Research Article

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Simulation of flood hydrographs in urban channels: a tool for urban planning

Abstract

Floods caused by extreme hydrological events and their consequences are one of the major challenges faced by local government authorities about urban planning. In this context, we studied the urban cross channel sections behaviour located in the Jatobá stream catchment, in the city of Belo Horizonte, Brazil. Different precipitation scenarios were used as input parameters for the hydraulic simulation. For this purpose, the accumulated rainfall was disaggregated and a frequency analysis was performed to compute different duration times (from 10 to 120 minutes) and return periods (from 2 to 100 years). Then, hydrological and hydraulic simulations were carried out using HEC-HMS and HEC-RAS models, respectively. The results showed that the average time until the channel overflows was 58 minutes and the average duration time for the overflow was 28 minutes. The channel overflowed in 77.14% of the simulated scenarios. The simulations were carried out for different rainfall return periods and time duration to characterize extreme events for this catchment, aiding the decision- making process and assisting in the development of strategies to improve the drainage system.

Keywords: floods, hydrological extremes, precipitation scenarios, HEC-RAS, HEC-HMS

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Abbreviations: HEC-HMS, hydrologic, modelling system; HEC-RAS, river analysis system; CEPED-UFSC, center for studies and research in civil defense and engineering at the federal university of Santa Catarina; BHCH, belo horizonte city hall; GIS, geographic information system; SMURBE, municipal secretariat of urban policies; SCS, soil conservation service; CN, curve number; ALEA, local hydrological variables annual analysis; Cd, distribution coefficient; CONTRAN, national traffic Council

Introduction

Floods in urban centres

Floods represent a major problem around the world, being one of the most frequent, challenging and devastating natural disasters due to their rapid occurrence in a short period.[1] In Brazil, specifically from 1991 to 2012, the death toll from flash floods were 1,964 and more than 400 people died due to floods.[2] Most of these events were recorded in the southeastern region of the country, where more than 983,584 people were injured and more than 1,400 of these people died.[2] Different authors used different methods, time scales and input data to better understand the characteristics of the floods, such as precipitation dataset from weather radar and definition of the soil humidity condition before the rainy event,[3,4] use of Geographic Information System (GIS) tools to spatialize rain in greater detail,[5,6] time scale analysis[7] and comparison between hydrodynamic models with empirical and concentrated ones.[1,7–9]

Belo Horizonte, capital of the Minas Gerais state, has an estimated population of 2,521,564 inhabitants (Brazilian Institute of Geography and Statistics [IBGE], 2020)[10] and a demographic density of 7,167.00 inhabitants/km2 (IBGE, 2010).[11] Like most Brazilian cities, it grew in a disorderly way, disregarding the topography, vegetation and water courses that, in addition to being channelled, were covered by the road system. According to Bertone[12] changes in the natural environment have been intensified in order to shape it according to society interests and these have caused disturbances in the ecological balance s, worsen the impacts of climate change, resulting in disasters.

The growing urbanization and the use of impervious surfaces, associated with the increase in the intensity and frequency of rainfall due to global warming,[13] has been the cause of more severe flooding events due to runoff increase. The channelling and impervious covering of river beds are examples of changes made in order to drain rainwater quickly and avoid flooding. Once performing these procedures, it is expected that the volume and speed of runoff will be reduced. However, it results in opposite effects, such as intensification of the erosion process, increased sediment load, silting and flooding.[14–16] Jacobson[17] states that the hydrological impacts of urbanization come from the perviousness reduction of urban areas as buildings, roads and other paved areas which increase stormwater runoff. Imperviousness also results in an increase in flood peaks and a reduction in the concentration time, which is the time required for the entire basin area to contribute to the outlet, i.e., the time it takes for a drop to travel from the most far to the catchment outlet.[18,19] Belo Horizonte is an example of these problems, given that, today, the city has been impacted by urbanization, presenting recurrent cases of floods.

In this regard, it is extremely important to investigate strategies to mitigate the impacts resulting from these events. This study aims to provide subsidies to analyse the hydraulics conditions in order to reduce vulnerability in the socio-environmental sphere. Besides, the anticipation of these extreme events is crucial for issuing alerts in a timely and efficient manner.[20] An extreme event (meteorological or climatic) is generally defined as the occurrence of a parameter (meteorological or climatic) above (or below) a limit value, near the upper (or lower) ends ('tails') of the range of observed parameter values[21,22] found that 53% and 47% of extreme precipitation events in southeastern Brazil during the southern summer period are associated with the passage of frontal systems and the occurrence of the South Atlantic Convergence Zone, respectively.

These events are part of the planet's natural variability, however, the increase in temperature, induced by global warming, coupled with changes in land use, can make them more intense and frequent. Reboita[23] projected, based on climate simulations, for the period 2070-2095, an increase in the rainfall volume for extreme events of precipitation in the summer for the State of Minas Gerais. The combined use of hydrological and hydraulic models, together with the forecasting of meteorological systems, is a study aspect that has been widely applied in the analysis of extreme events in urban environments.[24–26] From the results and analysis of the flood studies, it is possible to reduce the damage caused by these events. Therefore, these analyses make it possible to forecast disasters and implement an alert system for the population, so that everyone is informed about the best way to act in the face of these events.[9]

Alert risk management

Events such as floods are being progressively more recurrent in great cities like Belo Horizonte and are consequences of the fast and growing urbanization process.[27] According to Licco[28] not only should the magnitudes of natural forces be taken into account in the analysis of the damage sources, but, more importantly, the proportion that disasters take, which is related to the vulnerability of the population. Given this scenario, measures must be taken by the organizations responsible for each location. Aiming to mitigate damage and managing risks efficiently, municipal agencies have sought to propose guidelines, presenting various solutions, such as structural (for example, construction works) and non-structural (for example, integrated systems of water management). To solve these problems, there are techniques to be analysed during the project design. The risks, mainly, of human life must be analysed, and a program should be defined together with the civil defence, establishing an early warning system, in addition to proposing methods for rapid impact assessments and damage estimation, aiming a better contingency planning.[29]

One of these programs is the alert system to reduce losses. This system aims to prevent extreme events in advance by providing civil defence and emergency services some advance notice for evacuation and protection of property, reducing the risk of death, and locating areas with a higher probability of extreme events occurrence. The alert system is based on monitoring that uses hydrological models to simulate and represent the water movement in nature, and these models require very complete data from the hydrographic basin and extensive knowledge in hydrology.[30–33]

It should be noted that the Belo Horizonte City Hall (BHCH) has a program to deal with drainage issues, the DRENURBS Program, which has in its conception the treatment of sanitary, social and environmental problems in river basins. One of its objectives is to reduce the risk of flooding with actions to control floods and sediment production (Belo Horizonte City Hall [BHCH], 2016).[34] The City Hall also has Sanitation Plans (BHCH, 2016) and Contingency Plans for Facing Disasters in the Municipality (BHCH, 2018),[35] which include actions and measures to mitigate risks due to floods and other related issues. These documents contain the mapping of risk areas and the actions that must be taken in the face of each type of disaster. For example, faced with a flood scenario, there is a methodology to be followed to reduce risks, from traffic interventions to the rescue and reception of displaced and/or homeless people.

In this context, BHCH has been adopting measures, such as the real-time monitoring of rainfall and water level, through measurements of meteorological and fluviometric stations, and the dissemination of information to society, operating the Hydrological Monitoring and Flood Alert System, checking meteorological events 24 hours a day, and alerting the local government authorities involved with civil defence actions in the case of extreme events.[36]

Through this local monitoring, it is possible to take effective measures against the possible risks, because by predicting the amount of precipitation and the response that the channel has before it, it is easier and faster to decide what actions should be taken. For this, the responsible authorities must keep constant communication, reviewing and analysing in real-time the forecasts made by meteorologists. Also, it allows the city to plan long-term strategies, such as, planning the storage of water that can be used in several areas as a supply in times of drought.

Although they are powerful tools in monitoring and forecasting, hydrological and hydraulic models have limitations and uncertainties. For example, during the simulation, the model can assume that precipitation is evenly distributed over the basin area for a given period. There are also uncertainties regarding the structure of the modelling program, parameters, and input data.[37] For this reason, the accuracy of these forecasts is a very important aspect and studies must be carried out to improve them, making traces of estimate errors using uncertainties to improve the forecasting ability of the probabilistic system.

Ramos[38] asserts that the uncertainties of hydrometeorological forecasts must be evaluated and passed on to the agencies responsible for issuing the alerts, to make more assertive decisions. According to the author, the effectiveness in the interpretation of results and communication helps in the planning of the territory and in the correct management of the city, also aiming to offer a structure for the analysts to make better decisions related to future scenarios, to increase the preparation for flood events and decrease false alerts and losses. The actions to be taken in the face of these extreme event scenarios must be defined jointly by specialists, together with the agencies responsible for carrying them out.

Thus, our proposal is to develop a methodology using GIS information, combined with hydrological simulation, aiming to analyse the hydraulics conditions of an urban channel. Based on these premises, the central aim of this case study is to perform a hydrodynamic analysis of a 585-meter-long watercourse in an urban environment to discuss the channel's behaviour in this section in the face of extreme rainfall events, combining a hydrological model with a hydraulic model.

Material and methods

Catchment characterization

The Jatobá channel is located in the sub-basin of the Arrudas stream, in Belo Horizonte and, according to BHCH data, the region has a high level of flooding. According to the Municipal Secretariat of Urban Policies - SMURBE (BHCH, 2008),[39] the catchment has a contribution area of 23.26 km², an average slope of 0.0429 m/m, and its main channel has an extension of 11,230 meters. Also according to BHCH (2016),[40] the catchment has a population of 157,341 inhabitants and is located in a high-level urbanization area with a small part of the watercourse identified as vegetation.[41]

The development of the study was carried out taking into account a region of the subcatchment. Thus, the section in question was chosen for the case study because it has a considerable flood rate and also a high volume of traffic, since it is located on an avenue that has,

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for example, shops, a school, and a football field, and is also access to another very important avenue in the neighbourhood, Senador Levindo Coelho. Figure 1 shows the extent of the areas affected by the floods in the Barreiro region. The catchment delimitation area was obtained using data and files provided by BHCH and using BH Map (a database that uses the Spatial Reference System EPSG 29193).[42] The main data used in this stage were the shapefiles of the catchment's division established by the Drainage Master Plan (BHCH, 2016), which presents the areas affected by floods and the existing watercourses. The files were inserted in the Google Earth Pro software, which allows viewing, generating maps, and relating geographic data. The results can be seen in Figure 2.

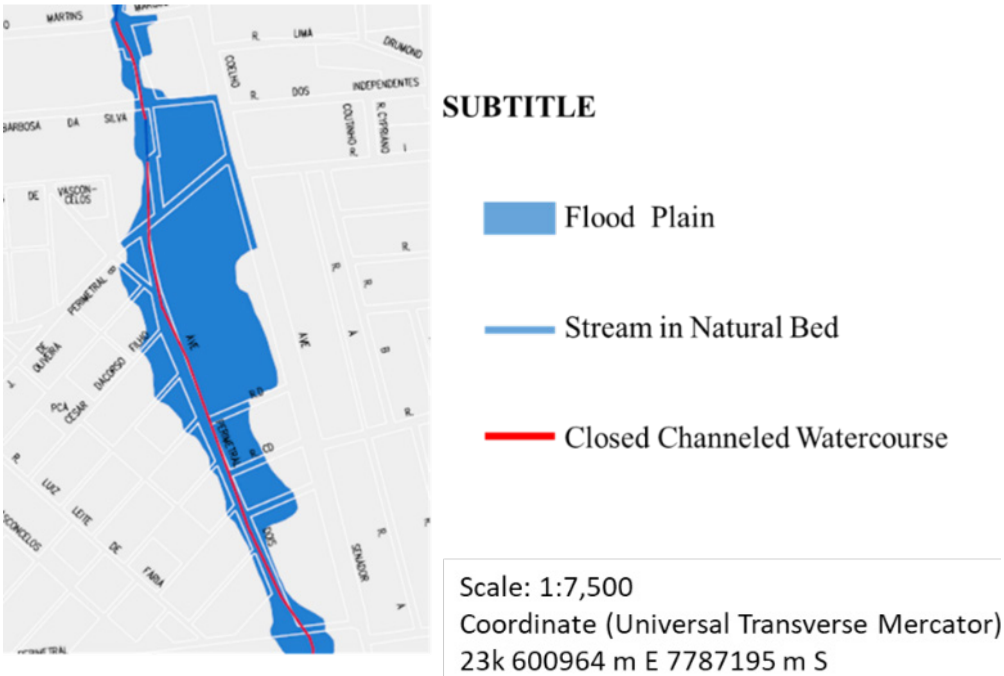

Figure 1 Flood plain of the study area.

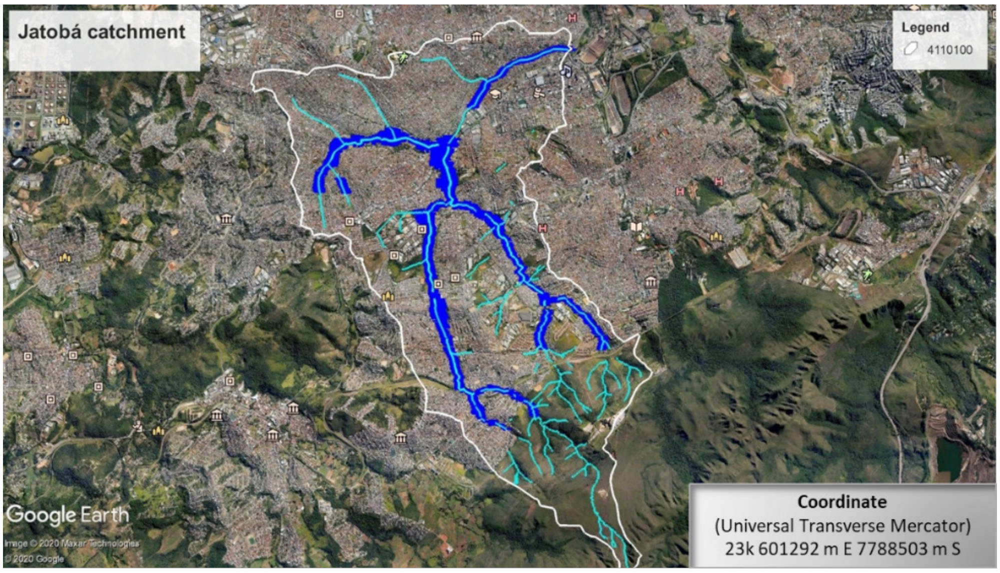

Figure 2 Delimitation of the Jatobá catchment stream, channels, and flood plain.

Hydrological modelling

Hydrological modelling is an essential tool regarding the representation of hydrological processes in computational terms and has been constantly evolving. This type of modelling will be used here to determine the flow that moves upstream of the channel considered in this study. The HEC-HMS model (Hydrologic Modelling System) was developed by the United States Army Corps of Engineers, and is designed to simulate processes of precipitation and runoff from watersheds, and can be applied in a wide variety of areas to solve problems, such as water supply and flood hydrology.[42] Here, this model was applied to simulate the rainfall-runoff process of the sub-basin upstream of the Jatobá creek (Figure 3), with identification 4110101, according to data from BHCH (2009).[43,44]

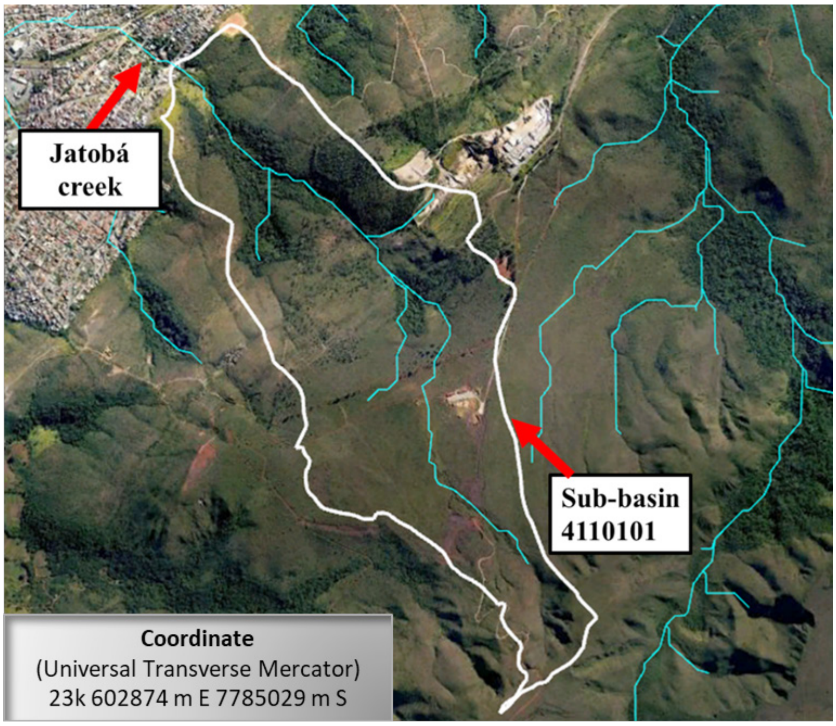

Figure 3 Delimitation of the Sub-basin upstream of the Jatobá creek.

The model simulates the subcatchment behaviour using several rainfall-runoff transformation methods, among them, the Soil Conservation Service (SCS) method, originally developed to estimate the direct runoff, estimating the potential of water in the soil from the adoption of the parameter known as Curve-Number (CN), which reflects the conditions of vegetation cover, among other physical-hydric attributes of the soil.[45] The Horton model, which is based on the physical theory of flow in a porous medium (Darcy equation), and the Green-Ampt model, which is a conceptual model used to calculate the loss of rain on permeable surfaces in a specific period.[46–49] Table 1 presents the catchments physical characteristics and CN estimation.

Table 1 Catchment characteristics. Data provided by BHCH

Catchment	Estimated CN	Channel length (m)	Upstream elevation (m)	Downstream elevation (m)	Area (km²)
4110101	86	2,805	1260	1005	1.81

The following equation (1) was used to calculate the initial abstraction:

$$Ia = 0.20 \times S \quad (1)$$

Where:

Ia - Initial abstraction;

S - Potential storage.

$$S = 25{,}400 \ / \ CN - 254 \quad (2)$$

Following the methodology of the model used, it was necessary to define a lag time. According to Martins (2000), the lag time is defined as the time between the centre of gravity of the hyetograph and the peak of the hydrograph. It can be determined from the graphs (hyetograph and hydrograph) or using equation which depends of the concentration time (3):[50]

$$T_l = 0.6 T_c \quad (3)$$

Whereby:

T_c - Lag time (h);

T_c - Time of concentration (h).

The concentration time (Tc) can be calculated using several equations. For this study, Corps of Engineers (4) was chosen for rural basins, described in Silveira[50] The chosen equation had the best performance, the lowest errors and met the sub-catchment parameters.

$$T_c = 0.191 \times L^{0,76} \times D^{-0,19} \quad (4)$$

Where:

L – channel length

D - Slope of the channel (m/m).

Precipitation daily data were obtained from the website of the Brazilian National Meteorological Institute (INMET, 2020)[51] from October 1961 to January 2020.

The next stage consisted of investigating the local frequency of annual hydrological events using the ALEA (Local hydrological variables annual analysis) program, which estimates parameters of the main density probability distributions used in this type of hydrological analysis through the maximum likelihood method (MMV, Department

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of Hydraulic Engineering and Water Resources, [EHR], 2013).[52] To confirm the validity of the sample, the following hypothesis tests were performed: randomness, independence, homogeneity, and stationarity, in which the sample was accepted. The next step was to define the plotting position of the graph (Weibull), the statistical distribution (LogNormal2P), and the parameters (MMV), with a 95% confidence interval through tests.

After the results were validated, the rain was disaggregated, which consists of using one-day precipitation (24 hours), obtained from rain gauges, for changes in rains with shorter durations. For these transformations, the so-called disaggregation coefficients are required, which are shown in Table 2.[53] Then the rainfall values were calculated for the time intervals of 10, 20, 30, 40, 50, 60, and 120 minutes and for the following return period 2, 5, 10, 50, and 100 years. This calculation was made from the results obtained through ALEA and using equation (5).

$$P_{X,Y} = Cd_Y * P_X \quad (5)$$

Where:

Cd_Y - Final precipitation for return period x and duration time y;

Cd_Y - Disaggregation coefficient for time interval y;

P_X - Precipitation for return period x.

From the precipitations obtained, we performed the simulations using the HEC-HMS. The rainfall distribution over time was carried out respecting the proportions of the breakdown coefficients (Cd). Only the time interval of 120 min suffered a change in distribution: in the initial 60 minutes the distribution was carried out in the same way as the previous intervals, and in the interval of 60 to 120 minutes the rest of the precipitation was distributed equally at 10 minutes intervals.

Table 2 Disaggregation coefficients

Time (min)	Cd
10	0.2
20	0.33
30	0.41
40	0.46
50	0.5
60	0.53
120	0.63

Hydraulic modelling

Hydraulic modelling relates the channel performance, concerning flow volumes, and their geometry, slope, and confluences. The modelling was performed using the HEC-RAS model, which allows simulating supercritical, critical, and mixed flows in networks of natural or artificial channels (HEC-RAS, [2019])[54] by solving Saint-Venant's equations – shallow water flow conditions. It is a software widely used in hydraulic and hydrological studies. Reis[55] proved the model effectiveness to identify areas vulnerable to floods.

The modelling used was adapted from those proposed by Anchieta[41] which contains the entire geometry of the Jatobá stream. For this case study, the chosen sections refer to the channel route through Perimetral II Avenue between Carlos Pinto Coelho Street and Djalma Vieira Cristo Avenue in the Barreiro region (Figure 4). The section was chosen based on the regional flood map provided by BHCH (2009),[56] in which the flow of vehicles and the size of the flood plain were taken into account.

Figure 4 Perimetral Avenue II.

To carry out the simulation, it was necessary to define the flow regime, the Manning coefficient (channel roughness), and the contraction and expansion coefficients. The flow regime chosen was non-permanent or variable, characterized by precipitations of great intensity and short duration.[57] The Manning value, i.e., coefficient of resistance or roughness, according to Anchieta[41] is one of the most

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relevant uncertainties, as this parameter may suffer variations due to several factors, such as the material flow of the bed, bed shapes, gutter geometry, insufficient vegetation, and data. Also, according to the author, the erroneous adoption of its value can lead to problems in the functioning of the structure.

Agreeing to Suárez[58] the estimation of this coefficient requires calculations and measurements of the variables in the cross-sections of the channel (depth, width, slope, for example). No matter how precise and correct the calculations are for determining the coefficients, a single value should not be considered, as the interference in the flow values also influences this parameter.[59]

For the simulation, the Manning coefficient adopted was 0.018 for the closed sections and 0.030 for the open sections. According to the study used here as a basis, this value was adopted for the closed sections since, apparently, the channels are lined with concrete, and still considers the wear and tear caused by the transport of material in periods of floods, as well as the deformations caused by weathering phenomena.[41] The values of the contraction and expansion coefficients were defined according to information in the HEC-RAS User Manual.[60]

The last data to be inserted are related to the type of flow regime. The unsteady flow was chosen here, which allows us to know the flows over time along the river or channel. Within these parameters, boundary conditions are defined. For the downstream section, the normal channel depth was classified from the Atlas of the Arrudas Macro drainage System, prepared by BHCH (2002),[61] and the slope was determined to be 0.796%. For the upstream section, the flow hydrograph was defined. The values used in the hydrograph were extracted from the results obtained through the HEC-HMS and the simulations were performed for the intervals of 10, 20, 30, 40, 50, 60, and 120 min and return period of 2, 5, 10, 50 and 100 years.

Results and discussion

Hydrological simulation

Understanding the physical catchment characteristics, it was possible to determine, through the equations mentioned above, the necessary parameters for the simulation, which are presented in Table 3. From these results, it is possible to perceive that the sub-basin upstream of the channel can be characterized as a rural basin since it has a small portion of imperviousness and a CN related to grasslands. The summary values are shown in Table 4.

Table 3 Input data used for simulations in HEC-HMS

Initial Abstraction (mm)	Delay Time (min)	Imperviousness (%)	CN
8.27	9.55	0.0019	86

Table 4 Precipitation values in millimetres after rainfall disaggregation using the method proposed by Abreu (2018)

	Return period (years)				
Running time (min)	2	5	10	50	100
10	15.65	20.4	23.42	26.99	32.54
20	25.82	33.66	38.64	44.53	53.69
30	32.08	41,82	48.01	55,33	66.71
40	35.99	46.92	53.87	62.08	74.84
50	39.12	51	58.55	67.47	81.35
60	41.47	54.06	62.06	71.52	86.23
120	49.29	64.26	73.77	85.02	102.5

Then, the hyetographs of each time interval were obtained (Table 5), respecting the disaggregation coefficients of the study used here as a reference It is worth to highlight that the value of precipitation over 120 minutes was equally divided into 10-minute interval. The intervals were defined to understand the catchment response of the basin to different rainfall volumes. The results of the disaggregation show a concentration of the water volume in the final 10 min of the rain, as can be seen in Figure 5, which presents a rainfall volume of 29% in those last minutes.

Table 5 Precipitation values (mm) for each time interval

	Return period - 2 years						
	Time interval (min)						
Rainfall duration (min)	10	20	30	40	50	60	120
10	15.65						
20	5.16	20.66					
30	6.42	4.17	21.49				
40	7.2	4.68	2.88	21.23			
50	7,82	5.09	3.13	1.96	12		
60	8.29	5.39	3.32	2.07	1.66	20.73	
120	9.86	6.41	3.94	2.46	1.97	1.48	23.17

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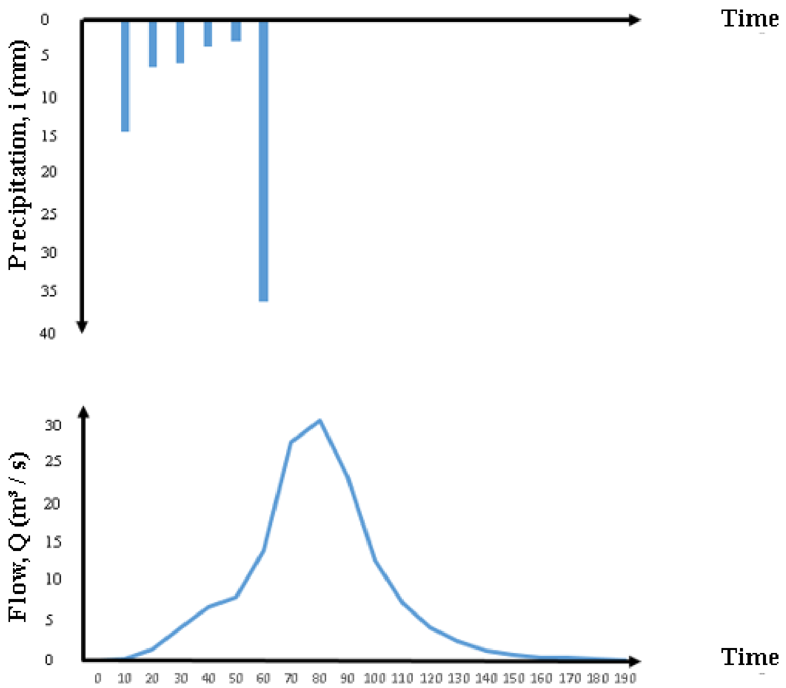

Figure 5 Hyetograph and hydrograph of a 60 minutes rain and 50 years of return period.

Hyetographs, resulting from the disaggregation method, were inserted in the HEC-HMS to determine the hydrograph of response to precipitation. As a result, from Figure 5, the hyetograph and hydrograph resulting from the simulation of a 60 minutes precipitation and 50 years of return period can be observed. It is possible to verify that between the end of precipitation until the peak of the hydrograph (maximum flow drained), approximately 20 minutes have passed, which represents a high volume of flow that will reach the channel in a short time, which can generate problems for a safely flow, conditional on the configuration of the upstream section.

Hydraulic simulation

The flow values that reach the channel upstream allowed us to perform the hydraulic simulation. First, the geometry data of the four sections of the channel were inserted. As previously stated, the values of the Manning coefficient used were 0.030 and 0.018, for open and closed sections, respectively. The section upstream of the channel is represented in Figure 6. It is an open section and presents a significant flood risk varying according to rainfall intensity.

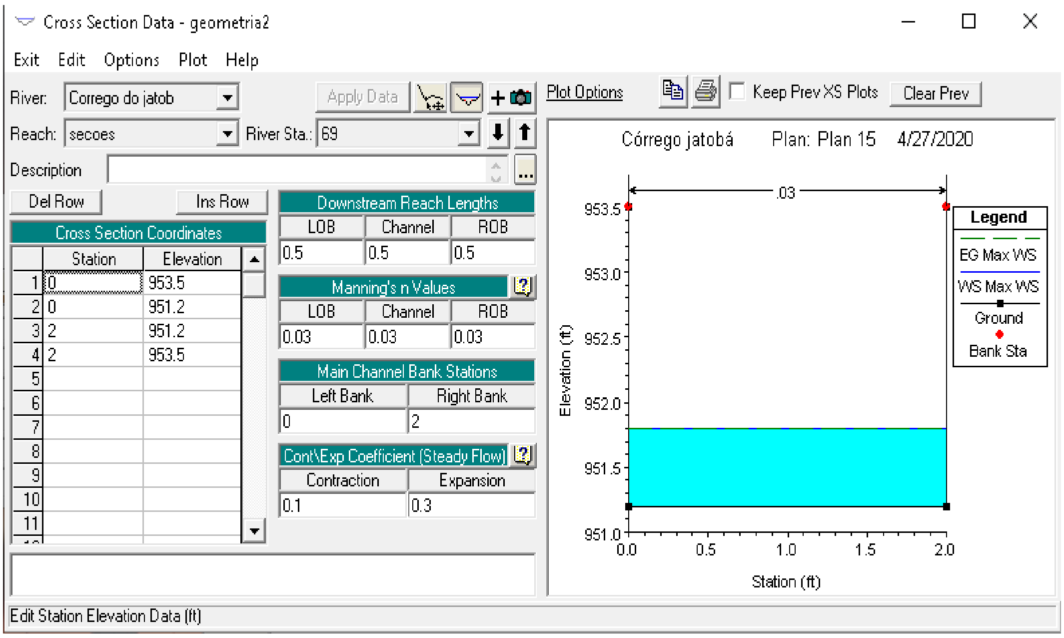

Figure 6 Configuration of section 69 upstream of the channel.

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The hydrograph was inserted as input to the HEC-RAS to simulate the non-steady flow regime for different time intervals and return period scenarios. 35 scenarios were simulated and the results referring to the channel overflow are shown in Table 6 below. From the results presented, it is noted that the channel overflowed in 77.14% of the simulated scenarios. Since urban macro-drainage construction works are designed to drain events with a return period of at least 10 years,[62] the channel in question has insufficient dimensions to drain precipitations of lesser magnitudes, such as, for example, the scenario of 41.5 mm rainfall volume with 60 minutes of duration, relative to 2 years of return period in which the channel overflowed.

Table 6 Results of the channel overflowing against the simulated scenarios

Channel overflow					
Time interval	**Return period (years)**				
	2	**5**	**10**	**50**	**100**
10	No	No	No	No	Yes
20	No	Yes	Yes	Yes	Yes
30	No	Yes	Yes	Yes	Yes
40	No	Yes	Yes	Yes	Yes
50	No	Yes	Yes	Yes	Yes
60	Yes	Yes	Yes	Yes	Yes
120	Yes	Yes	Yes	Yes	Yes

It is also noticed that the channel overflows at situations of less rainfall distributed in shorter intervals of time, such as, for example, a rainfall of 32.5 mm and a duration of 10 min. This can be explained because the rainfall duration and the response time of the channel to drain the generated flow has a directly proportional relationship, so, the shorter the rain duration, the shorter is the time that the channel will have to drain flow efficiently. This statement can also be confirmed, given another simulated scenario, such as, for example, a rain of 35.99 mm during 50 min related to 2 years of return period. Another important point to be taken into account is the relationship between the return period and the overflow of the channel. It can be evaluated that the longer the precipitation return period, the greater is the probability of the channel not being able to drain all the flow and overflow. This is since the longer the return period, the greater is the intensity and volume of the rain, as can be seen through the relationship between Table 4, which shows the rainfall volumes for each return period analysed, and Table 6, which presents the results of the simulated scenarios.

Shorter rainfall may pose greater risks, as they cause greater flooding heights. It was confirmed here that the events that lead to the highest overflow heights are precipitations of 60 minutes for the different return periods, with the maximum value being approximately 4.12 meters of water depth, which corresponds to precipitation of 100 years of return period. A representation of the overflow resulting from the worst-case simulation can be seen in Figure 7.

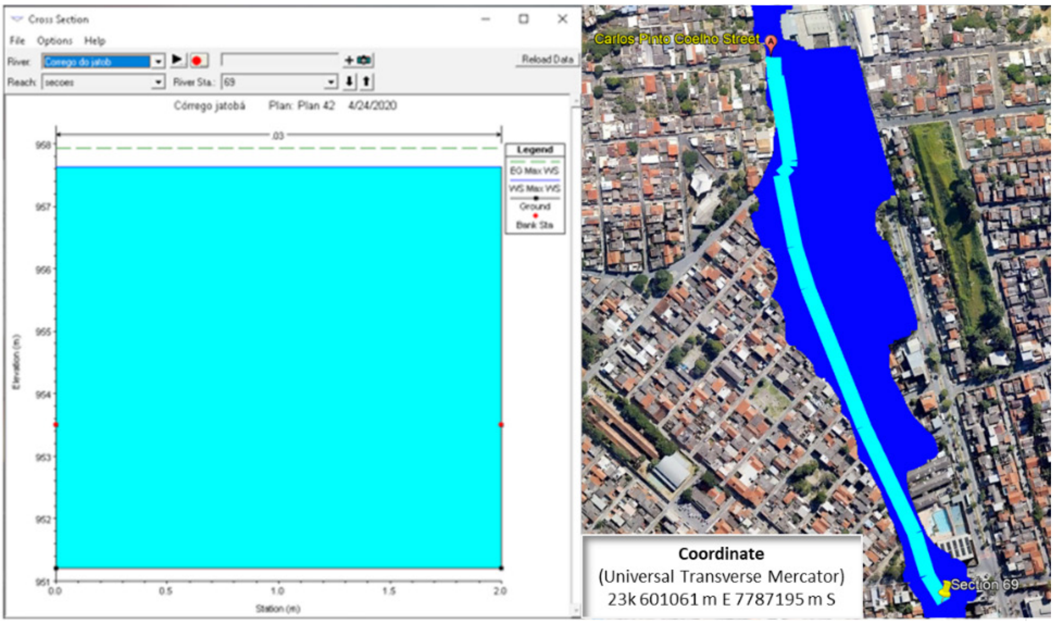

Figure 7 Overflow of the channel in the face of the worst simulated scenario and its location.

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From the Flood Charter, developed by BHCH (2009),[61] it is possible to perceive the extent of the areas affected by the floods. It can be seen in Figure 1 that the flooding of the study area sections can extend up to Senador Levindo Coelho Avenue, which is an important axis of vehicle flow in the Barreiro region and gives access to other avenues of great importance, such as Tereza Cristina Avenue, which can cause problems for traffic and risk people's lives, since it is a largely urbanized area. In addition to these avenues, other streets, responsible for driving the flow of vehicles in the region, can be directly affected, causing traffic blockages.

Therefore, it is important to note that it is not only the overflow of the sections that cause inconvenience and risk, as the higher flow generates high pressures on the surfaces of the channels, which can lead to damage and misalignment of the walls.[41] It is extremely important to know the time elapsed until the channel overflowed and its duration for different precipitations, so, from this information, it is possible to think about contingency plans and risk prevention. Table 7 presents the input data of the HEC-RAS program and the results obtained through the simulation.

Table 7 Input data and analysis of the results obtained through the simulation in the HEC-RAS, categorized by return period

Time interval (min)	Precipitation (mm)	Beginning of the flood (h)	Flood duration time (min)	Overflow height (m)
2 Years				
60	41.47	01:20	10	0.7
120	49.29	01:50	30	0.2
5 Years				
20	33.66	00:40	10	0.15
30	41.82	00:40	30	0.9
40	46.92	00:50	40	1.45
50	51	01:00	40	1.7
60	54.06	01:10	40	1.8
120	64.26	01:30	60	1.85
10 Years				
20	38.64	00:30	20	0.6
30	48.01	00:40	40	1.6
40	53.87	00:50	40	1.98
50	58.55	00:50	50	2.24
60	62.06	01:00	50	2.37
120	73.77	00:50	110	1.27
50 Years				
20	44.53	00:30	20	1.28
30	55,33	00:40	30	2.21
40	62.08	00:40	50	2.72
50	67.47	00:50	60	2.87
60	71.52	01:00	60	3.05
120	85.02	00:40	120	1.75
100 Years				
10	32.54	00:30	10	0.05
20	53.69	00:30	40	2.1
30	66.71	00:30	60	3.3
40	74.84	01:30	60	3.75
50	81.35	00:40	70	4.04
60	86.23	00:40	80	4.12
120	102.5	00:30	130	2.44

Table 8, generated from analysis performed using the results obtained in Table 7, shows the average time until the flood beginning and its duration with the rainfall intensity. It can be observed that the longer the return period, the longer is the duration of the flood, even for events that happen in the same time interval. This scenario can be explained because the longer the return period, the larger is the volume of precipitation in a given time interval, for example, a rain of 60 minutes in duration can cause floods for 40 to 60 minutes, depending on rainfall intensity.[63]

Table 8 Results of hydrological and hydraulic modelling for historical rains

Flood		
Precipitation (mm)	**Home (h)**	**Flood duration (min)**
31-40	00:25	13
41-50	00:58	28
51-60	00:50	40
61-70	00:57	47
71-81	01:06	77
81~100	00:40	90
> 100	00:30	130

Conclusion

It is concluded, therefore, that the channel is undersized for most of the events due to the lack of space and occupation of the watercourse, thus causing flooding in the sections of the channel in question differing on the time interval and the rainfall intensity. Also, risk mitigation measures must be considered for the region, such as clearing the avenues and streets around the stream during intense rain events. The meteorological monitoring and channel behaviour in defiance of extreme events is crucial for the decision-making process to avoid consequences that put people's lives at risk.

Given the study region and the simulations carried out, measures are proposed based on the Municipal Sanitation Plan and the Contingency Plan for Coping with Disasters in the Municipality of Belo Horizonte, such as an alert system, in which upon reaching 50% of the channel's capacity would issue a yellow alert, upon reaching 80% an orange alert and upon reaching 100% of capacity a red alert would be issued. It is also proposed that, based on the hydrograph response, an analysis of the channel behavior be carried out using flows in a uniform steady-state to determine the critical flow and, from that, determine a precipitation threshold for the issuance of alerts. Methodologies such as the real-time dynamic warning index can be used, which includes analysis of soil moisture, evaluation of various sources to determine excess runoff by soil saturation, and historical runoff data. These alerts would be disseminated to managers through e-mail and telephone, and by SMS to the registered population.

It is also concluded that measures are needed concerning traffic management. Assuming that the earlier the alerts are, the better is the damage mitigation results. The system must work before, during, and after the flood, and as a result, they can prevent drivers from being surprised by floods as they travel the route to their destination, thereby reducing the possibility of human loss. Therefore, it is necessary to determine the measures to be taken in emergencies, among them; for example, the mobilization of teams from the company of Transport and Traffic of Belo Horizonte (BHTrans), Military Police and Civil Defense for traffic management, interrupting the traffic in risk areas, coordinating and controlling deviation routes. To determine the actions to be taken regarding traffic, studies are needed to understand the flow's functioning, being necessary to assess the impacts that a flood event may have on the city's road system, using the hierarchy of roads as a parameter of analysis. From this, it would be possible to determine the degree of road importance for local traffic and the best deviations for the vehicle's flow.

In this context, deviations and blockages previously determined using the Flood Charter and Appendix V of the Contingency Plan, which contains examples of traffic intervention in case of flood, would be pointed out by the responsible authorities at least 10 minutes in advance. The Brazilian Traffic Signaling Manual, prepared by the National Traffic Council (CONTRAN, 2017), can also be used as a reference, since it determines that deviations in traffic must follow basic guidelines, such as the use of roads with the same characteristics, except in emergencies where the flow often deviates to streets with less capacity.

The hydrological modelling performed by HEC-HMS was suitable when simulating different rain scenarios, taking into account the occupation and use of the soil by the SCS-CN rain-flow transformation method. It should be noted that the choice of the transformation method was made according to the data. Regarding hydraulic modelling, it was crucial to simulate non-permanent flow to verify a real flood situation, that is, a rapid rise in the hydrograph. The HEC-RAS model also produced a satisfactory simulation, as it allowed the analysis of propagation in the channel, and even though the flood map was not produced, it was possible to verify the section filling and determine which rain caused the flood.

For further studies, it is proposed to carry out simulations to determine the flood plain because of various precipitation scenarios and also to model the traffic in the region, using some traffic simulation model, such as the Aimsun software, which can simulate different traffic systems. For the modeling of traffic, it is proposed to carry out the classified volumetric counting of vehicles. This methodology aims to determine the quantity, direction, and composition of the vehicles flow that pass through one or several points of a road system, in a determined unit of time, for a better understanding of the flow in the region and so, that it is possible to determine better routes of deviations to reduce possible accidents and human losses.

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Conflicts of interest

None.

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