Impact of urbanisation (trends) on runoff behaviour of Pampulha watersheds (Brazil)

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Abstract

The paper presents an analysis of runoff behaviour of four urban catchments between the municipalities of Belo Horizonte and Contagem in Brazil, linked to their land use. Two years of online measurement of flow data, combined with spatial analysis, was linked through runoff modelisation with EPA SWMM. The coefficients of Nash obtained varying between 0.75 and 0.87 demonstrated an adequate modelling approach. A 1-year rain series was applied to evaluate the runoff behaviour of actual land cover and that of 2002. The peak flows normalised to watershed surfaces revealed as the most urbanised (85%) watershed Ressaca with 178 L/ha/s, three times more runoff intensive than the least urbanised (41%) Mergulhão with 67 L/ha/s. Statistical analysis of land cover data and modelling results on watershed and sub-watershed level showed main correlations between hydrological parameters such as peak flow, average event flow and restitution time, but also between land cover and runoff coefficient. This approach gave a linear relation between runoff and green surface, with a runoff coefficient of 0.86 for fully urbanised zone and 0.43 for full "green" cover. Prospective simulation with actual urbanisation rates varying from 4 to 34 ha/year suggested an increase between 6 and 18% of the flows and a possible end of urbanisation within the next two to three decades. These findings should contribute to a better understanding of hydrological impact of Belo Horizonte urbanisation and to the restauration of its Lake Pampulha.

Keywords Urban catchment · Land use · Land cover · Wet weather discharge · Runoff · Urbanisation

Introduction

Brazil, as several other developing countries, suffers from fast urbanisation, accompanied by imperviousness and deficient infrastructures. Cities with a dense hydrographic network, like the two and half million inhabitants counting Belo Horizonte (BH), meet therefore everlasting difficulties linked to wet

weather management such as flooding, sediment built up and diffuse pollution, in most of their urban streams (Aroeira et al. 2010). Urbanisation and intensive land use have a negative impact on the water cycle, and a better knowledge of their relationship can contribute to a more sustainable and integrated water management (IWM) at the catchment scale (Miller et al. 2014). The IWM together with sustainable drainage systems can help to mitigate the impact of urbanisation and climate change (Dudula and Randhir 2016).

Stormwater management of Belo Horizonte is still based on traditional drainage systems seeking the improvement of water conveyance. Most of its drainage network was created using the 700 km of pre-existing urban creeks and was built in the last century, in the absence of hydrologic data, according to very simple design methods. The municipality launched his first stream monitoring network only in 2012. A consequence of these simplified approaches is the high uncertainty involved in the design of urban drainage structures and in flood management. More over water pollution by wastewater discharges and wet weather diffuse inputs, including solid waste and sediments, have caused the degradation of stream water quality,

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the reduction of conveyance capacities of storm sewers and channels and of flood control by silted detention ponds (Nascimento et al. 2006). In addition, increased imperviousness and occupation of flood prone areas contributed to amplify the frequency and impacts of floods. More recently, the municipality initiated projects of urban creek restoration associated with the implementation of blue-green corridors and detention ponds, contributing to change the former politics based on lining up the urban streams (PBH SMOBI and PBH Sudecap 2015). The population growth in Belo Horizonte has reached a saturation level with an average growth rate about 1.1% a year, from 1990 on, leading to an urbanisation of 95% of the municipal area. However, the land use law still allows densification of part of the municipal territory. Higher densification may represent a significant flood risk and impact on the receiving aquatic ecosystem especially for the outskirts of the metropolitan region (RMBH), where the population growth over the past decade was up to 5% a year (de Souza 2008) principally due to internal migration. This phenomenon is mainly due to the attractiveness of industrial and commercial activities, and the low cost of land as well as to the quality of public services. This urbanisation process is reinforced by informal settling especially in flooding zones and steep hill slopes (Nascimento et al. 2006; Duarte 2009).

The situation described above, in which catchment urbanisation results in modified stream hydro-ecology, is designed by Walsh (Walsh et al. 2005, 2012) as the "urban stream syndrome", including symptoms such as altered channel morphology, with disappearing riparian vegetation, where natural river bed makes place to deeper, wider, smoother and more stable river bed, with steeper hydrographs, high concentrations of nutrients and reduced biotic richness. These effects are often accompanied by other, not systematically observed symptoms, such as reduced base flow or increased suspended solid level. These symptoms are predominantly driven by urban stormwater runoff, which, in almost all urban areas of the world, has traditionally been managed for runoff control by a direct piped connection between impervious surfaces and streams (Vietz et al. 2016).

In urban areas, the rain falls on modified natural surfaces or on sealed, impervious surfaces to join pervious space or receiving water bodies. The water storage capacity linked to surface depressions of natural surfaces ranges from 0.5 to 15 mm, and for impervious surfaces, this range is reduced to 0.2 mm and 3.2 mm (Marsalek et al. 2008). This type of storage is more impacting at low rainfall intensities than during heavy storms. Impervious surfaces are of great importance in hydrological analysis, and their spatial distribution and connectivity is one of the most important factors determining flow velocity and volume of surface runoff (Mejía and Moglen 2010). High velocities due to imperviousness produce higher peak flows than in pre-urbanised conditions (Burns et al. 2005), and increase erosion and suspended solid levels,

resulting in higher flood risk and severity (Chen et al. 2009). Temporal and spatial scales of the runoff process depend on the geo-morphodynamic characteristics and will naturally vary from one catchment to another. Instream runoff is usually faster than overland flow, and its temporal scale varies essentially in function of rainfall intensity and channel morphology. The characteristic time scales of river runoff and overland flow vary from minutes for mountainous creeks to days for lowland rivers. "Urbanisation reduces the natural temporal and spatial scale of the runoff phenomenon due to high spatial heterogeneity of urban surfaces and by decreasing the catchment response time to precipitation" (Salvadore et al. 2015). Therefore, to understand fully the relation between urbanisation and runoff, a detailed spatio-temporal description of hydrological processes in urbanising watersheds is needed.

After previous study on qualitative impact of urban runoff in Belo Horizonte (Seidl et al. 2014), this work focuses, for the above mentioned reasons, on the relationship between land use and quantitative runoff characteristics in principal urban watersheds of the lake Pampulha, to better manage its water body in the future. The specific aim was to understand the actual relation between watershed land use and runoff, to characterise the evolution of past fifteen years and to indicate the consequences of actual urbanisation trend. The response is brought through hydrological modelling with EPA's Stormwater Management Model (SWMM) and statistic treatment.

Materials and methods

Watershed description

The catchment of the Lake Pampulha (Fig. 1) extends on 98 km^2 and is drained by eight small creeks: (1) Olhos d'Agua; (2) "AABB" creek; (3) Bráunas; (4) Água Funda; (5) Sarandi; (6) Ressaca; (7) Tijuco; and (8) Mergulhão. The creek Agua Funda appears in some official documents also as creek "Bom Jesus". Originally, Lake Pampulha was created to supply drinking water to the city of Belo Horizonte and served as décor for high-standard housing and architectural creations. However, since the 1970s, its water quality degraded as consequence of fast watershed urbanisation and poor wastewater and erosion control (PBH SMOBI and PBH Sudecap 2015). Consequently nowadays, lake silting and water eutrophication with episodes of cyano-bacteria blooms are the main problems to be resolved (Resck et al. 2007; Friese et al. 2010; Silva 2014). Despite its poor water quality, the lake became an important local tourist and recreational spot and contributes effectively to flood prevention downstream (Friese et al. 2010). The lake catchment is principally managed by the municipality of Belo Horizonte, with two important watersheds Agua Funda (4) and Sarandi (5) managed by the municipality of

Fig. 1 Studied watersheds. Dots:
river level metering; triangles:
rain gauges; in blue: data
collected by authors with 5-min
frequency; in red, data
made available by the municipal-
ity of Belo Horizonte with 10-min
frequency. Lake Pampulha coor-
dinates: 19° 55′ S, 43° 56′ W
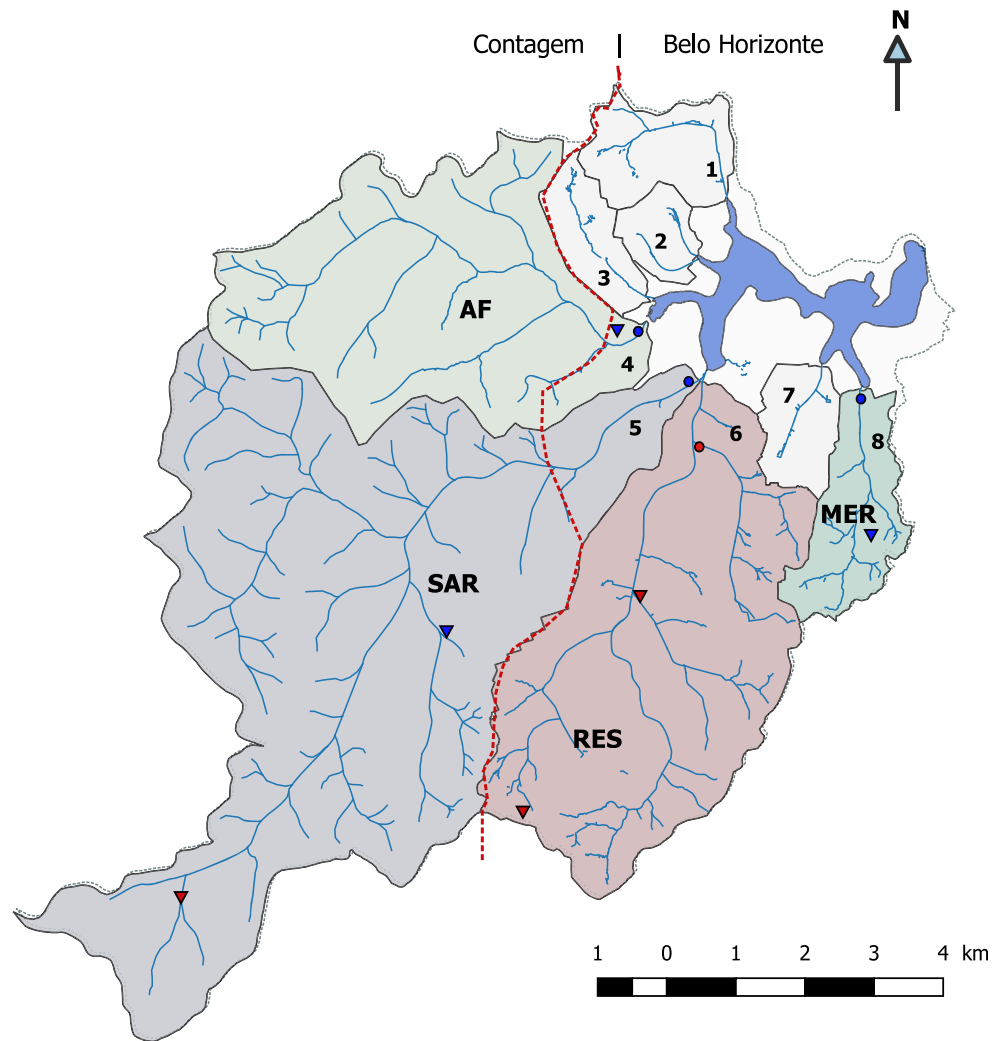
Contagem. The land use in Belo Horizonte watersheds is res-
idential with high standing close to the lake and wastewater
collection over 90%. The land occupation in Contagem is
residential and industrial, with mainly low-income housing
and poor sanitation. Part of the wastewater of Contagem wa-
tershed is conveyed via the Sarandi creek (5) to online flota-
tion treatment plant at the lake entrance to be treated for about
70% (Coutinho 2007; ANA and SNIRH 2018). During wet
weather, the treatment plant is bypassed.

The climate in the region is a tropical mountain climate, with
a dry cool season between April and September and a wet hot
season from October to March when 90% of the total annual
rainfall occurs (in average 1500 mm a year). Air temperature
shows relatively small amplitude over the year with a minimum
monthly mean of 18 °C in July and a maximum monthly mean
of 23 °C in February (Nascimento et al. 2006). To better man-
age the hydrographic network and to prevent flooding, the
municipality started in 2012 to operate a hydrological

monitoring network, having today 11 rain gauges and 27 points
of flow metering (Aroeira 2012). In the Pampulha watershed, it
possesses one point in Sarandi and two points in the Ressaca
watershed. All points are equipped with automated tipping
bucket rain gauges and ultrasonic water level sensors (Seba).
In 2012, the Federal University of Minas Gerais (UFMG)
started to monitor the Lake Pampulha in the framework of the
research project MAPLU, focused on better management of
runoff. The watershed monitoring was continued by the project
BRUM with emphasis on land use and hydrological behaviour
of the major watersheds. To cover most of the catchment dis-
charge, the watersheds Agua Funda (AF), Sarandi (SAR) and
Mergulhão (MER) were equipped in 2016 with fixed point
stations and monitored over two hydrological periods, running
from September (2016) to May (2018) at the outlet of each
watershed. The river water level and basic water quality (tem-
perature, conductivity, turbidity and oxygen) were monitored at
5-min intervals using level probe (Campbell CS451) and multi-

parameter probe (Aquaread Aquaprobe AP-2000) in canalised, rectangular, concrete river sections. The precipitation was monitored separately in each watershed using one or two tipping bucket rain gauges (Global water, 0.2 mm). Flow velocity during rain events was estimated in situ with floaters, in sections of 1 km, ahead of the monitoring points. For the Ressaca (RES) creek, flows and local rain data at 10-min interval were obtained from the hydrological monitoring network of the city of Belo Horizonte (Carvalho and Aroeira 2012).

All hydrological data were collected according to the WMO and EPA manuals (WCMD 2000; Meals and Dressing 2008; WMO 2008). Before their use, the collected data were treated for measurement errors, harmonised and crosschecked with existing data and standards. Nevertheless, it has to be stressed that data collection in regions with tropical climatic conditions and high criminality indexes like Brazil is more exposed to errors due to data discontinuity, insufficiency of calibration or collect frequency. Often it is not possible to choose the theoretically best place for rain or flow metering, constraints much stronger than in regions of northern hemisphere. These socio-environmental factors make the collection of adequate data series a long and tedious process.

Runoff modelling and calibration

To analyse the impact of land use on the runoff in space and time, runoff modelling was performed with EPA SWMM 5.1 (US EPA 2014; Rossman 2015). It is a widely diffused urban hydrological model, flexible and also suited to represent sustainable drainage systems (Elliott and Trowsdale 2007). In the SWMM model, both rainfall-runoff transformation on subcatchments and flow in the sewer network can be modelled. Each sub-catchment is considered a non-linear reservoir, with an outflow equation given by the kinematic wave approach (Singh 1988). The corresponding equations are:

$$\frac{dV}{dt} = A*(p-(100-\%imp)*i-e)-Q_V \tag{1}$$

$$Q_V = W*n^{-1}*(d-d_p)^{5/3}*s^{-1/2} \tag{2}$$

V The volume stored over the sub-catchment area A
A Sub-catchment area
p Rainfall
$\%imp$ Imperviousness
i Infiltration rate (CN method)
e Evapotranspiration rate, assumed as monthly constant
Q_V Flow-rate at the sub-catchment outlet
W Catchment width
n Manning roughness coefficient
d Water depth (V/A)
d_p Surface depression storage depth
s Channel longitudinal slope

Some of the parameters can be defined differently for the pervious and impervious parts of a catchment, in particular the surface characteristics "d_p" and "n". The first represents, for a given catchment, the amount of rainfall that can be stored on it before the beginning of the outflow. During frequent rain events, these factors are less important as surface remains wetted. The second parameter (Manning roughness) affects the response time of the catchment and the hydrograph shape. Manning's coefficient is also used by the SWMM model for the routing in channels and pipes, where a numerical solution of Saint-Venant 1-D equations, under dynamic wave assumption, is computed. For friction, Manning formula is used (Graf 2000) whereby the Manning's "n" plays a role of "velocity factor". Even if this parameter also affects the shape of hydrograph, taking in account the size of the catchment and the corresponding length scale, it will mainly slow down or accelerate the runoff.

To build a numerical model within SWMM and to determine the land cover evolution, 2017 GIS data of Belo Horizonte and Contagem municipality, combined with 2017 Google satellite (Google Earth) and street images (Google street view), were analysed manually. The land cover was analysed manually using QGis and Google Earth 2D at the altitude of 2000 m. Three land use categories were distinguished: non-constructed green space (i.e. forest or grassland), industrial occupation and housing. A detection limit of 20 by 20 m surface was chosen as balance between precision and time needed for manual estimation. Though the definition remained on parcel level, the precision obtained was better than 5%. For historical evolution, 2002 data were used. The models of Agua Funda, Ressaca and Mergulhão were constructed with 7 sub-watersheds (9 for Sarandi), based on hydrographic network and land use data.

The model calibration was performed using a genetic algorithm. This type of algorithm has been applied on hydrologic models since about 20 years (Franchini et al. 1998) and was here performed with Matlab program through an automated procedure (Petrucci 2012; Silva TF das et al. 2016). The parameters optimised were as follows: (i) the Manning coefficient of conduits (n-cond), (ii) the time necessary for a fully saturated soil to completely dry (dry time), (iii) the characteristic width of the overland flow path for sheet flow runoff (W), (iv) the Manning coefficient for overland flow over the impervious areas (n-imp), (v) the Manning coefficient for overland flow over the pervious areas (n-perv), (vi) depth of depression storage on the impervious areas (dp-imp), (vii) depth of depression storage on the pervious areas (dp-perv) and (viii) the Curve Number parameter (CN).

A selection of the most reliable, continuous collections of rain and river levels in the period of September 2016–June 2018, concomitant for the maximum of watersheds, was

performed, resulting in data sets of approximately 15 rain events and water levels for each watershed. The application of a continuous simulation allows to reduce the relevance of the initial conditions on the model performance. For each calibration, the first two-thirds of the data set (10 events) were used for the calibration itself, while the remaining one-third for validation (5 events). The objective function used in the optimisation is the Nash-Sutcliffe criterion (Nash and Sutcliffe 1970):

$$N = 1 - \frac{\sum t \,(Qo, t - Qs, t)^2}{\sum t \,(Qo, t - Qo, mean)^2} \tag{3}$$

where $Q_{o,t}$ and $Q_{s,t}$ are respectively the observed and simulated flow values at time t, $Q_{o,mean}$ is the flow observations' mean value. The indicator N, ranging from $-\infty$ to 1, is higher for a more accurate model. A value of 1 signifies a model perfectly matching the observed data, while a value of 0 indicates a model as accurate as the observations' mean value. This criterion is well suited for applications, like the current one, where the focus is on instant flow values and not on integrated values (e.g. daily runoff volume).

The calibration starts with parameters values based on field knowledge and modifies them according to the objective function. In some cases, the automatic optimisation results in parameter values exceeding the physical limits. In these cases, PCSWMM 2018 (James et al. 2010; Chi-Water 2018) was used to recalibrate manually and limit the parameter variation between plus or minus 50% of the initial value. PCSWMM is a commercial program based on EPA SWMM 5, with a Windows interface, including a genetic algorithm for optimisation and calibration. It is more user friendly, allowing finer calibration, without necessity of additional Matlab programming.

Data analysis

The spatial analysis of land use–runoff relationship was performed with 2017 data–calibrated models and a central point rain series. Whereas for calibration local rainfall data is essential, for the comparison of different catchments, it is important to discard this variability. Therefore, the hydrological behaviour of the different watersheds was compared using rain data of the most central station of Pampulha watershed, having 10 min's time step and the best quality standards (Table 1). The temporal evolution was thereafter estimated comparing the 2017 data with simulations using 2002 land cover and permeability data.

Several authors (Wu et al. 2013; Miller et al. 2014; Benini R de and Mendiondo 2015; Miller and Hess 2017) propose with more or less success different parameters to characterise hydrological impacts of urbanisation. Jacobson (Jacobson 2011) relates fourteen parameters found in the literature,

varying from flood duration to flashiness of stream flow. To quantify and qualify hydrological response of Pampulha watershed, the following indicators were calculated according to the literature mentioned previously: unit-area peak discharge, peak discharge to average flow ratio, peak lag time, restitution time and runoff coefficient. The unit area peak discharge is the quotient of peak discharge and the watershed area, and indicates the greatest amount of discharge generated by a unit area in a single precipitation event. A greater value of peak discharge indicates greater potential for flooding (Huong and Pathirana 2013). The peak discharge to average flow ratio is based on the same idea as the Richards-Baker Flashiness Index (Baker et al. 2004), that strongly impacted watershed will show an important variation of flows. The peak lag time is the delay between the rainfall maximum and the runoff peak, giving indication about the slope and imperviousness of the watershed like the restitution time, defined here as the time the watershed needs to evacuate 75% of the runoff. The runoff coefficient, sometimes called also runoff ratio, is the total discharge depth divided by total precipitation depth, indicating the proportion of precipitation that is discharged in surface channels. A higher value of runoff coefficient indicates an increase of surface runoff and may result in decreases in groundwater level because of less infiltration (Foster and Chilton 2004).

The land cover data and data produced by SWMM were statistically treated with Microsoft Excel 2013 and XLSTAT 2018 (Adinsoft 2018). These analyses include multiple Pearson correlation, agglomerative hierarchical clustering (AHC) with Kendall dissimilarity and principal component analysis (PCA) with bi-plot correlation.

Results and discussion

Calibration

Figure 2 shows the results obtained for the calibration process of 2017, optimising the whole set of model's parameters. The values of the calibrated parameters ranged between −50% and +50% of their respective initial values. The calibration was repeated if these limits were exceeded. The Nash criteria values obtained, both in calibration and validation, are high (> 0.75) and confirm the capability of the models to represent correctly the catchments observed hydrological behaviour. The differences between the level of fit may be caused by the difference in data quality, quantity and the different degree of difficulty to describe the creeks' hydrology. The AF watershed was calibrated with high frequency data, but with a rain gauge placed at the watershed outlet and creek bed approximation due to its natural morphology, able to change after each important rain event. The SAR watershed was also calibrated with high frequency data, but using two rain gauges

Table 1 Rain data of lower Ressaca watershed used for the inter-comparison of the Pampulha watersheds. Fifty percent of the events exceeds intensity of 3 mm/h or high of 1 mm. Usually no rain events are observed in the months of July and August

Period	Total (mm)	Separation time (h)	Number of events	Minimum (mm/h)(mm)	Maximum (mm/h)(mm)	Mean (mm/h)(mm)	Skewness coefficient
1 September 2016 to 30 June 2017	1067	0.5	257	1.20	108	9.83	3.16
				0.2	52.8	4.18	3.07

and a channel with known rectangular sections and gave therefore the best fit. RES has also regular sections, two rain gauges but only 10 min's frequency data, which is not sufficient for the tropical climatic conditions of Belo Horizonte. Finally, for or MER calibration were used high frequency meteorological data from university campus and its regular section.

Hydrologic behaviour

Fifty percent of rain events occurring in the region producing runoff are between 3 and 15 mm. An event of 15 mm and peak intensity of 50 mm/h have monthly return period and is more representative of the watershed behaviour than a yearly extreme, needing longer period to establish. Figure 3a shows therefore a response of the different watersheds to such a rain event. The (peak) flows normalised to surface may reveal the watershed characteristics. In our case, the peak flows at the outlet are decreasing, even for extremer events, in the order RES > SAR > MER > AF. For a monthly event, they pass from 80 L/s/ha for Ressaca to 15 L/s/ha for Agua Funda. The restitution time, defined as the time needed to discharge 75% of the event runoff, increases in the same order RES < SAR <

MER < AF, passing from 45 min for Ressaca to 125 for Agua Funda and Mergulhão. These values do not change significantly for extremer events.

The plot of exceedance frequency of the normalised peak flows for the different rain events (Fig. 3b) resumes the differences between the watersheds, mainly linked to their morphodynamic characteristics. The relation between the exceedance frequency and the peak flow in L/s/ha can globally be described by an exponential function, giving some indications about the watersheds:

– The y-axis intersection (regression equation constant) gives indications about the probable level of the annual peak flow, 20 L/s/ha for Mergulhão the less urbanised watershed and about 200 L/s/ha for Ressaca, the most urbanised one. From Table 2 and Fig. 3, one can see that these values are in the same range as the observed annual peak flow, varying from 19 to 179 L/ha/s.

– The slope (regression equation coefficient) describes the watershed and is higher for RES than for MER, meaning more extreme events for RES than for MER, probably due to the importance of its impervious surface.
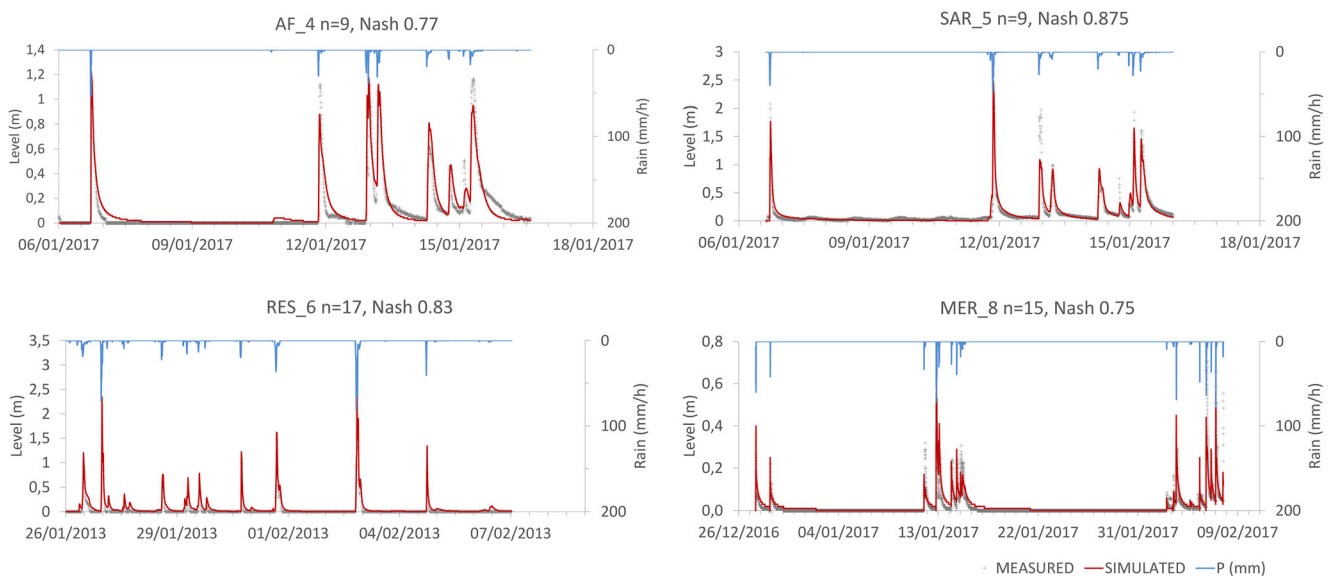

Fig. 2 Results of the calibration of the four main watersheds Agua Funda (AF), Sarandi (SAR), Ressaca (RES) and Mergulhão (MER). Blue line: rain intensity; marks: measured water level; red line: simulated water levels
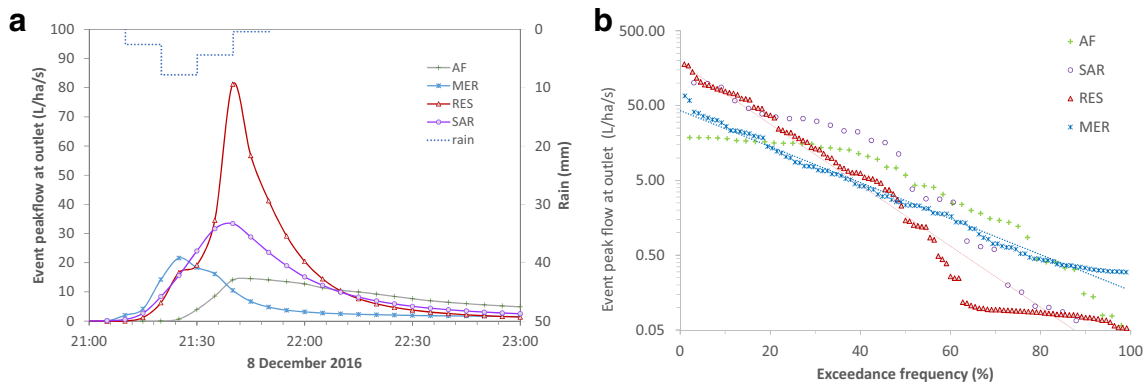
Fig. 3 **a** Normalised peak flows, for a rain event with 1-month return period for the four watersheds. **b** Exceedance frequency for normalised peak flows. Data issued from simulation with Ressaca rain data set of the wet season 2016/2017 (Table 1)

Though the function has elevated correlation coefficients, it does not describe adequately all flow ranges for the watersheds. RES shows frequent events with low flows, probably due to high degree of imperviousness, while AF shows several events at the peak level range, probably due to the expansion surface mentioned before.

Table 2 resumes the principal hydrological descriptors of the watersheds, having important difference in surface and land cover. The absolute values of peak flow give another image when normalised to watershed surface, pushing Ressaca in front of the largest Sarandi. Ressaca is also the one with the highest slope and urbanisation and shows therefore the shortest restitution time. Using the dissimilarity index (Adinsoft 2018) and all data of Table 2, Ressaca and Sarandi watersheds are similar and close to Agua Funda. The Mergulhão is the only one being significantly different from the three others. As shown in the next paragraph, this division corresponds roughly to the urbanisation intensity. Using Pearson's correlation matrix, we obtain only a significant correlation ($p < 0.05$) between unit area peak flow and restitution time—the higher the peak flow, the faster the runoff restitution. In general, high unit area peak flow is linked to imperviousness, though this relation might be influenced by the distance of impervious surfaces from the outflow (Mejía and

Moglen 2010). The first indication of relation between land cover and hydrology appears only at $p < 0.2$ for green surface and restitution time; the higher the green coverage, the longer is the restitution time. Other parameters like flashiness or difference between maximum flow and average flow are stronger linked to watershed surface ($p < 0.05$) than to other characteristics like unit area peak flow ($p < 0.1$) as would be expected (Baker et al. 2004). A possible explanation for the ambiguous position of AF watershed might be the presence of natural expansion zone of 1 to 2 ha close up streams of the outlet, functioning as a detention facility, giving Agua Funda the appearance of less urbanised watershed. This hypothesis is supported by higher peak flows and sharper hygrographs for the adjacent upstream nodes.

The order of magnitude of peak flow found is coherent with observations of Burns (Burns et al. 2005) for outskirts of New York, giving peak flows between 8 and 40 L/ha/s for unconstructed and moderately constructed watersheds or those of Boggs (Boggs and Sun 2011), observing flows between 170 and 340 L/ha/s for forested and heavily urbanised areas in North Carolina. Boggs noticed herby that the urban maxima were higher and frequenter than that of forested land. In Brazil between the few references can be cited Viola (Viola et al. 2014) mentioning peak flows between 1 and 10 L/ha/s for different types of agricultural land in South Brazil. Using the

Table 2 Hydrological characteristics of the watershed studied, using 2017 land cover and 2016/2017 rain data set and event approach. AF, SAR, and MER were modelled with 7 sub-watershed, SAR with 9. Peak flow corresponds to an event with 2-year return period. Lag time precision is 10 min, that of restitution time is 5 min. (1 L/ha/s ≈ 0.12 mm/day)

Watershed name	Watershed surface (ha)	Slope %	Green coverage	Runoff coefficient	Peak outflow (m³/s)	Peak outflow (L/ha/s)	Event mean outflow (L/ha/s)	Q_{avg}/Q_{peak} flashiness	Lag time (min)	Restitution time (min)
AF	1808	2.5	44%	0.78	33.8	18.7	0.19	1.01%	22	130
SAR	4076	2.0	40%	0.77	411.4	100.9	0.43	0.42%	25	72
RES	2086	8.0	15%	0.76	372.6	178.7	1.19	0.67%	22	51
MER	337	4.7	59%	0.47	22.7	67.3	1.02	1.51%	10	117

statistic approach of Snyder (Snyder 1938) on unconstructed watersheds, based on their morphology Mergulhão, should be twice as fast as Sarandi, with Ressaca and Agua Funda in between, giving the same flow range as found by Viola.
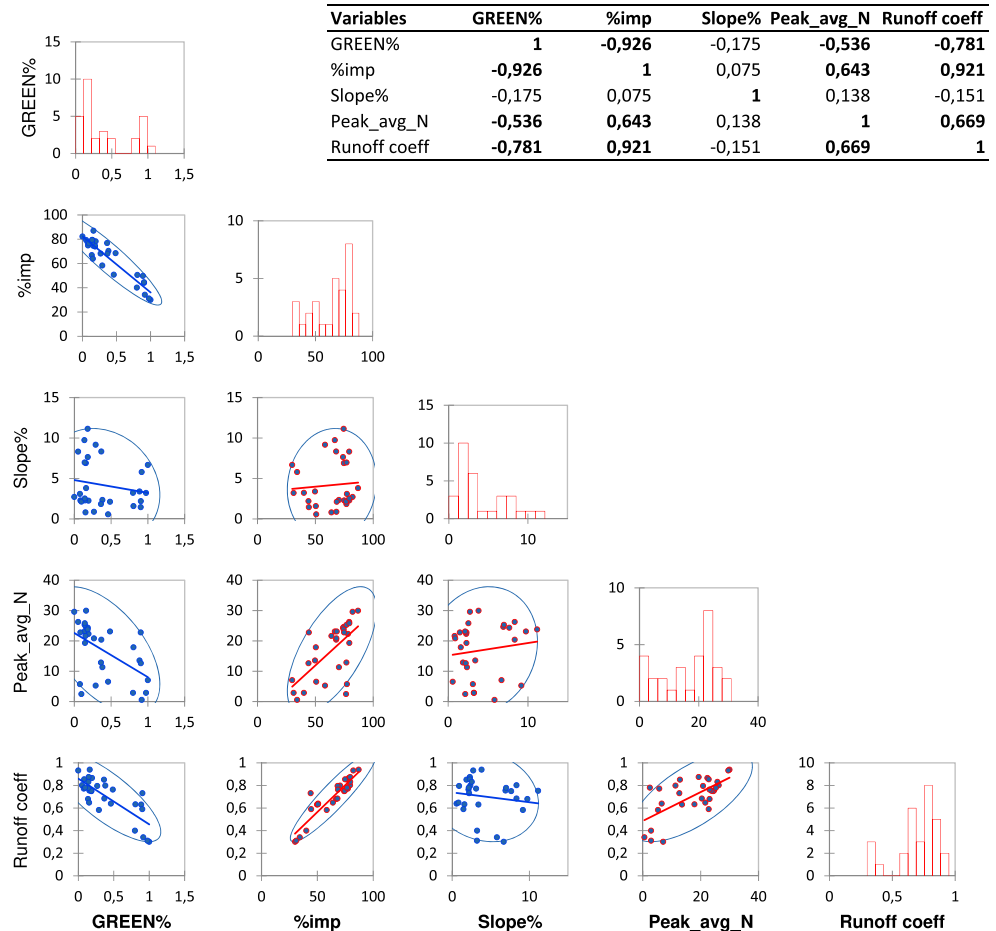
Land use impact

A regression analysis (Fig. 4) of principal landscape characteristics and hydrological parameters issued from the SWMM modelling on sub-watershed shows some interesting correlation between watershed characteristics and hydrological parameters. The strength of the relation is given by the correlation coefficient and the 90% confidence interval in the individual charts: the more ellipsoid it is, sticking to the regression line, the more significant the relation is. The most significant negative correlations (blue) are green area and imperviousness, consequence of conversion of natural permeable surface to less permeable housing and industry surface. The most positively correlated factors (red) is the imperviousness and the runoff coefficient, factors physically linked. Though more pertinent for urbanisation is the relation of average peak runoff and imperviousness. A positive tendency exists ($r^2 = 0.64$) between the degree of urbanisation and the peak flow, but

the relation should be better validated statistically using a greater number of watersheds.

A complementary statistical approach is the principal component analysis (PCA) using all parameters (Fig. 4). The PCA is subtler than the Similarity/Dissimilarity Matrix, especially when using data of all sub-watersheds. Using such a larger data set, the PCA shows better the dissimilarity and indicates that, inside a watershed, important differences may exist. The raw and normalised data give the same tendency separating MER from other watersheds, independently of the number of variables used, varying between 4 and 12. Figure 5 gives the result of 8 variables, half of them measured and half of them estimated by SWMM, showing the best separation. The vertical axe can be interpreted as physical watershed characteristic, while the horizontal tends to describe the hydrological behaviour. Most variables like imperviousness, peak runoff, and runoff coefficient are linked and push in the fourth quadrant, separating clearly the smallest and greenest (MER) from the more urbanised ones. The AF and the SAR behave similarly and appear in the same quadrants. A higher slope and less green, giving higher number of runoffs, push in the second quadrant, separating RES from AF and SAR. As expected housing and green surface, being opposite, are negatively correlated.

Fig. 4 Multi correlation (r^2) of normalised basic hydrologic parameters. Land use expressed as fraction of the total surface and flows in L/s/ha. Red: positive correlation; blue: negative correlation. Dots: observations; lines: 90% confidence intervals
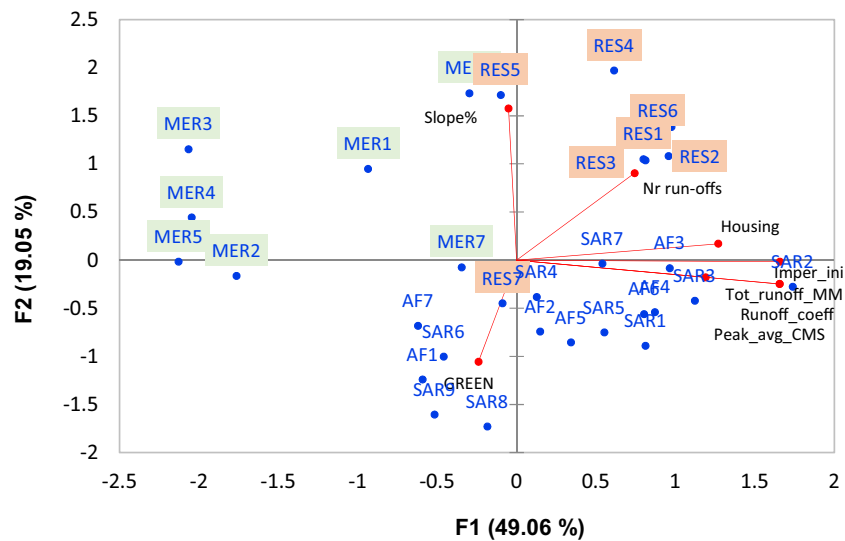
Variables	GREEN%	%imp	Slope%	Peak_avg_N	Runoff coeff
GREEN%	1	-0,926	-0,175	-0,536	-0,781
%imp	-0,926	1	0,075	0,643	0,921
Slope%	-0,175	0,075	1	0,138	-0,151
Peak_avg_N	-0,536	0,643	0,138	1	0,669
Runoff coeff	-0,781	0,921	-0,151	0,669	1

Fig. 5 Principal component analysis, explaining 68% of variance, of all sub-watersheds using field data and results of SWMM simulation. The less urbanised watershed MER is highlighted in green and the most urbanised watershed in orange. Slope%: average watershed slope; Nr runoffs: number of rain events above threshold; imper_ini: field imperviousness; Housing: housing surface; Tot_runoff_MM: total runoff in (mm); Runoff: runoff; Peak_avg_CMS: average of event peak in m^3/s; green: vegetated surface

Historical evolution

The knowledge of land use and hydrology on watershed scale helps to manage it and to predict the impact of future urbanisations. Figure 6 gives an example of the evolution of the land cover in the upper watershed of Agua Funda. The green area is delimiting the official green leisure area. This area is legally (star) and illegally (red stop) transformed to housing. In 15 years, 17% of the watershed green surface was urbanised. The four watersheds had similar change of land use, passing principally from grassland or wood to housing. The only significant difference is the industrialisation of the largest watershed Sarandi, where the expansion of housing is the same as that of industry. This reconversion rate of 1% of watershed surface a year is the same for all watersheds, meaning 4 ha/year for the smallest watershed Mergulhão and 34 ha/year for the biggest one Sarandi (Table 3)

Using the hypothesis that the landscape relief does not significantly change between 2002 and 2017 makes it possible to use the hydrological model of 2017 to evaluate the hydrological behaviour in 2002, using the land cover data of that period. From hydrological parameters (Table 2), we see a clear trend, accompanying the urbanisation: increase of average event flow with frequenter and higher peak flow. The most elementary hydrological impact of urbanisation is the increase of the runoff (coefficient) and was therefore used to characterise the impact of 15 years of urbanisation. As can be expected form literature (Mejía and Moglen 2010; Jacobson 2011; Miller et al. 2014), a strong positive correlation is present between imperviousness and runoff (Fig. 4). However, in the perspective of climate change, and carbon balance, it is more pertinent to look at the vegetated surface. A statistically significant linear relation can be observed between the runoff coefficient and the green surface coverage, for the totality of studied watersheds (Fig. 6). This relation is stronger for each individual watershed but does not change between 2002 and 2017. The global relation can be written as:

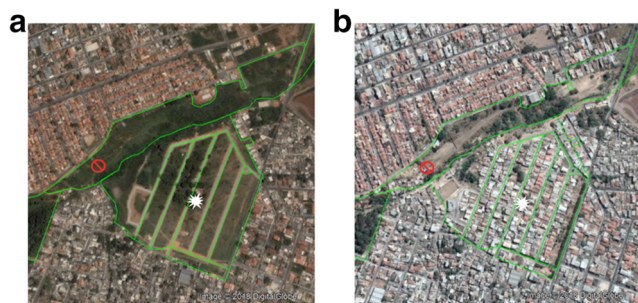$$\textbf{Runoff coefficient} = 0.86 - 0.43 \times \textbf{Green coverage} \qquad (4)$$

This relation means that the runoff coefficient of the Pampulha watershed moves from 0.43 (0.31–0.55) in unconstructed state to 0.86 (0.72–.0.96) when "no" more green surface is present. This relation can be read in two ways: urbanisation leads to higher runoff, and a city desiring to diminish its runoff has to convert impervious surface to green surface. This empirical relation has nevertheless some limits due to the precision of land cover estimation. "No green" means less than the detection limit of land coverage, being about 5%. For the smallest watershed Mergulhão, this "zero green" corresponds to about 17 ha. This limit could be divided by about

Fig. 6 Watershed Agua Funda, on **a** 28 November 2002 and on **b** 29 July 2018 (© DigitalGlobe, 19° 51′ 30.79″ S 44° 01′ 30.64″ O, altitude 1900 m). Star: legal urbanisation; red circle: informal urbanisation

Table 3 Result of SWMM simulation for land cover in 2002 and that of 2017. The urbanisation rate is calculated as the observed surface difference divided by the time difference. This rate was used to estimate a possible year of "full" urbanisation

Land cover	Agua Funda		Sarandi		Ressaca		Mergulhão	
	2002	2017	2002	2017	2002	2017	2002	2017
Mean event flow (m³/s)	1.72	1.86	1.48	1.74	2.31	2.49	0.321	0.343
Maximum flow (m³/s)	33.5	33.8	397	411	323	372	18.8	22.7
Average peak flow (m³/s)	12.7	14.4	71.5	88.4	37.6	42.5	2.23	2.81
Skewness	0.44	0.25	1.81	1.54	2.31	2.32	2.50	2.34
Urbanisation (ha/year)		19.4		33.7		25.1		3.95
Flows changes expected		3–6%		7–37%		8–13%		0–26%
Runoff coeff. range		0.54–0.96		0.55–0.85		0.46–0.81		0.31–0.72
Year hydrol. urbanised		2024		2054		2033		2057

four for the 2002 coverage, using automatic green surface recognition, allowing to take better in account the green within individual cadastral parcels. As the equation was elaborated in a specific geographical zone, it should be validated before transposition to other regions.

The knowledge of land cover evolution together with the hydrological modelling allows besides retrospective assessment to elaborate a prospective. The set of hydrological parameters (Table 3) gives the possibility to calculate tendencies. Simplifying the evolution between 2002 and 2018 as a linear process of imperviousness, we can calculate from past evolution a possible development in the future, using the end imperviousness (Fig. 7), to estimate the runoff in a fully urbanised situation and the time to reach it. Using the conversion rate and the hydrological tendency, the most urbanised watershed Ressaca will exhaust all its green in about 15 years. The hydrological parameters will hereby only slightly increase. The less urbanised Mergulhão might reach its hydrological end state in about 40 years with significant flow increase, but will probably never get so far, because of forest

conservation measures of the university campus. Using the hydrological tendency, the watersheds in-between AF and in less extent SAR, seem to urbanise faster than can be concluded from the land conversion rates. AF will have a slight increase in flow at outfall, probably as mentioned before due to hydraulic buffer at the watershed discharge, but Sarandi will know higher water fluxes, which even might lead to saturation of the existent network.

Conclusions and perspectives

The aim of this study was to establish better hydrological indicators for urbanisation follow-up and to determine whether the urban development of past 15 years of the Lake Pampulha watersheds has modified these parameters. The obtained results show, according to other authors (O'Driscoll et al. 2010; Verbeiren et al. 2013; Miller and Hess 2017), that green and constructed land are main factors lowering (green) and increasing (housing) the peak and the average annual

Fig. 7 Relation between green land coverage and the runoff coefficient for the four watersheds studied. Points with surface change of more than 20% are annotated; codes of 2002 have asterisks, while codes of 2007 are underlined. For each watershed, the most important change is marked with red arrow
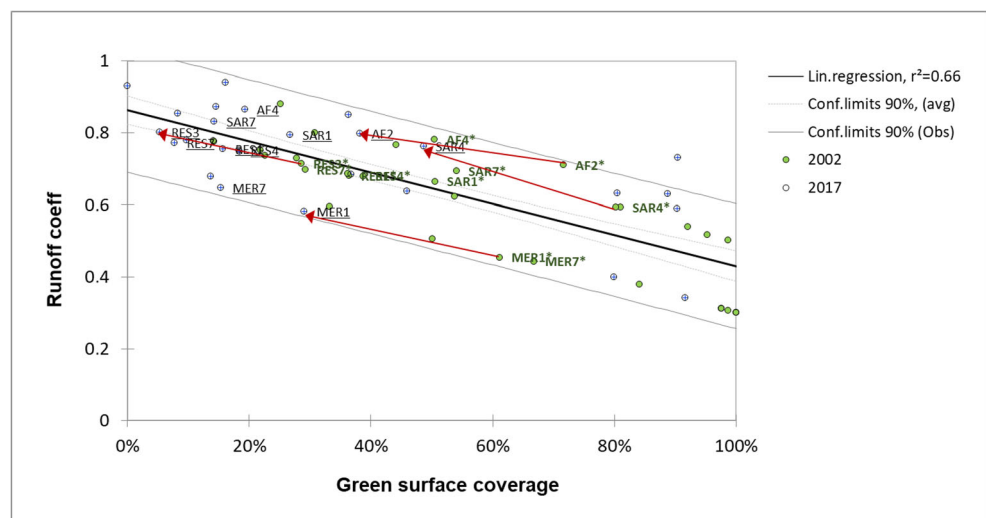
flow. Watersheds with high percentage of open or greened space like Mergulhão offer more surface for infiltration and retention, lowering their runoff compared to watersheds with high degree of imperviousness like Ressaca. In other words, to keep the initial capacity of runoff mitigation, watersheds with increasing urbanisation have to compensate this loss of infiltration capacity with measures like sustainable drainage. Even though the studied watersheds present a large range of imperviousness and land cover, their relative hydromorphological heterogeneity possibly masque the general tendency that denser urbanisation generates faster and larger discharges (Fritsch 2013; Salvadore et al. 2015). An apparently urbanised watershed like Agua Funda may therefore show behaviour close to a poorly urbanised one like Mergulhão. Nevertheless, different statistical treatments separate clearly the most impervious watershed from the less impervious one. The relation common to all watershed links green surface and runoff, making it possible to predict the evolution of runoff in the different watersheds. The studied area urbanises yearly 1% of its total area, transforming about 80 ha of green area into housing and industrial surface and increasing its runoff. The watersheds tend hereby towards an apparent final runoff coefficient of 0.86 when all important green surface is converted. This state is going to be achieved for the principal watersheds between 5 and 35 years from now on. The characteristic flows will herby increase between 6 and 18%, surpassing probably for the largest watershed Sarandi its conveying capacity. Though larger data sets are necessary to fully validate these findings, the authors are convinced that obtained results will contribute to a better understanding and evaluation of the hydrological impact of the urbanisation in the suburbs of Belo Horizonte and Contagem, facilitating the restoration of Lake Pampulha. Future research will herby be oriented on qualitative impact, namely the problems of urban erosion.

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