



Assessment of the hydrological response of an urban watershed to rainfall-runoff events in different land use scenarios – Belo Horizonte, MG, Brazil

Deyvid W. B. Rosa, Nilo O. Nascimento , Priscilla M. Moura and Gustavo D. Macedo

ABSTRACT

Intense urbanization results in greater soil sealing and a consequent increase in surface runoff. When high soil sealing rates and high slopes are encountered in small catchments, high volume and short duration precipitation events increase the probability of flash floods. This study evaluates the hydrological response of an urban catchment with regard to rainfall-runoff events in the following scenarios: current land use, without a detention basin which has been part of the system since the 1970s, with the maximum soil sealing allowed by legislation, and with green infrastructure implantation in 100%, 50% and 10% of the suitable area. Hydrological modelling was performed using the Storm Water Management Model (SWMM). Six level gauges installed along the length of the stream provided the data used in model calibration and validation. The model calibration process provided adequate results: the average Nash-Sutcliffe coefficient was 0.72, the mean error of peak flow was 11% and the mean error of the runoff volume was 12%. Rainfall based on 2-, 10-, 50- and 100-year events were simulated for each scenario, as well as two observed events. In the scenario without the detention basin, an average elevation of 10% in the peak flow was observed in the catchment outlet. In the scenario with maximum soil sealing, the catchment outlet peak flow increased by 30% on average. On the other hand, in the scenario with green infrastructure implementation in 100%, 50% and 10% of the available areas, the outlet peak flow was reduced by 60%, 30% and 5%, respectively. Results indicated the efficiency of the detention basin to reduce flooding, the importance of green area preservation to reduce peak flows, as well as the catchment potential of green infrastructure implementation and the hydrological benefits that they can provide, increasing infiltration and reducing runoff volume and peak flow.

Key words | GIS analysis, green and blue infrastructure, hydrological modeling, low impact development, stormwater management, urban flash floods

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INTRODUCTION

Flash floods are characterized by high peak flow rates observed during a short period of time, resulting from several factors highlighted by the occurrence of heavy rainfall events with high volumes and short duration (Gaume

et al. 2009). In the city of Belo Horizonte, the capital of Minas Gerais state in the southeastern region of Brazil, physical conditioning factors – small drainage areas, high slopes, narrow valleys and low infiltration capacity – occasionally combined with heavy rains, generate floods that have caused severe human and economic losses in recent decades (Baptista *et al.* 1997; Champs 2012). It is possible to identify changes in Belo Horizonte urban planning since its first positivistic conception up to the most recent interventions in its watercourses and current land use

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regulation, with the incorporation of concepts such as green and blue infrastructure (GBI) and low impact development (LID) in the local and regional planning process (Monte-Mór *et al.* 1994; Granceri *et al.* 2015; Monte-Mór *et al.* 2016; Nascimento *et al.* 2016).

This study seeks to assess the influence of changes in land use on the hydrological response of a Belo Horizonte catchment, the Leitão creek catchment, including the influence of GBI implementation, by means of a calibrated and validated hydrologic and hydraulic model. The potential benefits of GBI application will be evaluated regarding the reduction on peak flow rates and runoff volumes, and the consequent reduction of flood risk in the Leitão creek catchment. The results of this study can contribute to the formulation of urban policies focusing on the conservation of existing green areas and the adoption of GBI concepts.

The Leitão creek catchment, with an area of 10.6 km² and a population of approximately 120,000 inhabitants, 16,000 of whom live in favelas (IBGE 2010), is a densely occupied urban area. As an already built area, it is much more demanding for GBI implementation than in the case of new developments (e.g. Wright *et al.* 2016). Therefore, additional criteria for GBI selection and adaptation must be considered, especially with regard to the existing urban environment (road system, population density, types of buildings, existing green areas, squares and parks, etc.).

The term 'Green and Blue Infrastructure' is a combination of two concepts. The first refers to the green infrastructure, which is an urban infrastructure system whose primary objective is the conservation of nature, harmonizing land use and occupation with the preservation of local ecosystems (Benedict & McMahon 2012). The second refers to blue infrastructures, which are those destined to the efficient management of rainwater, such as detention and infiltration basins, individual reservoirs and others (Andoh 2011). Thus, the term Green and Blue Infrastructure, which emerged in the United States in the 1990s, refers to the interconnected network of permeable, vegetated and multifunctional spaces that structure the landscape around watercourses and areas of environmental concern (Herzog & Rosa 2010; Benedict & McMahon 2012; Fletcher *et al.* 2015).

The concept of low impact development, similar to that of GBI, was widely diffused in North America and New Zealand at the end of the last century. This especially concerns practices that seek to recover the natural characteristics of the hydrological cycle, reducing surface runoff and increasing infiltration and evapotranspiration (Dietz 2007; Elliott & Trowsdale 2007; Fletcher *et al.* 2015). Some of the most common LID-type solutions to be simulated in

this work are green roofs, infiltration trenches, permeable pavements, rain barrels and roof disconnection.

Many studies have been conducted to assess the potential of LID techniques for reducing urban impacts on the hydrological cycle at the local scale (McCutcheon & Wride 2013), sub-catchment scale (Zimmer *et al.* 2007; Palla & Gnecco 2015; Versini *et al.* 2015) and catchment scale (Shuster & Rhea 2013; Loperfido *et al.* 2014; Guan *et al.* 2015; Rhea *et al.* 2015; Bhaskar *et al.* 2016). In some of these studies, monitoring data were used to calibrate and validate their results, although monitoring data in catchments with wide implementation of LID techniques are still scarce (Hu *et al.* 2008; Yang & Li 2010; Shuster & Rhea 2013; Bhaskar *et al.* 2016).

As identified by Palla & Gnecco (2015) and Gironás *et al.* (2009), with the increase of precipitation intensity and return period, lower efficiencies of LID techniques in reducing the peak flow and runoff are observed. In continuous simulation, the efficiency of peak flow reduction by LID techniques remains high. This is exemplified by the 75% reduction observed by Zimmer *et al.* (2007) and the 60% reduction observed by Versini *et al.* (2015). Two Brazilian studies obtained notable reductions in peak flow with the implantation of LID techniques in small catchments when considering a 10-year return period (Drummond 2012; Bahiense 2013).

Li *et al.* (2017) reviewed 31 catchment and subcatchment scale studies, with and without monitoring data, that evaluated the hydrologic effects of LID implementation. In general, the results of these studies indicated that the implementation of LID techniques reduced surface runoff and peak discharge. Although reductions were lower for monitored data when compared to modeling results. This reduction was substantial in local sites and in sub-catchments scale studies. On the other hand, there is a lack of catchment-scale monitoring studies with large implementation of LID techniques that could quantify this alteration with more certainty.

Although reductions in peak flow and runoff volume due to LID implementation in the urban environment could be considered overestimated in some cases, the hydrological modeling of these devices is a good tool to evaluate the hydrologic benefits obtained via their use. The quality of the results obtained by the simulation, credibility and confidence of the models, are directly related to the adequate characterization of the structures, preferably with the use of measured data, and to the fact that the model is a combination of conceptual and physically based behavior (McCutcheon & Wride 2013).

In general, most studies cited were performed in developed countries or in China (Li *et al.* 2017). The present study focuses on a city area in Brazil, aiming at contributing to answering some emerging questions as follows: (i) What is the potential of a highly urbanized catchment to integrate GBI techniques? (ii) Can decentralized and alternative stormwater management techniques perform better than centralized and conventional drainage techniques in reducing urban flooding? (iii) How different is the hydrological response of LID techniques to design storms and to observed critical rainfall events? These questions motivated this work, highlighting important issues for urban development planning in Brazil with possible application in other urban areas in developing countries.

MATERIAL AND METHODS

The methodology used in this research consisted first of a review of studies and projects previously developed for the Leitão creek catchment followed by a characterization of the local climate and typical rainfall and runoff regimes, based on the assessment of climate and hydrologic times series.

The Belo Horizonte local climate can be classified as tropical highland, with an average annual precipitation of 1,600 mm, which is concentrated in the October to March period (Inmet 2019). During the rainy season, short duration and highly intense rainfall events of convective origin are frequent and critical for small urbanized areas such as the Leitão creek catchment. The average intensity of the 25-year 1-hour duration rainfall event is 66 mm/h according to the local IDF relationship (Pinheiro & Naghettini 1998). Typical low flows are around 1.0 m³/s; nevertheless, during high waters the creek discharge can quickly reach more than 50 m³/s at its mouth.

The Leitão catchment occupation began in the 1920s and was followed by the creek lining, from the headwaters of the catchment to its mouth of the Arrudas stream in the city downtown. Due to a lack of interceptor pipelines, sewage was dumped in the creek from the beginning of the catchment development. Solid waste was also frequently deposited on the creek banks, polluting its waters and increasing flood risk due to flow obstruction. The rapid urbanization of the catchment led to frequent floods downstream in Belo Horizonte downtown, and eventually to the implementation of a culvert channel all along the Leitão creek and of a detention basin, the Santa Lucia dam, controlling a sub catchment of about 3.0 km² in the upstream part of the catchment (Borsagli 2011), as structural measures

to reduce flooding in the area. In spite of these actions, flood risk remains high in the main road system implemented over the channelized Leitão and its tributaries.

For the present studies, georeferenced topographic data, satellite images, hydrological monitoring data and the stormwater infrastructure cadaster were provided by the local agencies Prodabel (GIS and socioeconomic data), Sudacap (infrastructure and hydrologic data), and Inmet (meteorological data). GIS tools were applied to obtain topographical, hydrological and land use characteristics of the catchment, including the delimitation of protected and green areas, and to identify and map the location of the areas most suitable to receive GBI devices according to the physical and infrastructural requirements described in the forthcoming paragraphs.

Six scenarios were defined for hydrological modeling. The first was the current scenario. The second was defined according to the maximum impervious level allowed by the Belo Horizonte land use law (Belo Horizonte 2010). The third scenario of further urban development considered the possibility that the Santa Lucia detention basin loses its flood attenuation role, which may happen in the case of improper maintenance, obstruction of outflow structures, siltation or even a decision to change the area land use.

The other scenarios were defined considering the implementation of green and blue infrastructure in the catchment areas that meet the requirements to implement these devices. The selected GBI devices were permeable pavements, green roofs, rain barrels, rooftop disconnection and infiltration trenches. Roads with slopes less than or equal to 5%, width exceeding 12 m and distances to streams of more than 30 m were selected for permeable pavement implantation. Roofs made of non-ceramic materials with area equal to or larger than 100 m² (the median of roof surface in the case study area), a limit necessary to grant stability for the model, were selected for green roof implantation. The other roofs were selected for rain barrel implantation and rooftop disconnection. Lots with areas larger than 72 m², at least 2 m from any construction with slopes less than 20% and at least 30 m away from streams were selected for infiltration trench implantation. These criteria were defined according to recommendations of the Storm Water Management Model (SWMM) User's Manual (Rossman 2015) and other technical references (Schueler 1987; Chesapeake Stormwater Network 2009; Rodríguez *et al.* 2014; Woods Ballard *et al.* 2015; Nascimento *et al.* 2016).

Additionally, restrictions related to infiltration capacity and groundwater depth were considered for all techniques that promote water infiltration in the soil. According to Costa (2002), the water table depth in this catchment is

almost always greater than 5 m. Considering that this depth tends to be lower in areas closer to water courses, a minimum distance of 30 m of stream channels was demanded for implantation of infiltration techniques. The hydraulic conductivity normally required for application of infiltration techniques ranges from $10^{-6} \text{ m}\cdot\text{s}^{-1}$ to $10^{-4} \text{ m}\cdot\text{s}^{-1}$. However, there are lower infiltration capacities in the catchment, on the order of $10^{-7} \text{ m}\cdot\text{s}^{-1}$ to $10^{-6} \text{ m}\cdot\text{s}^{-1}$. Nevertheless, the implantation of permeable pavements and infiltration trenches was admitted throughout the catchment, considering the possibility that these structures promote storage and partial infiltration (Woods Ballard *et al.* 2015).

Since the time for adopting GBI approaches in an already constructed environment may be long and requires specific policies and actions (e.g. regulation, funding, building capacity), it seems useful to consider that only part of the identified suitable places in the catchment will be effectively equipped in the assessment of combined GBI device performance. Thus, in the present study three scenarios of GBI implementation were simulated: 10%, 50% and 100% of the suitable GBI effectively implemented in the area. These percentage were applied to the quantity of GBI located in each sub-catchment – the catchment was subdivided into 27 drainage areas.

SWMM 5.1 was used for hydrologic simulations. The Soil Conservation Service (SCS) was selected as the infiltration model; therefore, the curve number (CN) and drying time must be inserted. The CN of each sub-catchment was estimated by associating values indicated by literature for each land use and soil type (National Resources Conservation Service 2004).

SWMM can simulate eight different types of LID structures: bio-retention cells, rain gardens, green roofs, infiltration trenches, continuous permeable pavement, rain barrels (or cisterns), rooftop disconnection and vegetative swales. These devices can provide storage, infiltration, and evaporation of direct rainfall or runoff captured from surrounding areas. Some, such as infiltration trenches, provide additional time for captured runoff to infiltrate the native soil below; others, like rain barrels, collect roof runoff during storm events for storage and release later or re-use rainwater during dry periods (Gironás *et al.* 2009).

The input parameters of LID devices on the SWMM were defined according to recommendations made by Rossman (2015), considering the characteristics for sandy clay loam and sandy loam, the predominant local soil type. The layer depths were defined according to those indicated by Schueler (1987) and Woods Ballard *et al.* (2015). The number of LID techniques, the mean area and the mean

width were obtained for each sub-catchment, using the geo-referenced data basis and the criteria described above.

Rainfall and discharge monitoring in the Leitão catchment have been performed since 2011 by the Belo Horizonte municipality. A time series from three rain gauges and six stream gauges (water level stations) located in the catchment was used for model calibration and validation corresponding to the current land use scenario. Due to many gaps and failures in the station data recording, only 20 events presenting a complete record in all six stations were found – seven of which were used for model calibration and the other 13 for validation. The time step of the observed hydrologic data was 10 minutes and the calibrated model was also used to simulate design events with 2-, 10-, 50- and 100-year return periods. Two major events observed for the time series, with different magnitude, were also selected for simulation – one event (occurring on 14 November 2011) with 2 years of return period and another (occurring on 12 December 2011) with 75 years of return period.

The hydrologic model performance was evaluated by comparing the flow data or simulated levels with the data observed in the six fluviometric stations installed along the watercourse, by visual evaluation of the observed and simulated hydrographs and the objective functions: Nash-Sutcliffe coefficient, percentage error of peak flow and of runoff volume. Calibration was performed manually, by trial and error, event by event, so that a set of parameters that optimized the objective functions was found for each event. In the end, the calibration events were again modeled with the mean of the resulting parameters. The set of parameters resulting from calibration was validated by modeling of independent events not used for calibration. It is emphasized that the objective functions were calculated for the whole duration of each event, of at least three days.

Uncertainties associated with hydrological simulation results were not estimated directly due to the complexity of simulated rainfall-runoff transformation processes. In this case, the methodology adopted consisted of simulation of the hydrological model while varying all the model parameters within the expected range of variation for each parameter, in order to obtain the minimum and maximum potential flows. Results of the model sensitivity analysis were taken into consideration to define which parameters should be reduced or increased in each case. The range of uncertainties associated with simulated data in the current scenario was plotted, providing a more realistic assessment of the results in other scenarios. More details regarding the methodology of this study can be found in Rosa (2017).

RESULTS

The topographic map and the land use classification map are shown in Figure 1(a) and 1(b), respectively. These maps were used to identify the green areas (Figure 2(a)) and suitable areas for GBI implementation (Figure 2(b)).

Comparing maps in Figure 1 and the map of existing green areas (Figure 2(a)), it is clear that the remaining green areas are located in high slope areas. Also, the favelas are located in the steeper areas in the catchment; the biggest one, called 'Agglomerado Santa Lúcia', is located just upstream from the detention basin (station 37 in Figure 1(a)). There are few parks and protected green areas in the basin and a big part of the vegetation is spread in little isolated fragments. In general, the low course of the creek (northern), which corresponds to downtown, is devoid of vegetation but, mainly due to its topographic and land use characteristics, offers the biggest potential for GBI implementation (90% of impervious area could be treated). The impervious areas

with less potential for GBI implementation are those occupied by favelas due to high slopes and occupation density.

Green and permeable areas cover about 390 ha or 38% of the total catchment area. The scenario of maximum urban development in the catchment, according to current legislation, would imply a reduction of pervious area to about 182 ha or 17.2% of the catchment area. According to the criteria used in the present study, 69% of the watershed impervious area could be treated with GBI devices such as green roofs, permeable pavements, infiltration trenches, rain barrels, and rooftop disconnection.

In calibration of the hydrological model, Nash-Sutcliffe coefficient (C_{NS}) values for water level and flow remained close to 0.70 for almost all events in all stations. The model generally produced similar results in the calibration and validation steps. Table 1 presents the results of the objective functions, C_{NS} and peak discharge and runoff volume relative errors, for each river station (presented in Figure 1(a)).

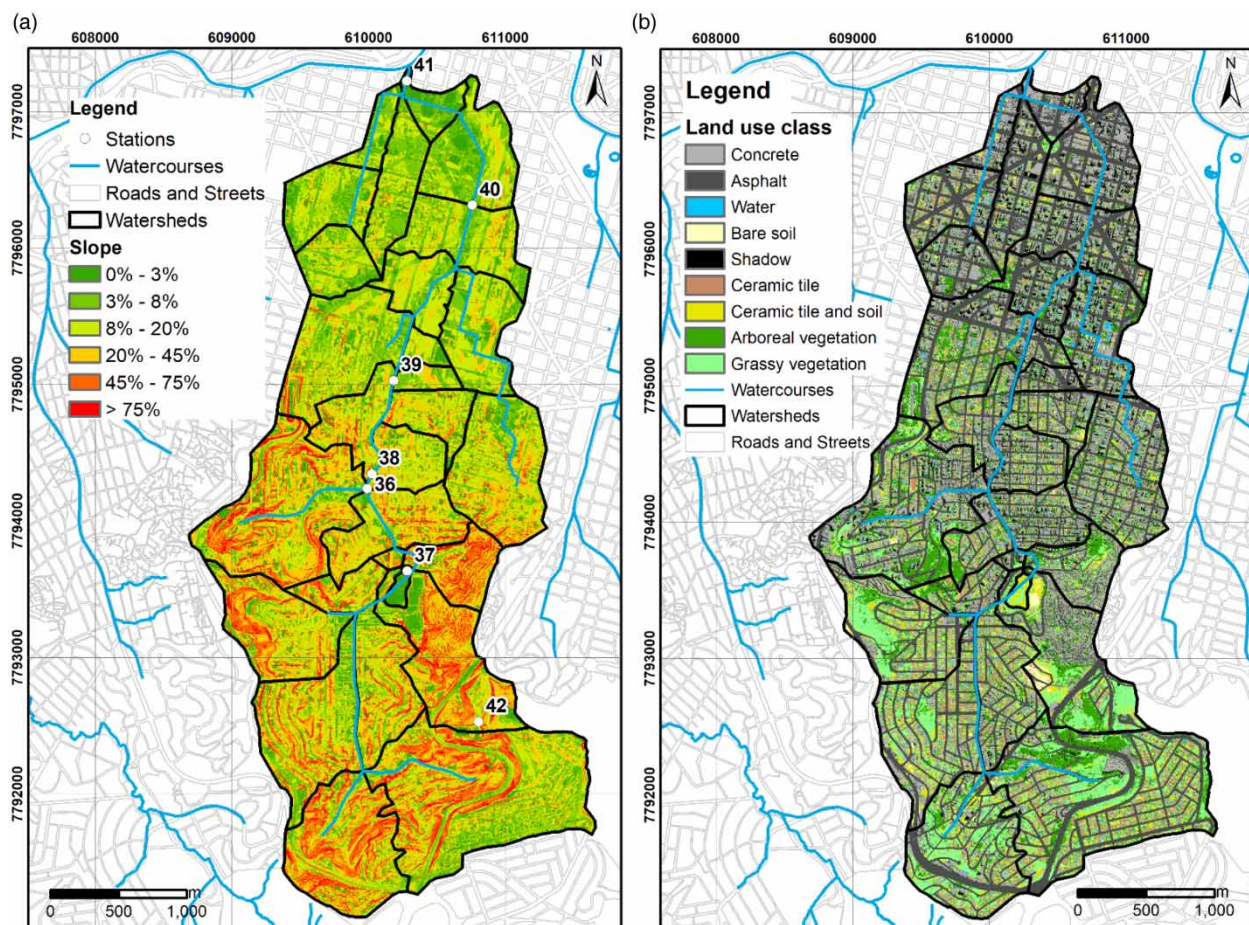


Figure 1 | Topographic map (a) and land use map (b) of the Leitão creek catchment. The numbers in the topographic map indicate the streamflow gaging stations from which data were used to calibrate and validate the hydrological model.

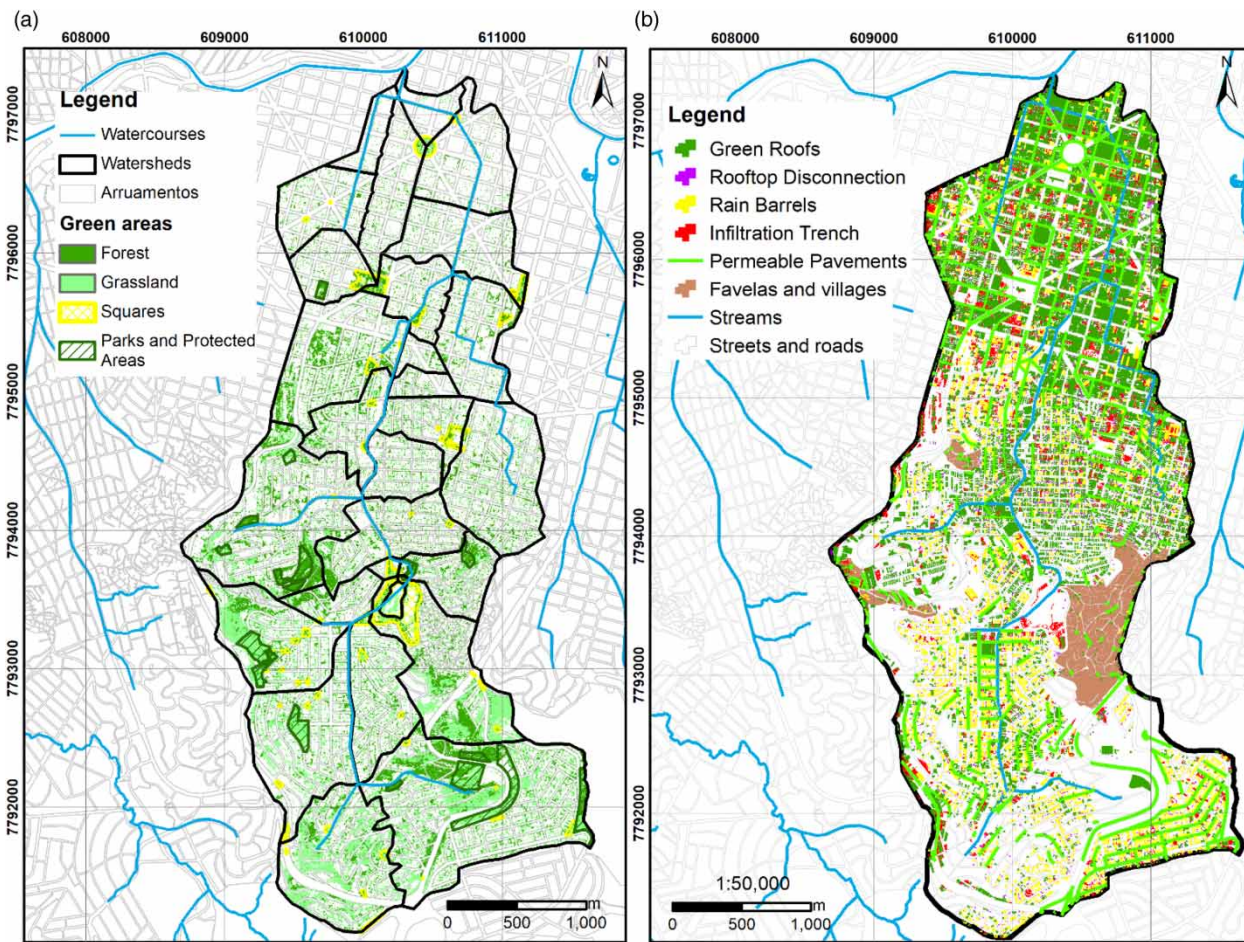


Figure 2 | Map of existing green and protected areas (a) and map of suitable GBI devices according to local characteristics (b) of the Leitão creek catchment.

Table 1 | Summary of the objective function results for the calibration events

Objective function		River stations						General
		E41	E40	E39	E38	E37	E36	
C _{NS} flow	Average	0.77	0.75	0.75	0.77	0.74	0.53	0.72
	Worst value	0.69	0.60	0.62	0.68	0.43	0.41	0.41
	Best value	0.87	0.91	0.88	0.83	0.90	0.73	0.91
	Standard deviation	0.07	0.10	0.11	0.06	0.20	0.18	0.09
C _{NS} water level	Average	0.60	0.70	0.78	0.80	0.77	0.57	0.70
	Worst value	0.36	0.57	0.67	0.67	0.44	0.38	0.36
	Best value	0.78	0.83	0.89	0.89	0.94	0.73	0.94
	Standard deviation	0.16	0.09	0.09	0.08	0.20	0.14	0.11
Peak flow relative error	Average	2%	1%	-3%	-6%	4%	-2%	0%
	Worst value	14%	28%	-26%	-28%	14%	31%	31%
	Best value	-1%	1%	3%	1%	0%	-2%	0%
	Standard deviation	10%	16%	13%	17%	8%	17%	11%
Runoff volume relative error	Average	-4%	11%	-6%	-5%	5%	18%	3%
	Worst value	-16%	32%	-25%	-18%	42%	31%	4%
	Best value	1%	1%	0%	2%	3%	4%	0%
	Standard deviation	10%	12%	13%	8%	22%	9%	10%

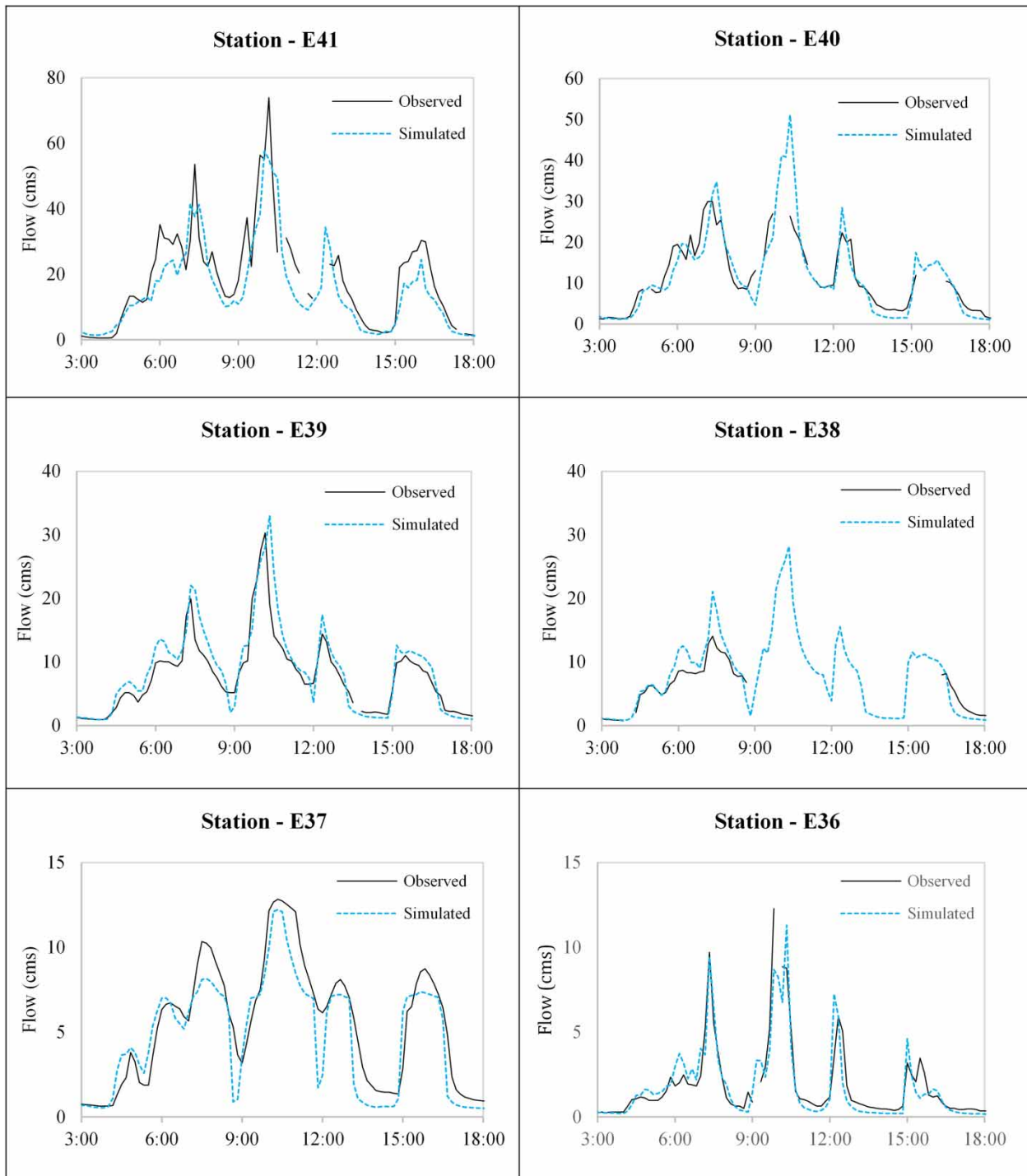


Figure 3 | Observed and simulated hydrographs for the 12 December 2011 event in the six streamflow gaging stations in model calibration. Discontinuities on observed hydrographs are due to failures in data registration.

C_{NS} values remained above 0.70 for all stations, except E36, to which no improvements in model calibration were possible. The similarity between the C_{NS} results for flow and water level indicates the possibility of using only one of

the data for calibration. Peak discharge relative errors were small, (1–6%), although standard deviations were higher (8–17%). Errors in volume simulation also remained around typical hydrological modelling errors in calibration.

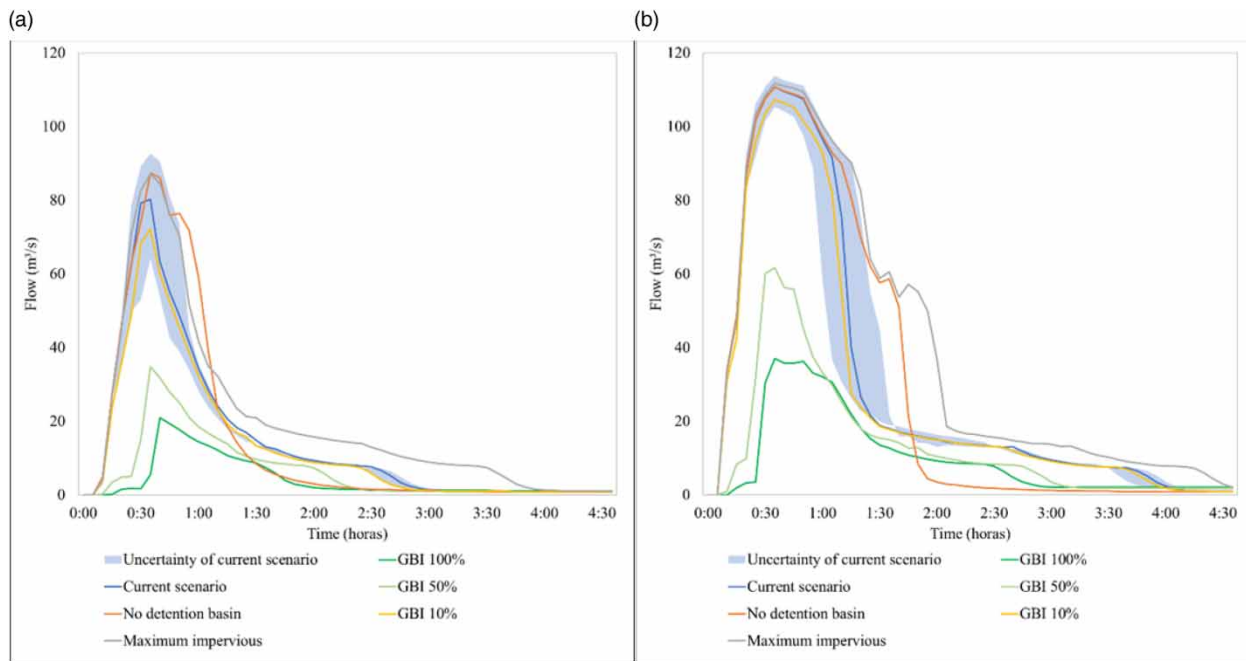


Figure 4 | Simulated responses at the catchment outlet for the 2-year (a) and 100-year (b) return period events according to different land use scenarios. Blue tinted area indicates uncertainty estimation around the current scenario hydrograph. The full color version of this figure is available in the online version of this paper, at <http://dx.doi.org/10.2166/wst.2020.148>.

During the calibration process, the need to increase the basin infiltration capacity was observed, altering the parameters initially estimated according to literature recommendations. Thus, two parameters had to be reduced: the percentage of impermeable areas and the CN. The average width of the sub-catchments (W), estimated initially by dividing the sub-catchment area by the average value of the maximum runoff length, was the parameter that suffered the largest change in calibration. The calibrated value of W was on average 9.9 times larger than the value estimated initially, and for some basins it was 32 times greater than the initial value. Alteration of these parameters could be explained by the adjustment needed to simultaneously increase the peak and reduce the base simulated flows compared to that observed. Calibration results for the event which occurred on 12 December 2011 are shown in Figure 3.

The model shows a good reproduction of the chronology of the events (rise and recession times of the events) and a reasonable representation of peak discharges in calibration.

Figure 4 shows hydrographs of the simulation of design events for the 2-year and the 100-year return periods considering the six different land use scenarios including three for GBI potential implementation in the catchment. Since the potential of adopting GBI in the catchment may not be fully exploited, scenarios GBI 50% and GBI 10%

hypothesize that only 50% or 10% of the potential GBI devices will be effectively implemented, respectively.

The simulations of the design events show a high efficiency of GBI, combined with the existing detention basin in the catchment, in flow attenuation, with peak reductions of 66–74%, depending on the event return period. This efficiency is more significant when one considers the use of 50–100% of the GBI potential in the catchment. Simulation results also suggest that the existing detention basin plays an important role in flow attenuation in the catchment, although controlling only 30% of the catchment area. As expected, further urban occupation of the catchment would lead to an increase in peak flow and runoff volume, suggesting that the current land use regulation in Belo Horizonte does not adequately take into account the impacts of urbanization in runoff generation and flood risk.

Figure 5 shows the rainfall and hydrographs for the simulation of the 12 December 2011 event, also considering the six different land use scenarios. Hydrographs in Figures 4 and 5 were calculated at the mouth of the catchment.

In Figure 5, the proximity between the peak times of the hietograms and the hydrograph indicates the rapid hydrological response of the study catchment. GBI scenarios show a slight delay in peak discharge; nevertheless, since these devices are diffusely set in the catchment, with a higher number located in its downstream, this effect is not

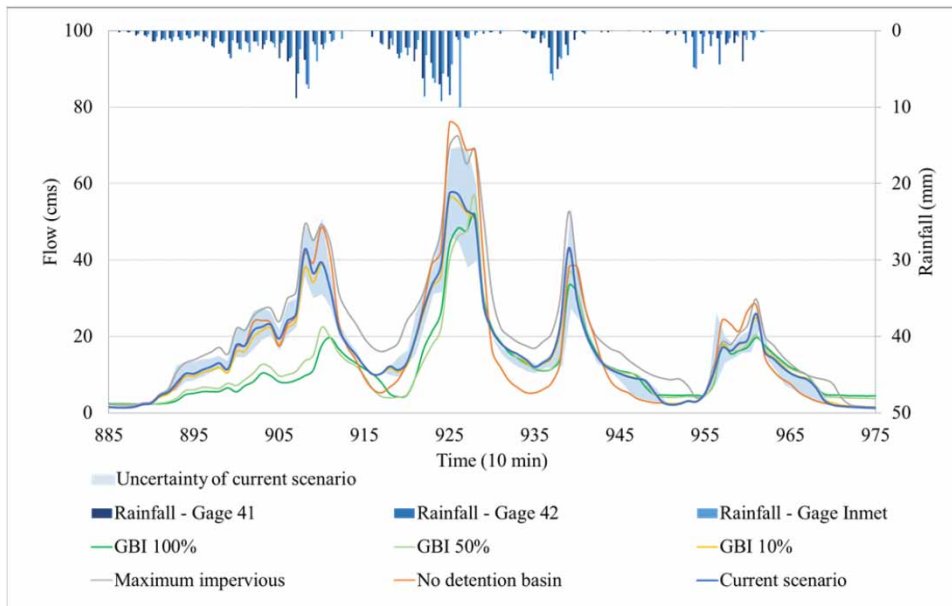


Figure 5 | Simulated responses at the catchment outlet for the 12 December 2011 event according to different land use scenarios. Blue tinted area indicates uncertainty estimation around the current scenario hydrograph. The full color version of this figure is available in the online version of this paper, at <http://dx.doi.org/10.2166/wst.2020.148>.

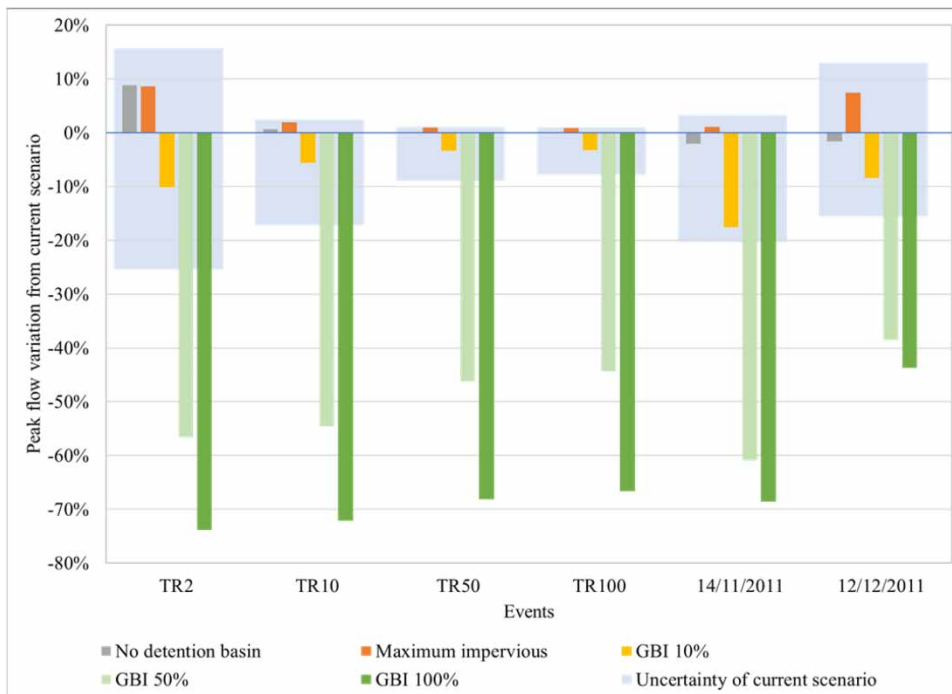


Figure 6 | Peak flow variations in the different simulated land use scenarios compared to the current scenario at the mouth of the catchment. Note: TR: return period.

significant. Except for the first rainfall block, when important reductions in runoff flow are observed for the scenarios with GBI implementation in 50% and 100% of suitable areas, the differences in the hydrological response

between all scenarios remained inside the uncertainty shadow of the current scenario. This suggests that for long duration rainfall events or a sequence of events separated by short duration dry periods, the evolution of soil humidity

and of water storage in the GBI devices reduces their efficiency in flow attenuation, a result that emphasizes the relevance of the simulation of observed rainfall events and of continuous simulation when assessing GBI performance at catchment scale.

Only for the second rainfall block, with a longer period of high intensity rainfall when compared to the three other blocks, a significant variation in peak flow between the current scenario and the scenarios without the detention basin and the scenario with maximum imperviousness is observed. Runoff volume increased 20.1% in the scenario of maximum imperviousness, and the hydrograph recession time was longer in all the resulting hydrographs. Peak flow reductions of 43.7% and 38.5% were estimated for the scenarios with GBI implementation in 100% and 50% of suitable areas, respectively. The runoff volume was reduced by only 7.7% and 6.9% in these cases. Reduction was even lower for the scenario with GBI implementation in only 10% of suitable areas: the peak flow was reduced by 8.4% and the runoff volume by 1.1%. The hydrograph of this scenario always remained very close to the current scenario, showing that the GBI implementation in only 10% of suitable area does not significantly impact runoff flow and volume. From the second rainfall block onwards, the hydrographs of the scenarios with GBI implementation were very close to the current scenario,

indicating the loss of efficiency of these structures for runoff reduction.

Figures 6 and 7 summarize the results regarding peak flow and runoff volume changes at the mouth of the catchment for design events and other rainfall-runoff observed events.

In the scenario with maximum catchment development, the peak outlet flow suffered a maximum increase of 8.6%. On the other hand, in the scenario with green and blue infrastructure implementation in 100% of suitable areas, the peak outlet flow was reduced by 66.6% for the 100-year recurrence time, and up to 73.8% for the 2-year recurrence time. These performances reduce with the GBI only partially implemented in the catchment, considering the suitable area: peak outlet reduction of 44.3% (100-year return period) to 56.6% (2-year return period) for GBI 50%, and 3.2% (100-year return period) and 10.1% (2-year return period) peak reduction for GBI 10%. Adopting GBI in only 10% of the catchment suitable areas is therefore not enough for a significant change in the rainfall-runoff relationship in the catchment.

As expected, the less frequent the event, the less efficient are the GBI devices in reducing peak flow. On the other hand, rainfall duration or a sequence of rainfall events with short duration dry periods may lead to GBI performance reduction as illustrated by the 12 December 2011 event, which has a return period estimated at 75 years and

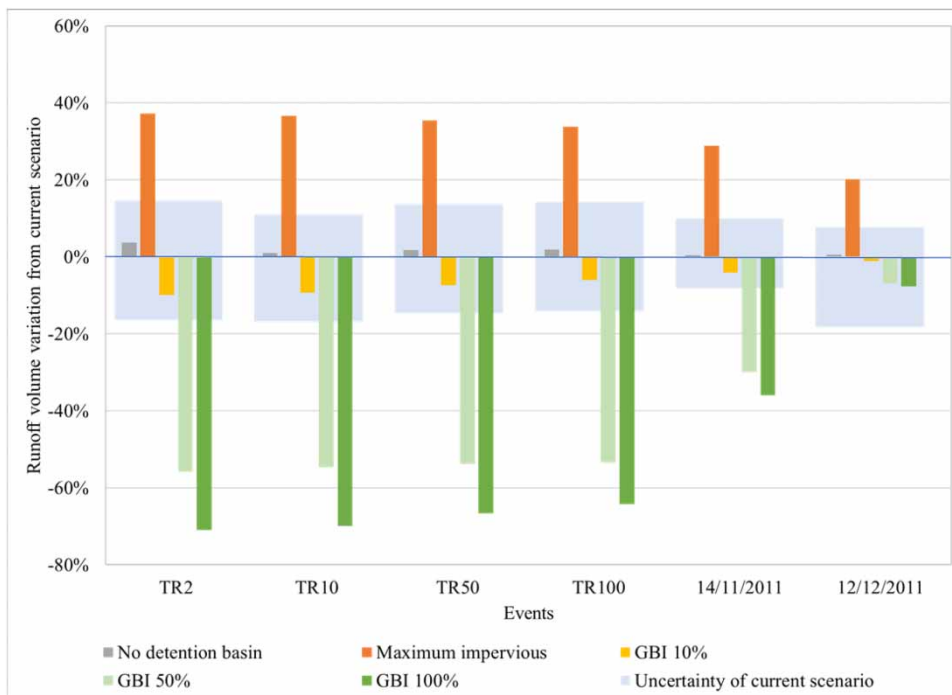


Figure 7 | Runoff volume variation for the different land use scenarios compared to the current scenario at the mouth of the catchment. Note: TR: return period.

for which GBI simulation shows a worse performance in peak reduction when compared to the 100-year return period GBI performance estimation. The return period of the event observed on 14 November 2011 was estimated at 2 years, which explains the high GBI performance in peak discharge reduction in this case.

The scenario with no detention basin did not affect the runoff volume, as expected. The scenario with maximum imperviousness led to an important increase in runoff volume for all simulated events. The scenario with GBI implementation in 10% of suitable areas presented reductions in runoff volume always less than 10%. Finally, the scenarios with GBI implementation in 50% and 100% of suitable areas presented the greatest reductions in runoff volumes, even for more intense precipitation events. The least impact on runoff volume for all scenarios was for the event of 12 December 2011.

Figure 7 shows that the influence of the GBI implementation scenarios on runoff volume presented a similar trend as for the peak flow attenuation. High efficiency was observed for GBI implementation in 100% and 50% of suitable areas, and feeble runoff volume reduction for GBI implementation in 10% of suitable areas. As expected, the efficiency of green and blue infrastructure reduces with the increase in rainfall intensity, and the removal of the detention basin exerts little influence on runoff volume. In the scenario with the maximum imperviousness allowed by legislation, the runoff volume would increase 37.3% for a

2-year rainfall return period, and 20.1% for the event that occurred on 12 December 2011.

Figure 8 presents the results regarding peak flow for a design event for a 2-year return period in all stream gages.

Figure 8 shows the difference in results along the watercourse. The main difference is in the scenario without the detention basin, in which an average increase of 70% in peak flow was observed along the stretch immediately downstream of it, at Prudente de Moraes Avenue, between stations E37 and E39. Since the detention basin is located upstream in the catchment, its role in flood control is less relevant near the catchment outlet (station E41), and if it is removed a maximum increase of only 8.8% in peak flows would be observed there. The scenario with maximum imperviousness led to more peak flow increase in the upstream stations compared to the outlet, probably because there are more green areas in the upstream subcatchments. And the scenarios with GBI implementation presented less reduction in peak flow in the upstream stations compared to the outlet, which could be related to the fact that in the downstream area there is more potential for GBI implementation.

DISCUSSION AND CONCLUDING REMARKS

This study evaluated the hydrological response of an urban catchment for rainfall events considering six land use scenarios: the current scenario, the current scenario with the

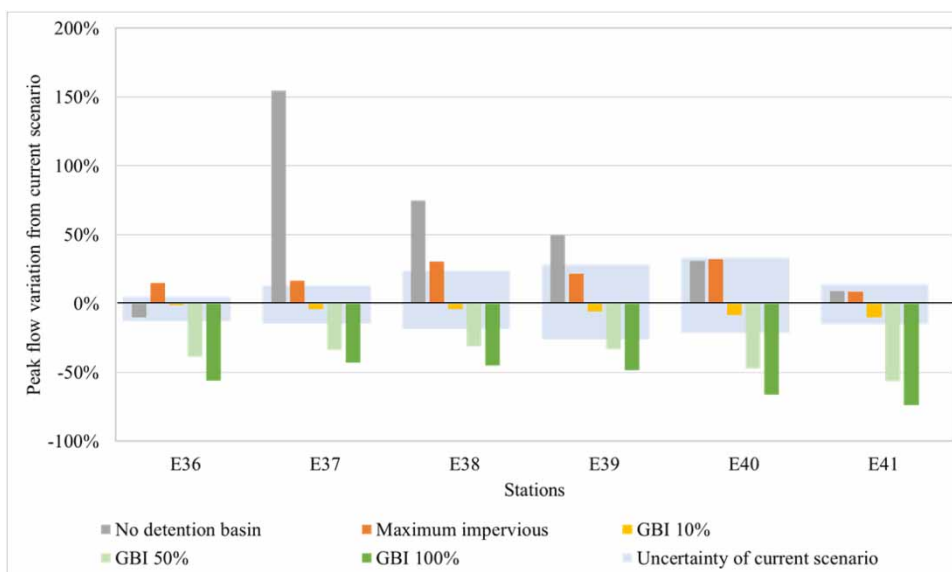


Figure 8 | Peak flow variations in the simulated different land use scenarios compared to the current scenario for design event for 2-year return period.

removal of the existing detention basin, considering the maximum impervious area allowed by local land use regulation, and three scenarios integrating the implantation of green and blue infrastructure in 100%, 50% and 10% of the catchment's suitable areas. For the construction of the scenarios, accurate cartographic and topographic bases were obtained, geoprocessing tools were applied, and hydrological characteristics were estimated.

For the model calibration (SWMM), rainfall and stream water level 5-year duration time series (2011–2016) from 3 precipitation and 6 stream gaging stations were employed. Uncertainty evaluation for the simulated hydrographs was performed based on parameter sensitivity analysis and on the calibrated parameter variability in the catchment. It is not frequent that in cities in the developing world one can count on detailed land use mapping, hydrologic data and cadaster of the urban drainage infrastructure as in the case of Belo Horizonte city, allowing, in the present case, a proper model calibration, validation and uncertainty estimation. Uncertainty estimation for the simulated hydrographs allowed a more objective assessment of changes in the catchment response according to different land use scenarios and rainfall events.

The GBI infrastructures hypothetically implemented in the catchment showed high efficiency in the reduction of peak flows in the simulation of design rainfall for several return periods. The significant reductions in surface runoff generated by design rainfall obtained in this study agree with the results presented by several studies carried out in the urban environment (Gironás *et al.* 2009; Bahiense 2013; Palla & Gnecco 2015), including the result obtained with LIDs simulation using other models (Zimmer *et al.* 2007). On the other hand, the simulation of observed and more complex events, longer than design events and with multiple precipitation blocks, such as the 12 December 2011 event, demonstrated that the GBI performance may suffer considerable reduction due to saturation. The same may be expected if initial soil moisture and water stored in the GBI devices are not in dry conditions as for the usual performance assessment with design storms. Therefore, in planning and designing GBI implementation it seems relevant to consider design rainfall combined with observed event simulations in order to obtain a more realistic view of their performance and benefits for the urban water cycle.

This paper also addresses the issue of adapting GBI devices in a built environment equipped with conventional drainage systems (Lerer *et al.* 2015; Romnée *et al.* 2015). In the face of potential effects of climate change and on the existing impacts of heat island development on air

temperature and on precipitation (Lin *et al.* 2011; Zhong *et al.* 2015), GBI offers a perspective of multiple benefits to the urban environment, such as reduction in air temperature, abatement of runoff and of wet weather diffuse pollution, enhancement of the urban landscape, among others (Kousky *et al.* 2013; Gordon *et al.* 2018; Nascimento *et al.* 2019). This paper focuses on the potential benefits of urban adaptation using GBI on runoff abatement at catchment scale from a detailed assessment of land use characteristics and potential and suitability to receive GBI devices. Several aspects related to formulating and implementing an urban policy leading to GBI adaptation are to be addressed in future studies such as tools to promote GBI implementation (e.g. urban regulation, economic incentives), associated costs and benefits, GBI acceptance by different stakeholders in the urban context, building and maintenance requirements, etc. Of the GBI devices simulated in the catchment, permeable pavements were located on public roads, some public buildings received green roofs and rainbarrels, and some public property lots received infiltration trenches. In contrast, most green roofs, rainbarrels, infiltration trenches and roof disconnection were applied to buildings and private land. These configurations highlight the importance of articulating public and private interests for the wide deployment of green and blue infrastructure on a scale that is sufficient to promote significant hydrological benefits. Catchment response to a low implementation of the GBI potential, as in the simulations here presented of only using 10% of this potential, shows that hydrologic benefits may not be significant.

This paper also addresses two possible consequences of urban policies and infrastructure management that may contribute to the increase of flood risk. In the first one, we simulate the loss of flood abatement capacity by an existing detention basin in the Leitão creek catchment and in the second one the possible impact on creek response to new urban developments in the catchment following the current land use regulation. The significant increase in the runoff volumes produced in the scenario with the maximum imperviousness highlights the relevance of preserving the green areas existing in the catchment with hydrological purposes. This scenario was built according to the limits allowed by the local municipal legislation and with the detention basin operating in the drainage system. The similarity of the hydrographs in the scenarios with maximum imperviousness and without the detention basin indicates that the hydrological effects of the reduction of the catchment's permeability (from 38% to 17.2%) would be equivalent to the removal of the detention basin from the drainage system. These

results suggest that impacts on runoff volume and discharge may possibly lead to an increase in the flood risk in the area and are, therefore, important for the decision-making process on urban planning and management.

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