape, maximum depth, length - available in the registration form of Belo Horizonte's City Hall - and the n-Manning - value defined by Silva (2014).

The compensatory techniques proposed and hypothetically installed in the sub-basins in later stages, according to the scenarios defined below, also demanded the insertion of a series of specific data for each one. To this end, the recommendations of Rossman (2015), Schueler (1987), and Woods Ballard et al. (2015), which will be defined later, were considered.

Construction of the hydrological modeling scenarios via urban renovation

In the present study, six scenarios were proposed aiming to contemplate the adoption of compensatory techniques in the face of future analysis. For the definition of these scenarios, a 20-year timeline was considered, as well as the perspective of urban renewal, *i.e.*, an annual rate of requests for regularization and licensing of real estate properties in the study area was estimated in order to be able to consider a potential number of lots that would adopt, as required by current or future laws, the proposed infrastructure, which, in this case, was the implementation of green roofs. To this end, information on property renovations was obtained from Belo Horizonte's Municipal Secretary of Urban Policy (SMPU). Specific data on the type of regulation, location, plot area, and built area, among others, can be found on the City Hall website (Belo Horizonte, 2023).

Once the information on the licensing and regularization processes was obtained, they were categorized by sub-basin, and the proportions of areas suitable for the implementation of green roofs were calculated. To this end, when the built area was contemplated with more than one floor, it was divided by the total number of floors. Considering that processes from three years (2014, 2015 and 2016) were analyzed, an average was calculated, for the years under analysis, of the areas suitable for the implementation of the structure.

In view of the dynamic reality of the municipality of Belo Horizonte, as well as the city's environmental management initiatives, the following scenarios were proposed (Figure 4):

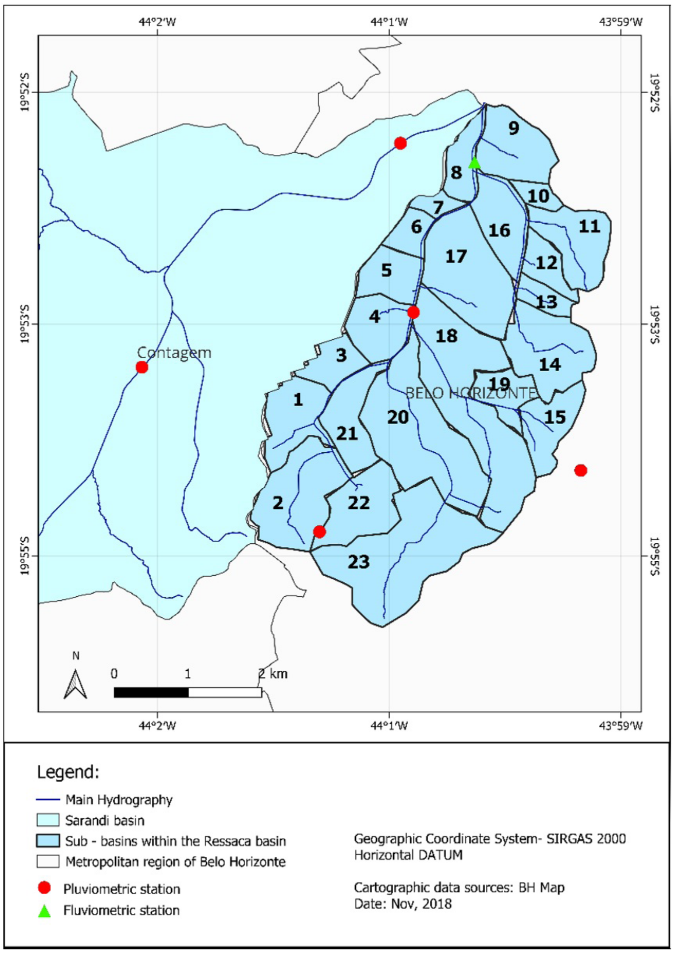


Figure 3. Map of the defined sub-basins. Source: Adapted from Cândido (2015).

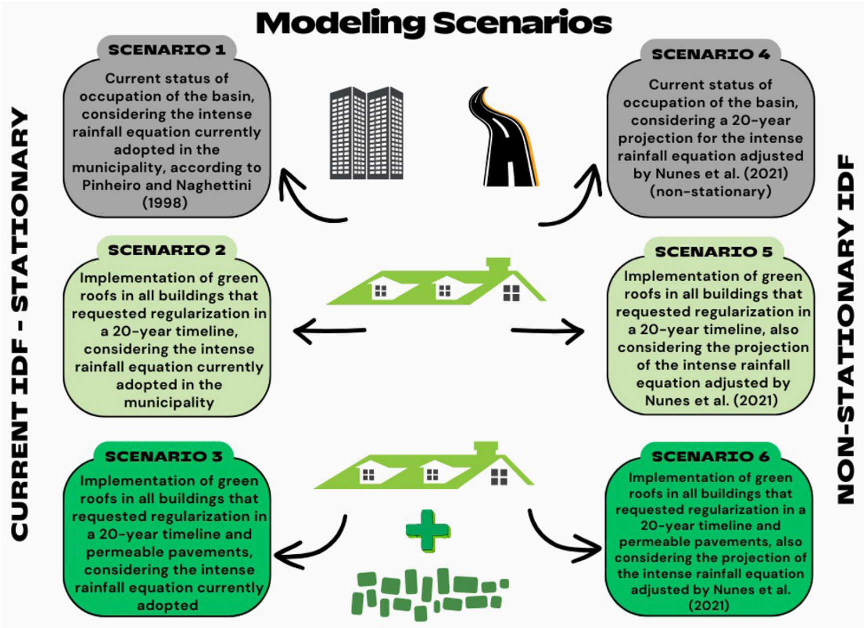


Figure 4. Hydrological modeling scenarios proposed in the study.

Design rainfall

With respect to Scenarios 1, 2, and 3, the design hyetographs (synthetic) were obtained using the IDF equation described by Pinheiro & Naghettini (1998) for return periods of 2, 10, and 50 years and durations of 10 to 240 minutes. The temporal distribution of the considered events was defined according to the dimensionless hyetograms (distribution of the 2nd quartile and 50% probability of occurrence) described in the methodology developed by Huff (1967). The critical-duration precipitation, *i.e.*, the one that produced the highest peak flow rates in the outlet area, was the precipitation used for the different return periods (RP).

For Scenarios 4, 5, and 6, the design hyetographs were obtained through the non-stationary IDF equation proposed by Nunes et al. (2021) for exceedance probabilities (EP) of 50%, 10%, and 2%, equivalent to the return periods of the initial scenarios. In addition, considering that the scenarios were proposed over a 20-year timeline, the period from 2018 to 2038 was defined as the project lifespan (considering the time constraint for applying the equation, defined by Nunes et al. (2021). In this sense, according to Nunes et al. (2021) the design rainfall estimation was carried out by Equation 1 (GEV model). For this, σ (scale) and ξ (shape) parameters were considered constants and μ (position) parameter varying according to the Equation 2:

$$G(x;\mu,\sigma,\xi)=\begin{cases} exp\left\{-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-1}\right\} \; if\ \xi\neq 0,\ for\, 1+\xi\frac{x-\mu}{\sigma}>0 \\ exp\left\{-exp\left(-\frac{x-\mu}{\sigma}\right)\right\} \; if\ \xi=0 \end{cases} \quad (1)$$

where μ, σ, and ξ represent the parameters of position, scale and shape, respectively, and x is the maximum annual precipitation.

$$\mu(\ )=\begin{cases} \mu_0\ ,\ \leq 2000 \\ \mu_0+\mu_1(t-2000), t\geq 2000 \end{cases} \quad (2)$$

where t represent time, in years.

The distribution parameters are presented in Table 1.

In view of the distance between the rainfall station used as a reference for the development of the non-stationary IDF equation, and the Ressaca stream basin, the spatial distribution of the design rainfall was used in order to represent the mathematical model more realistically. Depth-area curves were used to convert point rainfall to a catchment-wide average. This method was developed by the U. S. Weather Bureau (1958) and was recommended by Torrico (1974).

Parameters for compensatory technique modeling and selection of available areas for implementation

Geoprocessing tools were used to map the areas with the potential for implementing compensatory techniques. The Informatics and Information Company (Prodabel) of the Municipality of Belo Horizonte provided georeferenced files of the topographic base of the city, containing streets, blocks, lots, buildings, squares, the drainage network, and hydrographic basins and sub-basins, which enabled the accurate representation of the occupation of the Ressaca stream basin (Empresa de Informática e Informação do Município de Belo Horizonte S/A, 2011).

Some restrictions related to groundwater table depth and the hydraulic conductivity of the soil must be considered in the implementation of compensatory techniques that promote the infiltration of water in the soil. According to Costa (2002), the depth of the groundwater table in the region is almost always greater than five meters and tends to reduce near the bed of the watercourses. Thus, as described by Rosa (2017), a minimum

Table 1. Parameters of the non-stationary GEV distribution.

Parameters	10min	15min	30min	45min	60min
μ_0	101.34	78.64	59.92	48.23	39.00
μ_1	1.46	2.00	0.75	0.87	0.67
σ	23.38	19.71	14.68	12.79	9.86
ξ	-0.058	-0.098	-0.006	-0.191	-0.016

Table 2. Input parameters of permeable pavements and green roofs.

Layer	Parameter	Permeable pavements	Green Roof
Surface	Storage depth (mm)	0	100
	Plant cover (fraction)	0	0.2
	Surface roughness (Manning)	0.015	0.4
	Surface slope (%)	3	10
Soil	Thickness (mm)	450	100
	Porosity (fraction)	0.45	0.46
	Field capacity (fraction)	0.19	0.244
	Wilting point (fraction)	0,085	0.136
	Hydraulic conductivity (mm/h)	10.9	1.5
	Conductivity slope	5	10
	Matrix potential (mm)	110	218.5
Drainage	Thickness (mm)	-	50
	Void ratio (voids/solids)	-	0.5
	Roughness (Manning)	-	0.4
Pavement	Thickness (mm)	150	-
	Void ratio (voids/solids)	0.2	-
	Waterproof surface	0.1	-
	Permeability (mm/hr)	5000	-
	Clogging factor	270	-
Storage	Thickness (mm)	400	-
	Void ratio (voids/solids)	0.6	-
	Hydraulic conductivity (mm/h)	15	-
	Clogging factor	36	-
Bottom drain	Drainage coefficient (mm/h)	0.8	-
	Drainage Exponent	0.5	-
	Drain reference dimension (mm)	0	-

Source: Average values recommended by Rosa (2017) and Rossman (2015), depths recommended by Schueler (1987) and Woods Ballard et al. (2015).

distance of 30 meters from the watercourses was required for the implementation of the infiltration techniques. Also, considering that the normally required hydraulic conductivity for the application of these techniques varies between 10^{-4} m/s and 10^{-6} m/s, and that the infiltration capacity associated with the lithology of the basin is in the order of 10^{-6} m/s (Costa, 2002), it was established that these structures promote the storage and partial infiltration of affluent precipitation (Woods Ballard et al., 2015).

Green roofs

The simulated green roofs were of the extensive type, characterized by shallower soil depths when compared to intensive roofs, resulting in lighter structures that are easier to implement over already existing buildings (Woods Ballard et al., 2015). The input parameters of green roofs in SWMM model are presented in Table 2.

The selection of buildings for green roof implementation was based on the following procedure: survey and mapping of requests for regularization and licensing of properties in the study area, for each sub-basin, considering information from the years 2014, 2015 and 2016, available on the website of Belo Horizonte's Municipal Secretary of Urban Policy (SMPU). Once the data were collected, in order for the simulation of the green roofs in the SWMM, the annual average number of units, the average areas, and the average widths of the roofs for each sub-basin were calculated. The annual average number of units was also multiplied by 20 to simulate the 20-year timeline proposed in the scenarios.

Permeable pavements

The selected permeable pavements were of the modular type, built using concrete blocks whose joints are filled with permeable material (Woods Ballard et al., 2015), and of partial infiltration, with the presence of drainage pipes. The input parameters of permeable pavements in SWMM model are also presented in Table 2.

The criteria for implementing permeable pavements vary according to the relief and traffic characteristics of the area where the paving is intended to be carried out. In general, some criteria should be observed, such as: maximum terrain slope of 5%, soil hydraulic conductivity between 10^{-4} m/s and 10^{-6} m/s, and a minimum road width of 12 m (Rosa, 2017; Woods Ballard et al., 2015; Schueler, 1987). The exclusion of arterial roads was also considered.

In order to simulate the permeable pavements in the SWMM, the number of units and the average areas and widths of the structures were calculated for each sub-basin.

RESULTS AND DISCUSSION

Design rainfall

Based on the initial scenario (Scenario 1), rainfall events lasting between 30 minutes and 2 hours were inserted in the model, considering return periods of 10 and 25 years (Figure 5). It was noted that the 45-minute precipitation was the most critical, *i.e.*, it produced the highest peak flow rate at the outlet; therefore, it was the critical duration selected for this study.

For Scenarios 4, 5 and 6, the results regarding the estimation of the design rainfall, considering the critical duration of 45 minutes, were:

Calculation of the position parameters according to Equation 2 and Table 1:

$$\mu\left(2018\right) = 48.23 + 0.87\left(2018 - 2000\right) = 63.89\ mm/h \quad (3)$$

$$\mu\left(2038\right) = 48.23 + 0.87\left(2038 - 2000\right) = 81.29\ mm/h \quad (4)$$

Quantiles for exceedance probabilities of 50%, 10%, and 2% using the position parameter of 2038.

$$I\left(0.5\right) = 81.29 + \frac{12.79}{0.191}\left\{1 - \left[-ln\left(1-0.5\right)\right]^{0.191}\right\} = 85.82\frac{mm}{h} \times \left(\frac{45}{60}\right) = 64.37\,mm \quad (5)$$

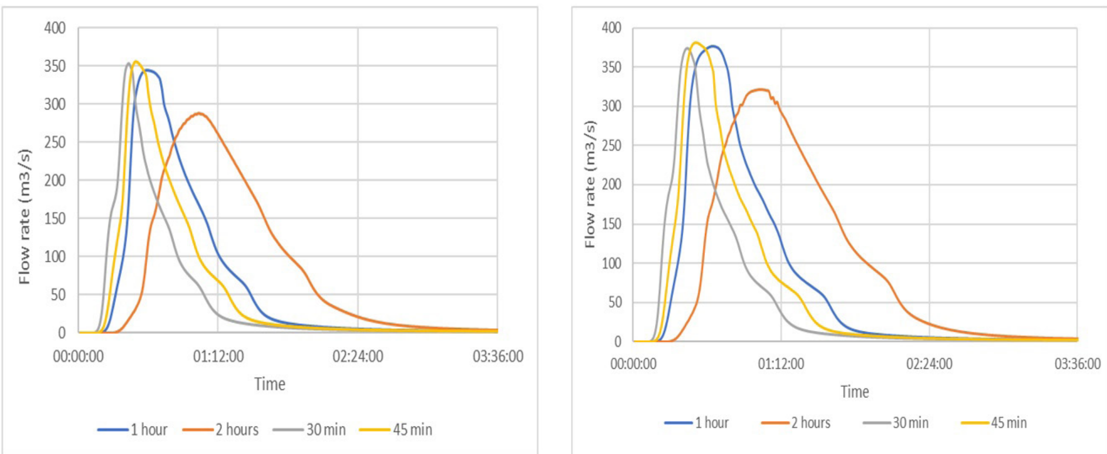
$$I\left(0.1\right) = 81.29 + \frac{12.79}{0.191}\left\{1 - \left[-ln\left(1-0.1\right)\right]^{0.191}\right\} = 104.68\frac{mm}{h} \times \left(\frac{45}{60}\right) = 78.1\,mm \quad (6)$$

$$I\left(0.02\right) = 81.29 + \frac{12.79}{0.191}\left\{1 - \left[-ln\left(1-0.02\right)\right]^{0.191}\right\} = 116.47\frac{mm}{h} \times \left(\frac{45}{60}\right) = 87.35\,mm \quad (7)$$

Also considering the spatial distribution of the design rainfall, as cited in the methodology, the estimates of the design rainfall are shown in Table 3.

Green roof modeling and selection of the available areas for implementation

Boxplot analysis for areas potentially treated with green roofs by sub-basin is shown in Figure 6a. It is observed that approximately 50% of the 23 analyzed sub-basins have areas with potential for the implementation of green roofs of up to 1.4 ha, which corresponds to only 1% of the total area of these basins. However, 25% of the total sub-basins have areas with potential greater than 3.09 ha, corresponding to a percentage of almost 5%. Thus, it is highlighted that the areas that were more suitable for the implementation of green roofs, seeing that they presented



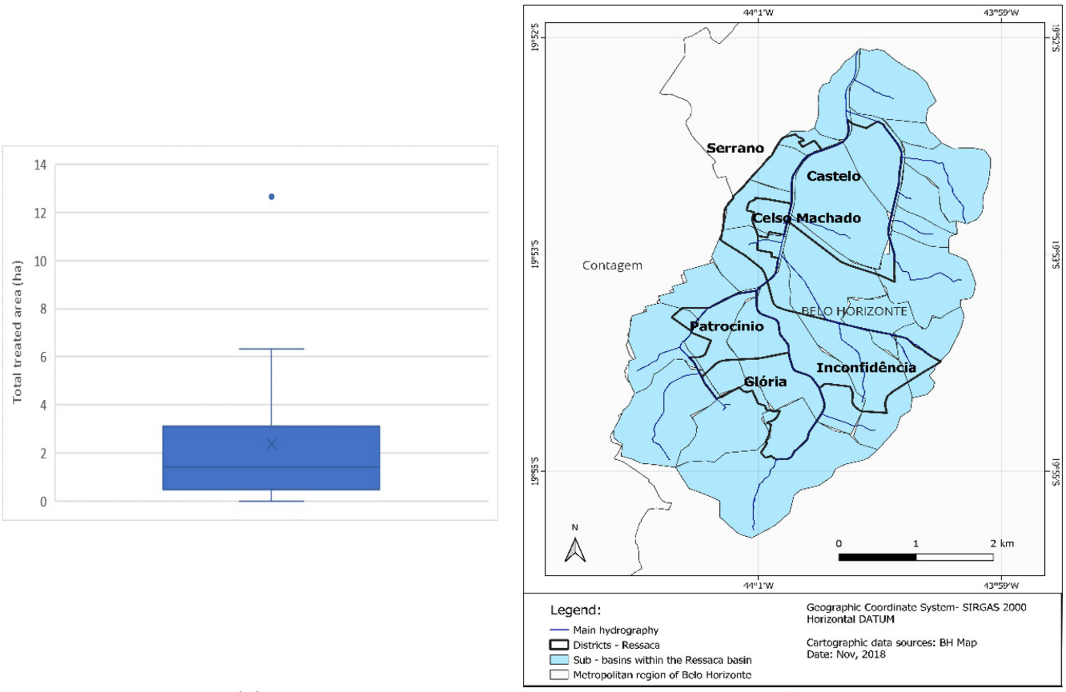
(a) (b)

Figure 5. Hydrograms resulting from the design hyetographs with different durations for return periods of 10 (a) and 25 (b) years.

Table 3. Design rainfall quantiles for the duration of 45 minutes and different Return periods / Exceedance Probabilities (mm).

RP (years)/EP (%)	2 years/50%	10 years/10%	50 years/2%
	Design rainfall (mm)		
IDF Pinheiro & Naghettini (1998)	28.23	39.87	50.05
Non-stationary IDF (Nunes et al., 2021)	50.85	62.03	69.01

RP: return periods; EP: exceedance probabilities.



(a) (b)

Figure 6. Boxplot analysis for areas potentially treated with green roofs by sub-basin (a) and districts with greater concentration of areas selected for green roof implementation (b)

higher rates of renovation, were the regions corresponding to sub-basins 5, 9, 16, 17 (outlier), 18 and 20, more specifically, the districts of Celso Machado, Serrano, Castelo, Patrocínio, Glória and Inconfidência (Figure 6b).

Permeable pavement modeling and selection of areas available for implementation

The road classification maps by average slope and the final selection of areas suitable for permeable pavement implementation are shown in Figure 7.

The areas that were most suitable for the implementation of permeable pavements and that showed the highest concentration of these structures were the northern and central regions of the basin, more specifically, the districts of Itatiaia, Serrano, Castelo, Paquetá, Itacolomi, Alípio de Melo, Patrocínio, and Inconfidência (Figure 7b), which are the regions with the highest concentration of stretches with slopes below 5%, as can be seen in Figure 7a.

It can be noted that some districts coincide regarding the possibility of receiving the two proposed infrastructures (green roofs and permeable pavement), namely the districts of Castelo, Serrano, Inconfidência, and Patrocínio, again demarcating the North and Central regions.

It is also worth mentioning that the sum of the areas treated using the proposed techniques, in the 20-year timeline, is quite similar, corresponding to the percentage of 3.5% of the total area for green roofs and 3.8% of the total area for permeable pavements.

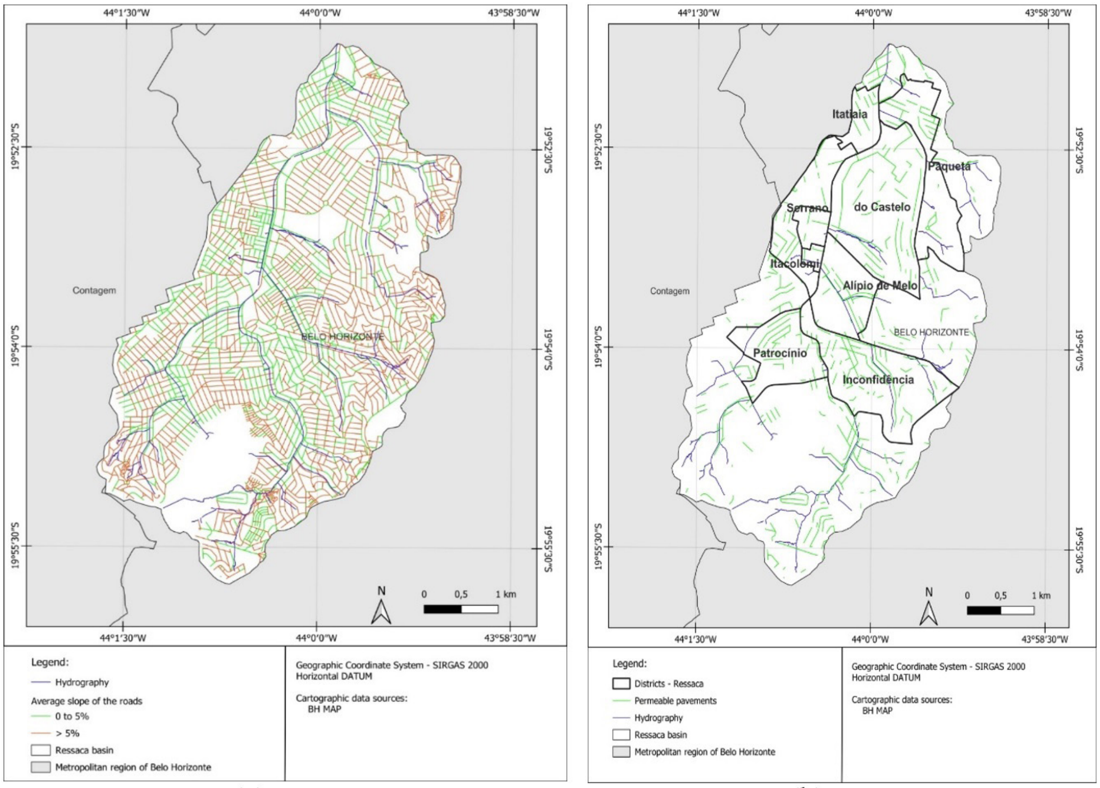
Hydrological Response for scenario modeling considering the current IDF (Pinheiro & Naghettini, 1998)

The results of Scenarios 2 and 3, compared to Scenario 1, for rainfall events with 45 minutes of duration and return periods of 2, 10, and 50 years, are summarized in Figure 8.

For a return period of 2 years, in Scenario 2, with the implementation of green roofs in all buildings with regularization and licensing requests over the 20-year timeline, a 4.4% reduction in peak flow rates was observed compared to Scenario 1 (peak flow of 277.1 m^3/s), which corresponded to the current setting of the basin. Also, when considering Scenario 3, with the implementation of green roofs and permeable pavements, there was an 8.3% reduction in peak flow rates compared to the original scenario.

Considering the return period of 10 years, a reduction in peak flow rates of 3.2% was observed in Scenario 2 compared to Scenario 1 (peak flow of 356.1 m^3/s). As for Scenario 3, a 6.8% reduction in peak flow rates was noted, also when compared to the original scenario. Considering the last scenario return period, equivalent to 50 years, there was a greater drop in the efficiency of the adopted techniques, with a peak flow reduction in Scenario 2 equal to 2.8%, and in Scenario 3, of 5.9%, both when compared to the original scenario (peak flow of 397.1 m^3/s).

In general, the simulations showed no significant variations in the concentration and recession times of the hydrograms. Palla & Gnecco (2015) found an increasing trend in concentration and recession times associated with the increase in the percentage of impermeable areas treated using compensatory techniques, indicating that it would be necessary to treat a larger area of the



(a) (b)

Figure 7. Maps indicating the slopes of the roads (a) and the areas selected for permeable pavement implementation, considering the districts with greater concentration of these areas (b).

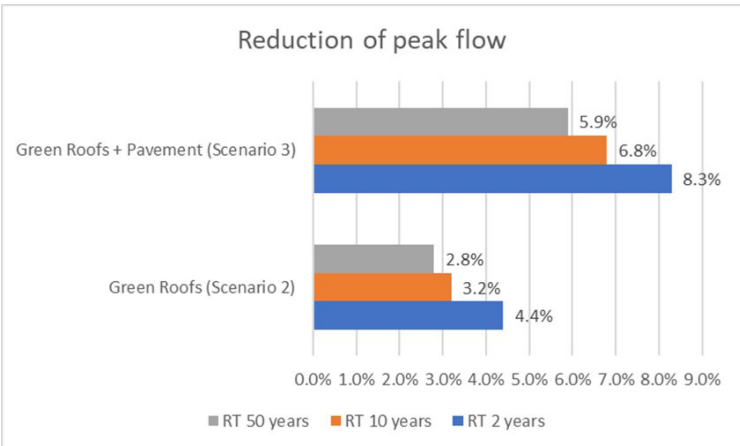


Figure 8. Variations in peak flows corresponding to the proposed scenarios.

basin in order for some significant delay in the concentration and recession times of the hydrograms.

It can be noted that with the increase in the return period, equivalent to design rainfall of greater magnitude, the efficiency of the techniques adopted tended to decrease. This fact can be explained by the retention capacity of the basins, which is strictly related to the physical characteristics of the implemented structures (Palla & Gnecco, 2015) and not the treated impermeabilized area.

Similar results were reported by Palla & Gnecco (2015), who found reductions in peak flow rates for rainfall return periods of 2, 5, and 10 years of 45%, 37%, and 31%, respectively, in scenarios of maximum LID (low impact development), and by Gironás et al. (2009), who observed percentage reductions in peak flow rates in the order of 36%, 33%, and 21% for rainfall with RT of 2, 5 and 100 years, respectively.

The divergence in the efficiency in reducing peak flow rates in the aforementioned studies, when compared to the reductions observed here in, was due to the simulation of the implementation of compensatory techniques throughout the study basin, which differed from the restriction used here, where realistic and feasible bases for the urban renewal scenario were adopted.

It is also important to add that initial moisture conditions influence on the efficiency of green roofs, as well as the general characteristics considered. According to Gong et al. (2018), extensive green roofs with lower substrate hydraulic conductivity, deeper substrate and lower rainfall depth, in general, present higher runoff retention performance. On the other hand, in the same study, no significant correlation was found between rainfall duration, prior dry period, average rainfall intensity, drainage layer type and the runoff retention rate.

The variations in runoff volumes corresponding to the proposed scenarios are shown in Figure 9.

Considering a return period of 2 years, in the original scenario (1), the total runoff volume at the outlet was 546.348 m^3. Meanwhile, in Scenario 2, with the implementation of green roofs, there was a 4.8% decrease in total volume, equivalent to 519.917 m^3. As for scenario 3, the volume decreased by 11.0% (486,004 m^3).

For return periods of 10 and 50 years, the total volumes for the original scenario were equal to 778,782 m^3 and 983,544 m^3, respectively. According to our results, in the other scenarios, the percentage changes in runoff volume remained very close to those obtained in the simulation for a RT of 2 years (4.9% and 10.9%, respectively).

Based on the results described above, the efficiencies in the reduction of runoff volumes did not present significant variations for the same scenario when considering different return periods. The performance of the permeable pavements was very close to that of the green roofs. This was due to the fact that the latter were not explored in a scenario of maximum installation potential but from the perspective of urban renewal. The trends observed in the generated results are in agreement with other similar studies found in the literature (Palla & Gnecco, 2015; Rosa, 2017; Walsh et al., 2014).

It is noteworthy that the observed efficiencies should be considered with caution, as sequential rainfall events were not analyzed.

Hydrological Response for scenario modeling considering the non-stationary IDF

Considering an exceedance probability of 50%, in Scenario 4 - non-stationary IDF – a 44% increase in peak flow rates was observed when compared to Scenario 1 (peak flow of 277.1 m^3/s), which corresponded to the current setting of the basin without the implementation of compensatory techniques. For the exceedance probabilities of 10% and 2%, increases of 22% and 14% in peak flow rates were detected compared to Scenario 1. In this sense, the initiative to implement strategies that could contribute to the reduction of runoff becomes even more evident.

The results of Scenarios 5 and 6, compared to Scenario 4, for rainfall events with 45 minutes of duration and exceedance probabilities (EP) of 50%, 10%, and 2% (equivalent to return periods of 2, 10, and 50 years, respectively), are summarized in Figure 10.

In Scenario 5, for an exceedance probability of 50%, with the implementation of green roofs in all buildings with regularization and licensing requests within the 20-year timeline, and considering the non-stationary IDF, a reduction in peak flow rates of 2.8% was observed compared to Scenario 4, which corresponded to the non-stationary scenario without the implementation of the techniques. When considering Scenario 6, with the implementation of green roofs and permeable pavements, there was a 5.8% reduction in peak flow rates compared to Scenario 4.

Meanwhile, for an exceedance probability of 10%, in Scenario 5, there was a reduction in peak flow rates of 2.8% compared to Scenario 4; as for Scenario 6, a 5.7% decrease in peak flow rates was observed, also when compared to the scenario without technique implementation. Considering the last exceedance probability associated with the scenarios, equivalent to 2%, there was a drop in the efficiency of the adopted techniques, with a reduction in peak flow rates in Scenario 5 equal to 2.6%, and in Scenario 6, of 5.1%.

It can be noted that with the reduction in the exceedance probability, the efficiency of the adopted techniques tended to decrease, but on a significantly lower scale than the scenarios that considered the current IDF (1, 2, and 3). This fact can be justified again by the retention capacity of the basins, still related to the physical characteristics of the implemented structures, which tend to lose efficiency with the increase in design rainfall.

It is also worth mentioning that the increase in peak flow rates observed when comparing Scenarios 1 and 4, although quite expressive, could be attenuated with the implementation

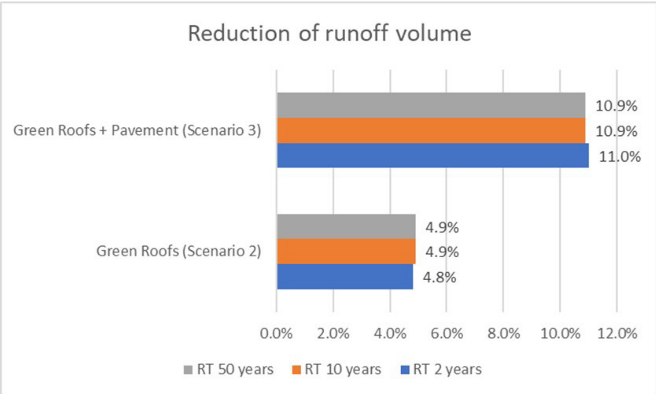


Figure 9. Variations in runoff volumes corresponding to the proposed scenarios.

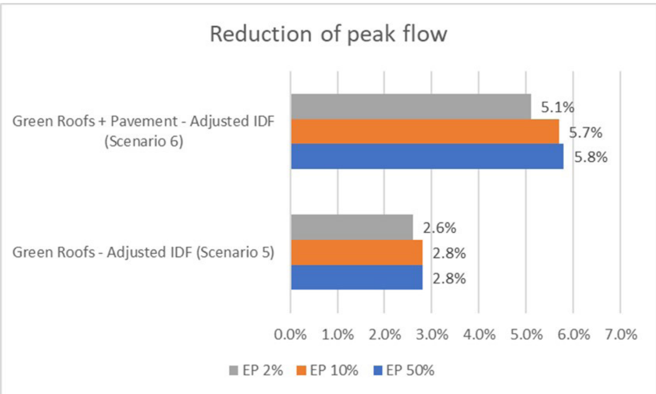


Figure 10. Variations in peak flows corresponding to the proposed scenarios.

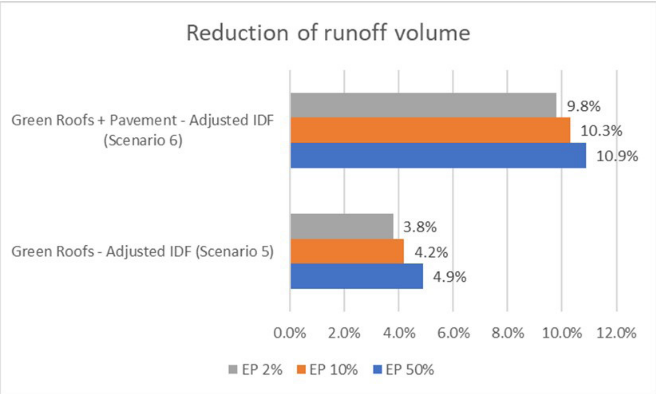


Figure 11. Variations in runoff volumes corresponding to the proposed scenarios.

of compensatory techniques. When analyzing the 2% exceedance probability, for example, approximately 40% of the increase could have been offset by implementing green roofs and permeable pavements in the urban renewal proposal.

The variations in runoff volumes corresponding to the proposed scenarios are shown in Figure 11.

Considering an EP of 50%, in Scenario 4 (without technique implementation and non-stationary IDF), the total runoff volume in the outlet was 999,592 m^3, 83% higher than that drained in the original scenario (Scenario 1). In Scenario 5, with the implementation of green roofs, there was a reduction of 4.9% in the total volume, equivalent to 950,908 m^3. In Scenario 6, the runoff volume decreased by 10.9% (890,870 m^3).

For EPs of 10% and 2%, the total volumes for Scenario 4 were equal to 1,225,410 m^3 and 1,366,791 m^3, respectively. In the other scenarios, the percentage variations in runoff volume remained relatively close to those obtained in the simulation for an EP of 50% (-4.2% and -10.3% - Scenario 5; - 3.8% and – 9.8% - Scenario 6).

The efficiencies in reducing the runoff volumes did not present significant variations for the same scenario considering different exceedance probabilities, a fact that was also observed in the stationary scenarios. On the other hand, the marked variations between scenarios that did not consider the implementation of techniques, but that differ in relation to the IDF (Scenarios 1 and 4), were expected, which reinforces the need for management that favors the implementation of strategies that not only reduce runoff volume, but that also contribute to changes in the local climate.

In this sense, Wang et al. (2023), in a study that explored a novel approach to assess the hydrological performance under Shared Socio-economic Pathways (SSPs) based on longterm rainfall time series, affirm that integrated grey-green infrastructures in response to non-stationary and multi-scenario climate change in urban catchments with high built-up density, can provide a novel perspective on hydrological performance, particularly for reducing peak flow following extreme rainfall events.

Finally, it is important to mention that some methodological limitations may influence the efficiency of the presented results. Among them, the analysis of 20-year scenarios, based on an urban renewal rate of just three years, may not faithfully represent the reality of the basin. As a recommendation, an urban and population expansion study could be considered. Also, for the analysis of future scenarios, climate projections could be used, as in the studies by Sousa et al. (2019) and Martins et al. (2018).

CONCLUSION

By evaluating the impact of the implementation of green roofs and permeable pavements in the Ressaca stream basin, from a perspective of urban renewal, considering the six hydrological modeling scenarios, the first three corresponding to the current intense rainfall equation (Pinheiro & Naghettini, 1998) and the others formulated using the non-stationary IDF equation (Nunes et al., 2021), it was possible to note that the scenarios evolved in a way that evidences the beneficial effects of implementing such strategies.

The implementation of the proposed infrastructures within the Ressaca creek basin, or in any other basin in the municipality of Belo Horizonte, is still a major challenge. Currently in the city there are regulations that favor the implementation of compensatory measures, but an effort is necessary on the part of the public power to disseminate and encourage the implementation of these structures in the reality of urban basins.

In order to complement this study, it is recommended to evaluate the reduction of floodplain in the Ressaca stream basin resulting from the implementation of compensatory techniques proposals. It is also emphasized that it is necessary to test other combinations of compensatory techniques, in order to maximize the impermeable areas treated, as well as climate projections. Additionally, it is necessary to carry out a cost-benefit analysis of the proposed techniques.

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Aline de Araújo Nunes: First author who contributed to literature review, methodology proposal, analysis and discussion of results, as well as writing and formatting of the article.

Márcio Benedito Baptista (in memorian): Principal advisor on research who contributed to the methodology and discussion of the results.

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