# STUDY OF URBAN HIGH-WATERS IN AN AREA OF INFLUENCE BY MINING ACTIVITIES: ASSESSMENT OF THE CURRENT AND FUTURE SCENARIOS USING RAINFALL-RUNOFF MODELING

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The study presented herein deals with the changes in the rainfall-runoff regimen within the hydrographic basin of Córrego Seco Creek, situated within the metropolitan region of Belo Horizonte, State of Minas Gerais, Brazil; to assess changes in the local hydrology related to land usage. The basin under study features a wide diversity of land usage, including mining, residential, commercial and industrial areas. The IPH-II/WIN_IPH2 model was used and input data consisted of seepage measurements taken in the field, using constant-load double-ring infiltrometers; rainfall data obtained by tipping bucket type pluviograph; and runoff data using micro-diver datalogger. The study identified the basin's current response to 10-year, 25-year and 50-year rainfall events, and also assessed different future land-usage scenarios and their probable consequences. The results and the calibrated model will be useful in the development of compensatory urban drainage measures within the basin, and to also identify storage that that should be restored to avoid the occurrence of high-waters.

Keywords: rainfall-runoff model, urban hydrology, mining.

## INTRODUCTION

The transformation of hydrographic basins within urban areas, in their totality or otherwise, is responsible for the onset of environmental problems and increased flood frequency and intensity within their region. This fact is due to the reduction of permeable areas and the occupation of watercourse floodplains. Such floods not only cause economic damages, but also pose hazards to public health and the well-being of the public at large. The Brazilian model of urban development has favored the frequency of floods, the production of sediments and deterioration of the quality of both surface and underground waters.

The elaboration of the studies related to the work presented herein occurred in the Córrego Seco micro-basin, situated in the municipality of Nova Lima, in the central region of the State of Minas Gerais, Brazil (Figure 1). The occupation of this area configures an urbanized region with residential, commercial and small-industry areas, open-pit iron ore mine and remnant areas of native vegetation. About fifteen years ago, in the neighborhood of Jardim Canadá, this creek had an ephemeral regimen (hence the name Córrego Seco, or Dry Creek), which has gradually become intermittent because of the outflow of underground waters. Contrary to all tendencies of basin occupation, the creek has become perennial along most of its extension due to the discharge of sewage into the rainwater drains throughout Jardim Canadá. Córrego Seco's waters also receive contribution by effluent discharged from the Jardim Canadá Sewage Treatment Station operated by COPASA - Companhia de Saneamento de Minas Gerais.

The objective of this study is to assess the processes involved in the transformation of the rainfall-runoff regimen within the Córrego Seco basin and how the expanding tendency of the current situation, related to impermeability (concreted / paved) areas throughout Jardim Canadá could influence surface runoff, in association with the presence of Capão Xavier mine.

The IPH II rainfall-runoff transformation model was calibrated using data output by WIN IPH2 software, based on measurements of rainfall and of water levels in Córrego Seco creek that were later converted to runoff data. The calibration parameters were divided into two groups; the first consists of seepage data measured *in loco* and the second consists of data that characterize the basin's physical environment, pre-established on bibliographical data on the basis of similarity with other basins.

Therefore, the model was calibrated by varying only the values of the following parameters, namely: precipitation retention ($R_{MAX}$) and aquifer discharge ($K_{SUB}$). The amount of retention in the surface reservoir ($K_S$) was calculated by a specific methodology. These procedures when associated with the referred software enabled one to achieve a sensibility with regards each parameter's effect in the manual calibration process, and yielded agility to the overall process of calibrating the hydrological model.

An open-pit iron ore mine, named Capão Xavier, belonging to VALE - Companhia Vale do Rio Doce is located alongside Córrego Seco basin, which together with this basin discharges rainwater into a containment reservoir to retain sediments in the waters originating within the mine. This reservoir occupies the former open clay pit previously owned by Magnesita. This configures a retard and amortization mechanism affecting the high-water events caused by surface water runoff in the basin.

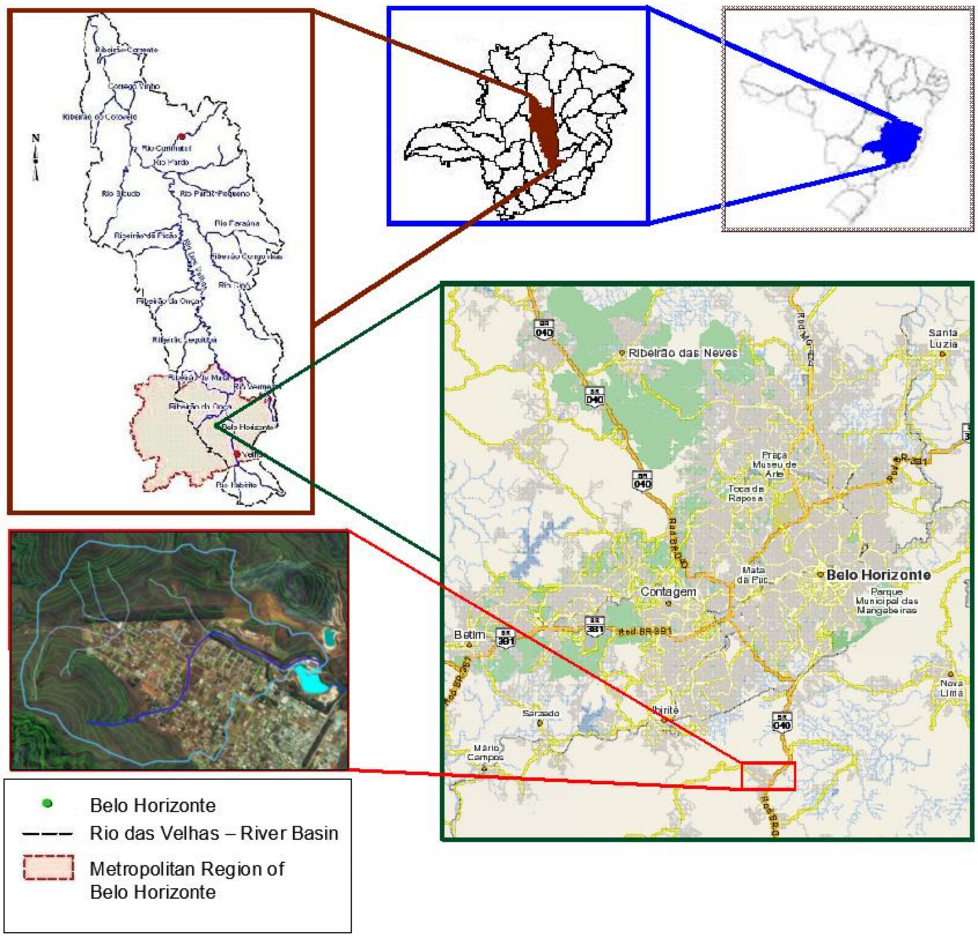


Figure 1 – Location of the studied area

The existence of the Capão Xavier Mine has provoked strong alterations to the rainwater runoff regimen within the Córrego Seco basin, by the construction of a deviation channel in the creek, the reversion of part of the waters that originally flowed to an adjacent basin, by the installation of a dewatering system to pump rainwater from the open pit and its surrounding area to the aforementioned containment reservoir, as well as the formation of the reservoir per se. Therefore they are profound changes, which contrary to expectations related to a reversion within a basin, have engendered a positive impact over Córrego Seco creek, by amortizing the high-waters events.

## METHODOLOGY

The elaboration of the study proceedings encountered the need to acquire knowledge of the requisite parameters and data to calibrate the IPH II rainfall-runoff transformation model, and the ample bibliography associated with the procedures and results for such a stage in the study. The results obtained by Germano, Tucci and Silveira (1998) indicated the means to obtain the initial figures for the $K_S$, $R_{MAX}$ and $K_{SUB}$ parameters used in the hydrological calibration model.

The rainfall data measurements were taken using a tipping bucket type pluviograph installed 1,230 meters from the runoff measurement point on Córrego Seco creek. This distance is considered to be sufficiently short enough to minimize errors due to possible rainfall spatial distribution variations. The rainfall and runoff measurement period extended over the months of September to November 2010, from which six rainfall events were selected for initial assessment in relation to corresponding runoffs measured in the Córrego Seco creek.

The water-level measurement point on Córrego Seco creek, which was selected for subsequent calculation of the runoff data, was located on the channeled stretch situated upstream from the referred containment reservoir. The micro-diver groundwater datalogger was installed in a dry well made of PVC pipes tied in place by steel wires and concreted on the creek bed, as shown in Figure 2.

The water level figures obtained on the creek were converted into runoff data by use of Equation 1, adapted from Manning's Equation, where runoff Q is expressed as $m^3/s$ and H represents the height of the water level measured on the creek.

Figure 2 – Water level measurement well on Córrego Seco Creek

$$Q = 7{,}071068 \text{ x } \left(\frac{2{,}085H+1{,}764H^2}{4{,}17+4{,}06687H}\right)^{2/3} \text{ x } \left(2{,}085H+1{,}764H^2\right) \qquad (1)$$

The decision was made to withdraw the seepage variables that were deduced from the seepage measurements taken by constant charge double-ring type infiltrometers, from the calibration procedures with the intention of achieving a closer degree of fidelity between the calibrated model and the real characteristics of the basin. The locations chosen to take these measurements were based on the pedological map of the region and considering ease of access to the measurement points' locations. The calculations were elaborated on the basis of methodologies presented by Pinto (2005) and Gregory (2004). The data was handled pursuant to the methodology presented by ALVES SOBRINHO et Al. (2003), where the parameters designated as Initial Seepage ($I_0$), Minimum Seepage ($I_b$) and parameter K, of the Horton equation, are optimized using equations 2, 3 and 4:

$$\mathrm{CMR} = \frac{\left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i\right)}{\sum_{i=1}^{n} O_i} \qquad (2)$$

$$\mathrm{CA} = \frac{\sum_{i=1}^{n}(O_i - \bar{O})^2}{\sum_{i=1}^{n}(P_i - \bar{O})^2} \qquad (3)$$

$$\mathrm{EF} = \frac{\left[\sum_{i=1}^{n}(O_i - \bar{O})^2 / \sum_{i=1}^{n}(O_i - \bar{P})^2\right]}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad (4)$$

In the above equations, CMR is the residual mass coefficient, CA is the adjustment coefficient, EF is for efficiency, $O_i$ are the observed figures, $P_i$ represents the estimated figures, N stands for the number of observation events, $\bar{O}$ is the average of the observed figures and $\bar{\mathbf{P}}_{\text{is}}$ the average of the estimated figures. The data was transferred to a calculation spreadsheet in which the figures for residual mass coefficient, for the adjustment coefficient and for efficiency were calculated, permitting thereby the adjustment of an equation for the data plotted on the seepage adjustment curve. Subsequent to the above equations, the MS EXCEL solver function was used to minimize the efficiency (EF) parameter in relation to parameter K of the Horton's equation 5.

$$i = i_0 + (i_0 - i_t)h^t \qquad (5)$$

In Horton's equation 5, $i_o$ is the observed initial seepage rate expressed in mm/h, $i_t$ is the final seepage rate in mm/h, t is seepage time expressed in minutes, h is the result of the expression (-K) and K is the empiric parameter related to the type of ground in question.

The work was conducted in three distinct stages, namely, the first, during which data was obtained via measurements or was provided by VALE - Companhia Vale do Rio Doce and then processed. The rainfall and runoff measurement data enabled cross-referencing of information and the selection of rainfall events with corresponding runoff measured in the creek. Ground seepage capacity measurements were also conducted during this stage, to produce Horton equation results for subsequent input into the software. The second stage involved the calibration of the rainfall-runoff model and elaboration of the specific IDF (Intensity Duration Frequency) for the region under study. The critical rainfalls for 10-year, 25-year and 50-year return periods were calculated in the third stage, and they were transformed into surface runoffs for both the portion of the basin occupied by Jardim Canada neighborhood and for Capão Xavier Mine.

## INITIAL PARAMETERS

Land occupation types and vegetation types were analyzed from among the first set of data, thus enabling the elaboration of Figure 3 and the data in Table 1. Note that the size of the impermeable area of the region is actually quite small. The green areas that exist around the designated building lot areas are permanent reserves and will not be subjected to any changes whatsoever over the years because they are part of the environment preservation area denominated APA Sul da Região Metropolitana de Belo Horizonte – RMBH. The area occupied by the Capão Xavier Mine will be recovered after the mine has been exhausted and the open pit is to be transformed into a lake, whose waters are to be used by COPASA (water and sanitation company) for public water supply to the metropolitan region of Belo Horizonte, pursuant to an agreement signed between the two companies when the mine's environmental license was granted. However, for assessment purposes, the interior of the open pit and the machinery and transport vehicle transit areas were considered to have extremely low permeability due to the characteristics of the ground and the degree of compaction encountered there.

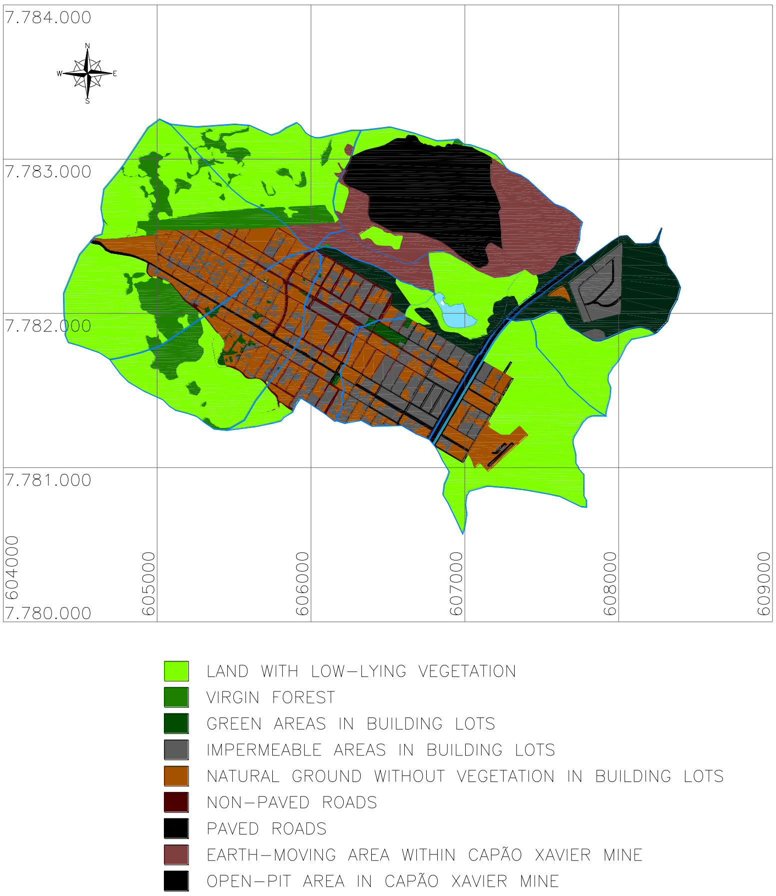


Figure 3 – Occupation of the land

The process used to calculate the retard caused by the retention within a simple, linear reservoir, envisaged by the Clark methodology (TUCCI, 1998) was conducted by using Equations 6 and 7 pursuant to Dodge and the methodology pursuant to MINE and TUCCI (1999), subsequent to discretization of the sub-basins relative to Bairro Jardim Canadá neighborhood and the preservation areas. The coefficient for the retard within a simple, linear reservoir is represented by $K_s$ in these equations, while $t_c$ is the concentration time expressed in hours obtained by Equation 8 pursuant to Kirpich, A is the area of the basin or sub-basin expressed in $Km^2$ and S is the declivity of the basin in m/10,000m. The Kirpich equation yields a concentration time figure, $t_c$ expressed in minutes, L is the length of the main thalweg, expressed in Km, and H is the difference in elevation of the main thalweg, given in meters.

$$K_S = \frac{t_c}{2} + K \qquad (6)$$

$$K = 80{,}75 \times \frac{A^{0{,}23}}{S^{0{,}70}} \qquad (7)$$

$$t_c = 57 \left(\frac{L^3}{H}\right)^{0{,}385} \qquad (8)$$

Table 1 – Size of impermeable areas within Córrego Seco Basin

| SUB-BASIN | AREA (Km²) | IMPERMEABLE AREA | | PERMEABLE AREA | |
|---|---|---|---|---|---|
| | | AREA (Km²) | % | AREA (Km²) | % |
| SB 01 | 1.32 | 0.03 | 2.06 | 1.30 | 97.94 |
| SB 02 | 0.72 | 0.03 | 3.72 | 0.70 | 96.28 |
| SB 03 | 0.54 | 0.17 | 31.80 | 0.36 | 68.20 |
| SB 04 | 0.52 | 0.00 | 0.00 | 0.52 | 100.00 |
| SB 05 | 0.09 | 0.00 | 0.00 | 0.09 | 100.00 |
| **Totals** | 3.19 | 0.23 | 7.03 | 2.97 | 92.97 |

Tables 2 and 3 present the data on Córrego Seco's hydrographic sub-basins within the area of study, which encompasses Bairro Jardim Canadá neighborhood and Capão Xavier Mine area, respectively. This table presents the concentration time figures and K and $K_S$ variables.

Table 2 – Data and calculation of $K_S$ – Bairro Jardim Canadá Basin

| SUB-BASIN | AREA (km²) | THALWEG | | | CONCENTRATION TIME (hours) | $K_S$ |
|---|---|---|---|---|---|---|
| | | LENGTH (m) | DIFF. IN ELEVATION (m) | DECLIVITY (m/10,000m) | | |
| SB 01 | 1,32 | 1,782.67 | 143.00 | 802.17 | 0.27 | 0.935306 |
| SB 02 | 0.72 | 1,506.78 | 143.00 | 949.05 | 0.23 | 0.730545 |
| SB 03 | 0.54 | 1,833.96 | 54.00 | 294.44 | 0.41 | 1.513322 |
| SB 04 | 0.52 | 1,123.38 | 142.00 | 1,264.04 | 0.16 | 0.548429 |
| SB 05 | 0.09 | 814.63 | 26.00 | 319.16 | 0.21 | 0.934040 |
| Basin Total | 3.19 | 2,586.60 | 151.00 | 583.78 | 0.4126 | 1.427354 |

Table 3 – Data and calculation of $K_S$ – Capão Xavier Mine Basin

| SUB-BASIN | AREA (km²) | THALWEG | | | CONCENTRATION TIME (hours) | KS |
|---|---|---|---|---|---|---|
| | | LENGTH (m) | DIFF. IN ELEVATION (m) | DECLIVITY (m/10,000m) | | |
| SB 07 | 1,0849 | 1,143.68 | 83.00 | 725.73 | 0.20 | 0.919175 |
| SB 08 | 0.2281 | 427.78 | 37.00 | 864.92 | 0.09 | 0.549744 |
| Adjustment Basin | 1,3130 | 1,143.68 | 83.00 | 725.73 | 0.2024 | 0.955874 |

The numerical value used for the XN pair that defines the shape of the time-area histogram was 1.5, as indicated for intermediary shaped basins. (TUCCI, 1998).

The data from the seepage tests surveys, that was obtained by use of constant-charge double ring infiltrometers, whose rings' internal and external diameters are 250 and 500 mm respectively, and which are associated with the aforementioned methodology, yielded the seepage curves and enabled completion of the Horton equations, presented in Figure 5, relative to the 10 seepage tests, for which the location map is presented in Figure 4.

The numbers for the parameters used in the Horton equation should be expressed pursuant to unitary $\Delta t$ numbers pursuant to the methodology used for the IPH II rainfall-runoff transformation model. The sequence used to make the seepage tests equation results adequate is presented in Tables 4 and 5, for Bairro Jardim Canadá's basins and Capão Xavier Mine basins. The figures were pondered in the calculations by considering each point's area of influence pursuant to the Thiessen Polygon Method. The results of the foregoing are also presented in Tables 4 and 5.

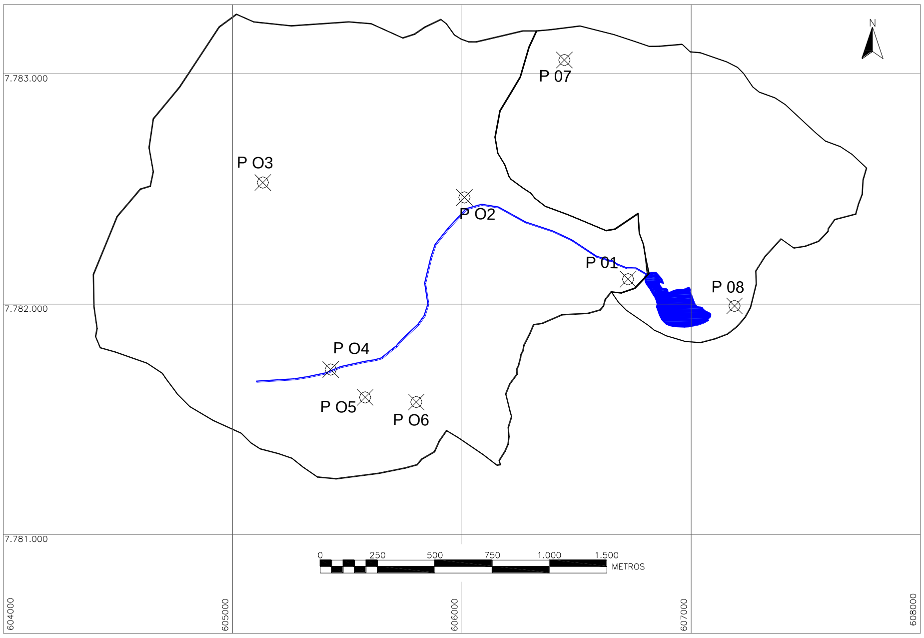


Figure 4 – Map showing the location of the seepage test points.

To begin the model simulations for the work in hand, the $K_{SUB}$ and $R_{MAX}$ were adopted on the basis of figures presented by Germano, TUCCI and SILVEIRA (1998), as shown in Table 6. The figures were determined on the basis of the similarity of usage for the various sub-basins.

Table 4 – Results of seepage tests in Bairro Jardim Canadá

| SEEPAGE TEST POINT LOCATIONS | | | RESULT OF TESTS OVER TIME $\Delta t$ | | | | AREA OF THIESSEN POLYGON (Km²) |
|---|---|---|---|---|---|---|---|
| **TEST POINT** | **UTM COORDINATES Zone 23 K** | | **$I_0$ (mm/h)** | **$I_b$ (mm/h)** | **K** | **H** | |
| | Easting | Northing | | | | | |
| P 01 | 606765 m E | 7782038 m S | 27.00 | 1.50 | 1.14 | 0.32 | 0.77 |
| P 02 | 606025 m E | 7782382 m S | 50.22 | 10.48 | 1.62 | 0.20 | 1.15 |
| P 03 | 605132 m E | 7782528 m S | 20.67 | 0.78 | 0.81 | 0.44 | 0.15 |
| P 04 | 605428 m E | 7781716 m S | 38.06 | 10.44 | 0.72 | 0.49 | 0.58 |
| P 05 | 605578 m E | 7781595 m S | 35.75 | 14.66 | 1.21 | 0.30 | 0.34 |
| P 06 | 605721 m E | 7781595 m S | 20.48 | 12.91 | 1.17 | 0.31 | 0.19 |
| **Total Basin Area** | | | | | | | 3.19 |
| **Pondered figures** | | | **37.64** | **8.42** | - | **0.31** | - |

Table 5 – Results of seepage tests Capão Xavier Mine

| SEEPAGE TEST POINT LOCATIONS | | | RESULT OF TESTS OVER TIME $\Delta t$ | | | | AREA OF THIESSEN POLYGON (Km²) |
|---|---|---|---|---|---|---|---|
| **TEST POINT** | **UTM COORDINATES Zone 23 K** | | **$I_0$ (mm/h)** | **$I_b$ (mm/h)** | **K** | **H** | |
| | Easting | Northing | | | | | |
| P 01 | 606765 m E | 7782038 m S | 16.19770 | 0.89865 | 0.06851 | 0.93378 | 0.25162439 |
| P 07 | 606447 m E | 7783060 m S | 15.00880 | 6.82205 | 0.02873 | 0.97168 | 0.56246900 |
| P 08 | 607189 m E | 7781992 m S | 5.45455 | 1.21435 | 0.08857 | 0.91524 | 0.49888600 |
| **Total Basin Area** | | | | | | | 1.3130 |

| | | | | | |
|---|---|---|---|---|---|
| **Pondered figures** | **11.6064** | **3.5561** | **-** | **0.9430** | **-** |

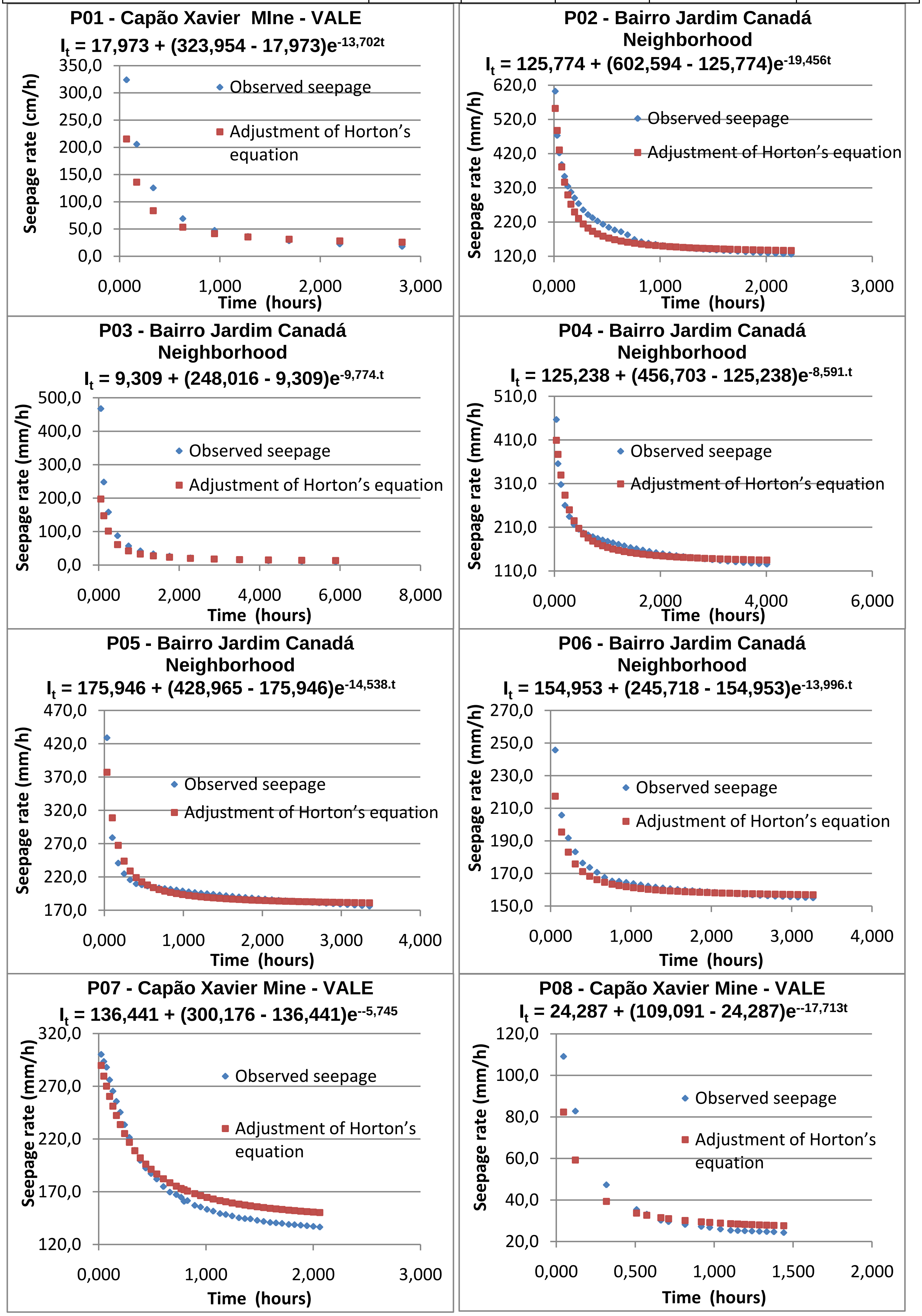
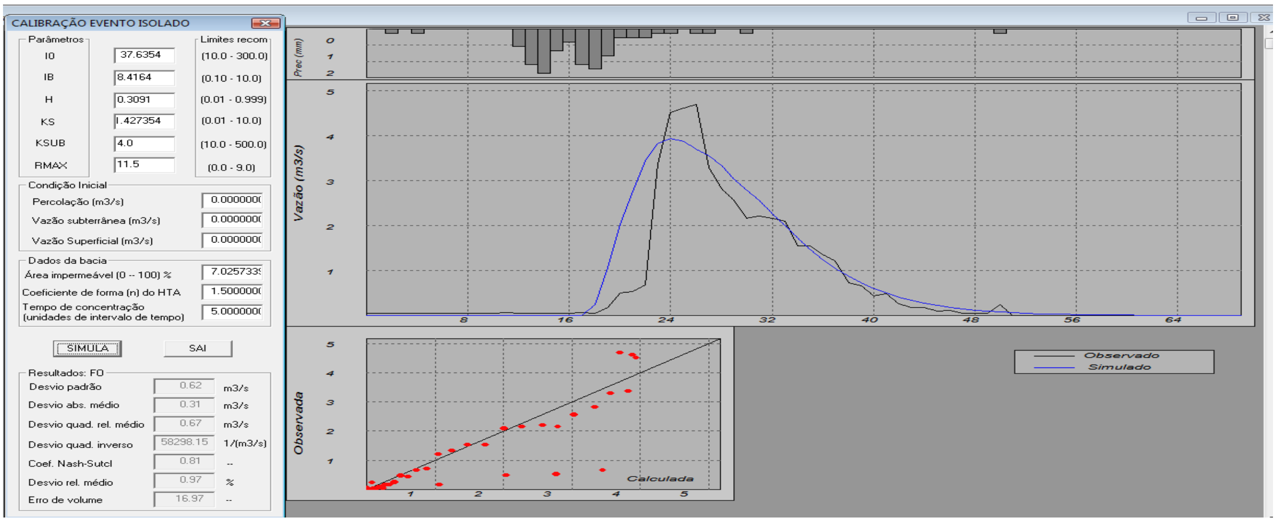


Figure 5 – Curves and equations for seepage tests

Table 6 – Initial $K_{SUB}$ figures

| **Location** | **SUB-BASIN** | **BASIN CHARACTERISTICS** | | | **$K_{SUB}$** | **$R_{MAX}$** |
|---|---|---|---|---|---|---|
| | | **Green Area** | **Urban Area** | **Characterization** | **$h^{-1}$** | **mm** |
| Bairro Jardim Canadá | SB 01 | 73.03 % | 26.97 % | Rural | 30 | 0 |
| | SB 02 | 52.46 % | 47.54 % | Semi-urban | 20 | 4,5 |
| | SB 03 | 23.03 % | 76.97 % | Urban | 10 | 10 |
| | SB 04 | 96.27 % | 3.73 % | Rural | 30 | 0 |
| | SB 05 | 100.00 % | 0.00 % | Rural | 30 | 0 |
| | Pondered data | | | | 20 | 4.5 |
| Capão Xavier Mine | SB 06 | 4.26% | 95.74 | Impermeable | 2 | 15 |
| | SB 07 | 16.74% | 83.26 | Rural | 30 | 0 |
| | Pondered data | | | | 7 | 13 |

The calibration of the rainfall-runoff transformation model, by way of the WIN IPH2 software, yielded various results for the measured rainfall and runoff events, as well as serving for decision making purposes (Figure 6). The results were transcribed to the graphs shown in Figure 7, where for each $R_{MAX}$ constant number there's a corresponding Nash-Sutcliffe Coefficient for the $K_{SUB}$ variable numbers. On the basis of the aforementioned graphs, effort was given to obtain the $R_{MAX}$ and $K_{SUB}$ figures for which their Nash coefficients presented a better overall result for the group of rainfall events that were analyzed.


CALIBRAÇÃO EVENTO ISOLADO

Parâmetros — Limites recom

| | | |
|---|---|---|
| I0 | 37.6354 | (10.0 - 300.0) |
| IB | 8.4164 | (0.10 - 10.0) |
| H | 0.3091 | (0.01 - 0.999) |
| KS | I.427354 | (0.01 - 10.0) |
| KSUB | 4.0 | (10.0 - 500.0) |
| RMAX | 11.5 | (0.0 - 9.0) |

Condição Inicial

| | |
|---|---|
| Percolação (m3/s) | 0.000000( |
| Vazão subterrânea (m3/s) | 0.000000( |
| Vazão Superficial (m3/s) | 0.000000( |

Dados da bacia

| | |
|---|---|
| Área impermeável (0 -- 100) % | 7.025733! |
| Coeficiente de forma (n) do HTA | 1.500000( |
| Tempo de concentração (unidades de intervalo de tempo) | 5.000000( |

Resultados: FO

| | | |
|---|---|---|
| Desvio padrão | 0.62 | m3/s |
| Desvio abs. médio | 0.31 | m3/s |
| Desvio quad. rel. médio | 0.67 | m3/s |
| Desvio quad. inverso | 58298.15 | 1/(m3/s) |
| Coef. Nash-Sutcl | 0.81 | -- |
| Desvio rel. médio | 0.97 | % |
| Erro de volume | 16.97 | -- |

Figura 6 – Example of calibration results for the rain in 10/05/2010

Upon analysis of these graphs it became evident that as the $R_{MAX}$ figures increase the Nash-Sutcliffe Coefficients increase for all the rainfall events, to reach very good levels between 11.5 and 12 and then go on reducing in relation to higher $R_{MAX}$ levels. The graphs, as shown, served as a basis for decision making with regards those figures that were considered to be very good for calibration of the rainfall-runoff transformation model, in relation to the four rainfall events in the Córrego Seco basin that were analyzed. These figures were $R_{MAX}$ = 11.5 and $K_{SUB}$ = 4.

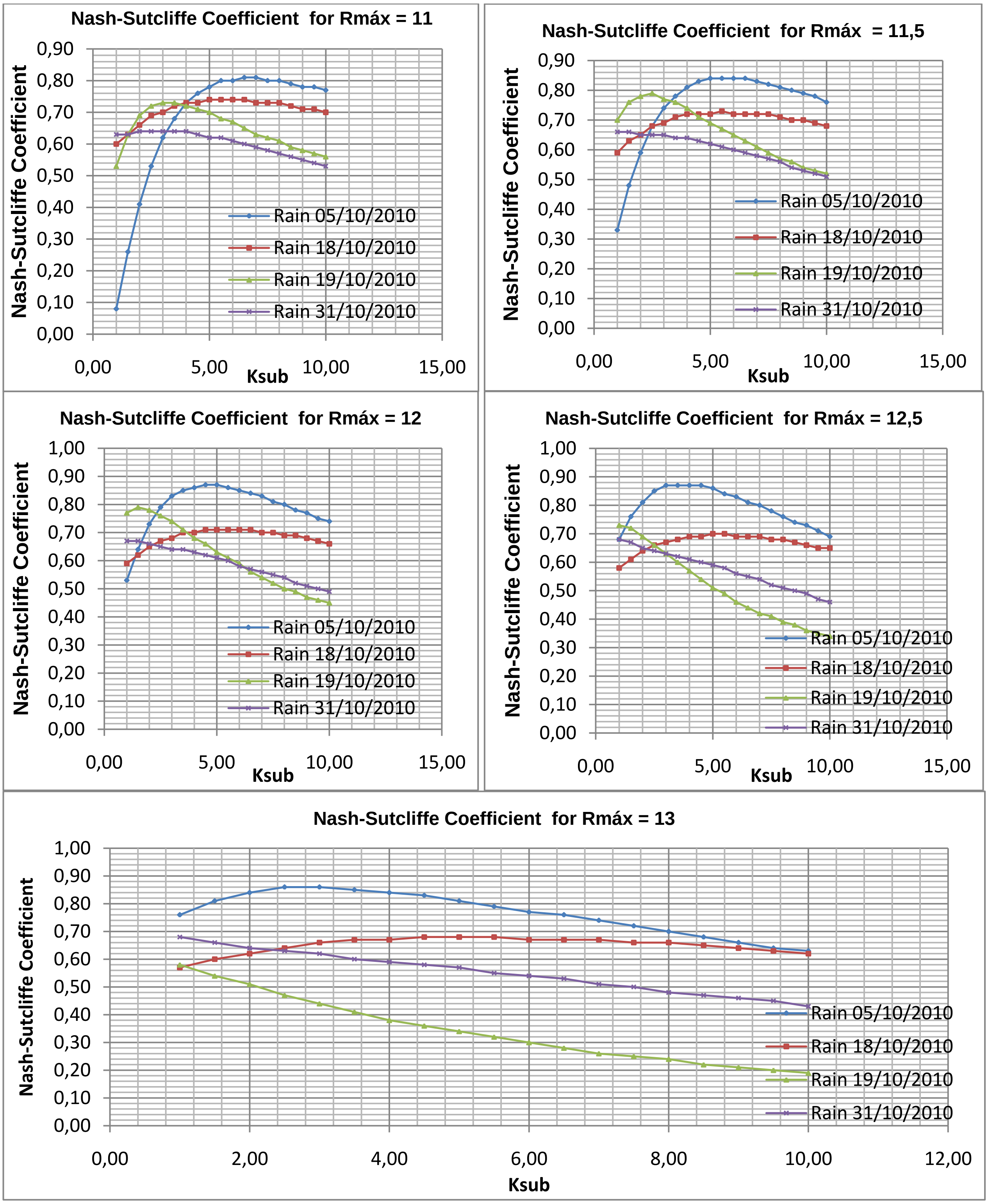
## RAINFALL-RUNOFF SIMULATION FOR THE CURRENT SCENARIO IN THE BASIN USING THE CALIBRATED MODEL

By using the alternating blocks method for elaborating the rainfall hyetograph and the PINHEIRO and NAGHETTINI (1998) equation (10) to calculate pluviometric intensity the rainfall-runoff transformations based on the calibrated variations were obtained. The simulations were conducted for rainfall events lasting 115, 150, 270 and 290 minutes for 10-year, 25-year and 50-year return periods. Figure 8 shows the rainfall events hyetograph and the hydrograms for the runoffs from the basins for the same rainfall events.

$$\hat{I}_{T,d,j}=0,76542\ d^{-0,7059}P_j^{0,5360}\mu_{T,d} \tag{10}$$

Where $\hat{I}_{T,d,j}$ is the intensity of the average precipitation of d duration, at location j, associated to the return period T, expressed in mm/h, d is the duration of the precipitation in hours, $P_i$ is the total average annual precipitation of the location j expressed in mm and $\mu_{T,d}$ is the regional dimensionless quantile.

The adopted rainfall events had the same duration as the rainfall events measured in the model calibration process. However, as the return period for those events were not investigated a perfect comparison between the measured rainfall events and the calculated events was not possible.


Nash-Sutcliffe Coefficient for Rmáx = 11

Nash-Sutcliffe Coefficient for Rmáx = 11,5

Nash-Sutcliffe Coefficient for Rmáx = 12

Nash-Sutcliffe Coefficient for Rmáx = 12,5

Nash-Sutcliffe Coefficient for Rmáx = 13

Figure 7 - Nash-Sutcliffe Coefficient

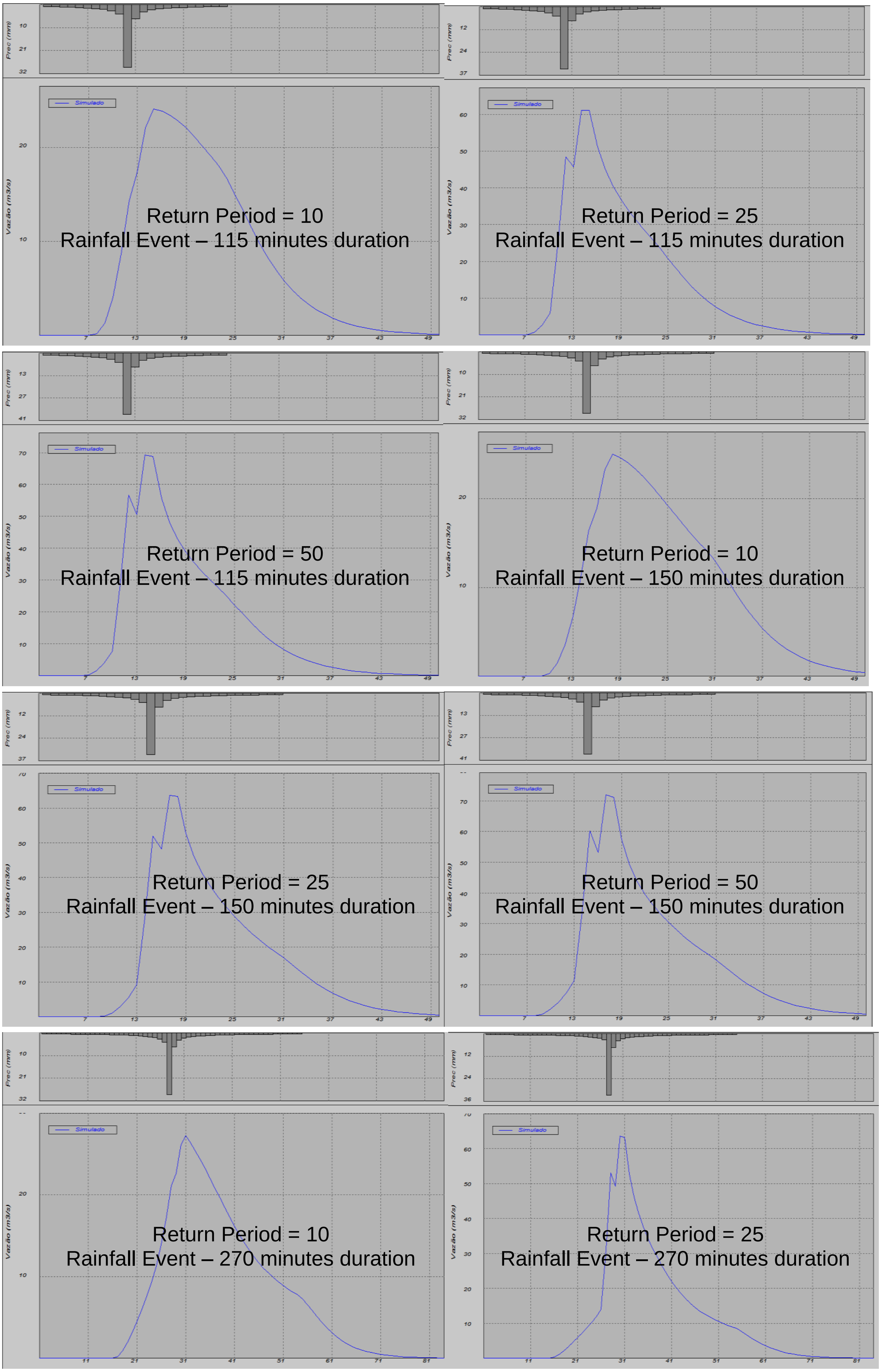


Figure 8 – Rainfall-runoff transformation for rainfall events with durations of 115, 150, 270 and 290 minutes

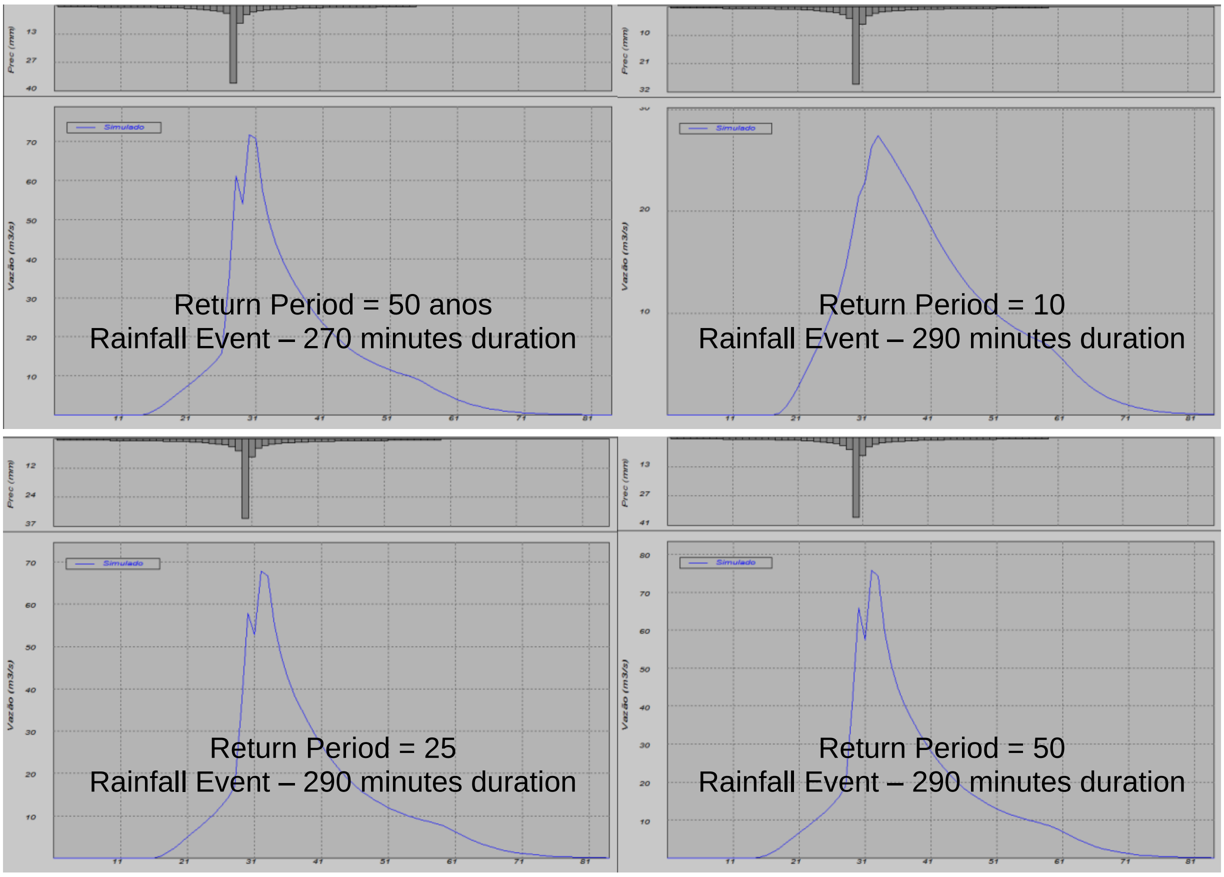


Figure 8 (continuation) – Rainfall-runoff transformation for rainfall events with durations of 115, 150, 270 and 290 minutes

The similarity between the responses for simulated rainfall events of equal return periods is noteworthy, for those with durations of 115 and 150 minutes as well as those of 270 and 290 minutes. However, one can perceive in the case of longer duration rainfall events that the basin appears to be more concentrated in relation to time, with steeper ascending and receding curves. One likely cause of this effect is that during a longer rainfall event the ground tends to become saturated, thus causing increased surface runoff, together with the filling of surface reservoirs, which in turn discharge the totality of their intercepted waters. Accordingly, the basin upon receipt of the largest amount of rainfall has the least amount of retention capacity and thereby produces a more concentrated runoff response in relation to time. This response corroborates the observation by CASTRO (2007) with regards the approximation of results between rural and urbanized basins for rainfall events of long duration.

A strong jump occurs, as expected, in the rate of runoff from the basin when the return period changes from 10 to 25 years and from 25 to 50 years. Because the basin is partially urbanized, however, with large areas of natural ground, covered mainly by low-lying vegetation and grasses, the responses to rainfall events are fast and the interval between the peak runoff and the largest block of rainfall visible on the hyetograph is relatively short. The characteristics of the ground and underground constitute another factor to be considered. The presence of iron-ore gangue material, which outcrops in many places, contributes to the low capacity to retain rainwater, as shown by the proximity between the runoff peaks and the rainfall peaks on the graph curves, to be considered together with their significantly elevated levels.

Table 7 presents the peak runoff results for the hydrograms shown in Figure 8, together with the net water levels in the channel. No flood waters were seen to exceed the maximum capacity of the channel as per the results of the simulations conducted in this study for the channeled portion of the Córrego Seco creek.

Bairro Jardim Canadá neighborhood, which is situated in the Córrego Seco Basin, is currently undergoing accelerated occupation and urbanization, where the law governing the Use and Occupation of the Land for the Municipality of Nova Lima, RMBH (Metropolitan Region of Belo Horizonte) stipulates the maximum degree of overall urbanization and impermeability on building lots, where 30% of the area of each lot must be kept clear for seepage purposes. Under that condition, the maximum degree of impermeability, namely 28.80%, was determined for the sub-basin where the neighborhood is inserted, as against the current degree of impermeability, which is 7.03%

Table 7 – Summary of maximum runoff for simulated rainfall events and water level in the channel.

| RAINFALL EVENT DURATION (minutes) | RETURN PERIOD (years) | BAIRRO JARDIM CANADÁ SUB-BASIN | | CAPÃO XAVIER MINE SUB-BASIN |
|---|---|---|---|---|
| | | RUNOFF ($m^3/s$) | WATER LEVEL IN CHANNEL (m) | RUNOFF ($m^3/s$) |
| 115 | 1 | 14.59 | 0.946 | 4.17 |
| | 10 | 24.12 | 1.199 | 17.50 |
| | 25 | 61.11 | 1.831 | 20.61 |
| | 50 | 69.30 | 1.935 | 23.27 |
| 150 | 1 | 15.06 | 0.961 | 4.26 |
| | 10 | 25.05 | 1.231 | 18.26 |
| | 25 | 63.68 | 1.864 | 21.41 |
| | 50 | 71.97 | 1.968 | 24.08 |
| 270 | 1 | 17.80 | 1.040 | 4.58 |
| | 10 | 27.28 | 1.270 | 19.72 |
| | 25 | 64.61 | 1.876 | 21.73 |
| | 50 | 72.76 | 1.977 | 24.44 |
| 290 | 1 | 18.11 | 1.049 | 4.67 |
| | 10 | 27.42 | 1.273 | 19.87 |
| | 25 | 67.82 | 1.917 | 21.82 |
| | 50 | 75.76 | 2.012 | 25.51 |
| **Total channel depth (m)** | | | 2.790 | - |
| **Maximum channel capacity ($m^3/s$)** | | | 161.239 | - |

New rainfall-runoff transformation simulations were conducted based on the foregoing, for the maximum impermeability scenario. The comparison between the runoff peaks and the rainfall peaks for the 50-year return period showed a significant increase, but the highest indices occurred predominantly for the 10-year return period, when the impermeability factor is changed from 7.03% to 28.8% in the future scenario, as demonstrated in Table 8 and the graph shown in Figure 9. The results as presented clearly demonstrate that for rainfall events of greater return period, i.e. of greater intensity, the effect of the fact that the basin is basically semi-urban significantly lessens especially for rainfall events of longer duration.

The hydrograms for the runoffs related to rainfall events of very short duration, 30 minutes, and long duration, 290 minutes are shown in Figure 10, for both the current and maximum scenarios of impermeability within in the basin. One can see from this figure the influence to the surface runoff caused by rainfall duration and the urbanization factor, which is responsible for increased impermeability of the ground. The interval between runoff peaks for longer duration rainfall events lessened and the response hydrograms became closer. One can discern that a considerable approximation occurs between the volumes of surface runoffs within the basin for both impermeability scenarios in keeping with increases in return periods for rainfall events of long duration. This fact is explained by the effect caused by ground saturation and the filling of Nash type surface reservoirs, which in turn yield runoff in a manner similar to impermeable ground.

The pumping system for dewatering the base of the open pit in Capão Xavier Mine during rainfall events (Sump Pumping System) extracts the accumulating water from the base of the pit and conveys it to an intermediary reservoir, from where the water is subsequently pumped to the containment reservoir formed by the former open clay pit, formerly owned by Magnesita. Both pumping systems feature equal operational characteristics, given the similarity of their installations and therefore have the same type of motor-pump units. Each of the two systems features two Flygt BS 2250MT suction pumps connected to 400 mm diameter carbon steel pipes. The hydraulic study conducted on the sump pumping system, represented by the pump performance curve X the elevator pump system performance curve, yielded the exact working pressures and discharge rates.

Table 8 – Simulated runoffs for basin permeability scenarios: 7.03% (current) and 28.8% (future)

| RAINFALL EVENT DURATION (minutes) | RETURN PERIOD (years) | RUNOFF ($m^3/s$) | | DIFFERENCE BETWEEN RUNOFFS (%) |
|---|---|---|---|---|
| | | IMPERMEABILITY 7.03% | IMPERMEABILITY 28.8% | |
| 115 | 1 | 14.59 | 19.83 | 35.92 |
| | 10 | 24.12 | 38.92 | 61.37 |
| | 25 | 61.11 | 74.34 | 21.64 |
| | 50 | 69.30 | 83.03 | 19.82 |
| 150 | 1 | 15.06 | 20.76 | 37.83 |
| | 10 | 25.05 | 39.96 | 59.55 |
| | 25 | 63.68 | 76.89 | 20.74 |
| | 50 | 71.97 | 85.61 | 18.96 |
| 270 | 1 | 17.80 | 24.41 | 37.14 |
| | 10 | 27.28 | 42.16 | 54.57 |
| | 25 | 64.61 | 78.17 | 21.00 |
| | 50 | 72.76 | 86.73 | 19.19 |
| 290 | 1 | 18.11 | 24.74 | 36.62 |
| | 10 | 27.42 | 42.32 | 54.34 |
| | 25 | 67.82 | 80.74 | 19.06 |
| | 50 | 75.76 | 89.16 | 17.69 |

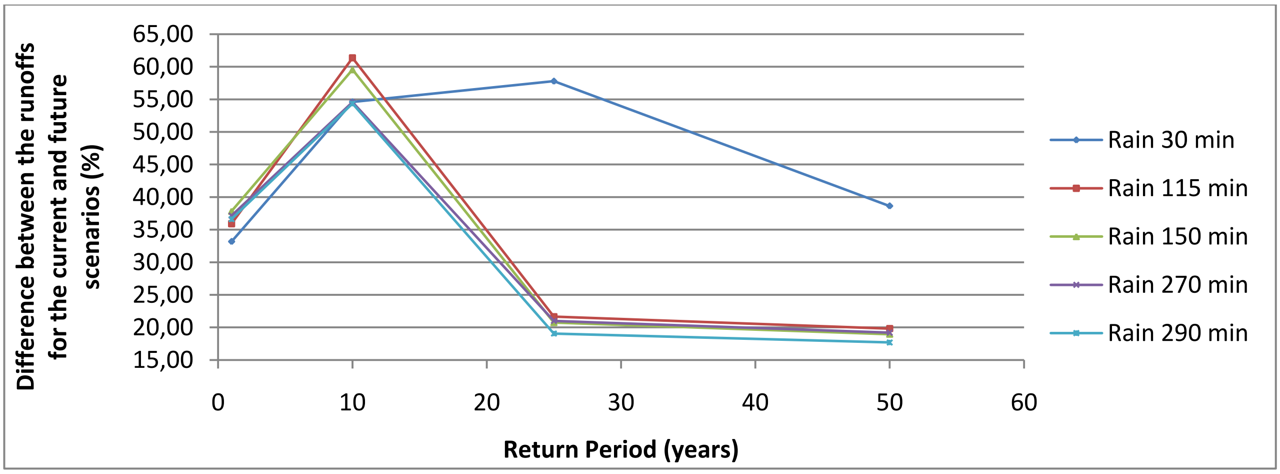


Figure 9 – Difference between the runoffs for the current and future scenarios.

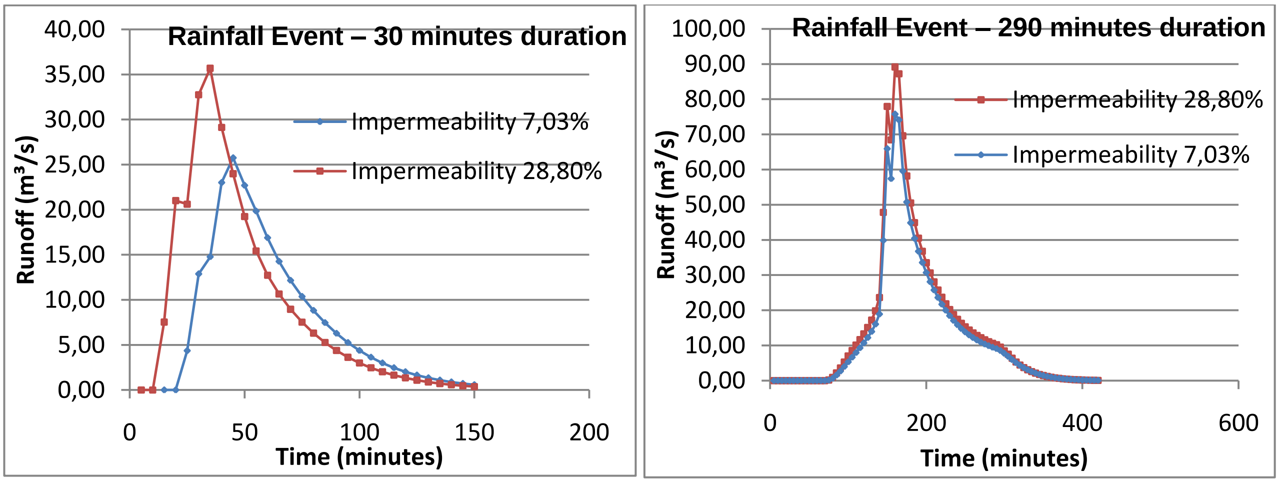


Figure 10 – Runoff from Bairro Jardim Canadá sub-basin, 7.03% and 28.80% degrees of impermeability, for 50-year Return Period.

The pumping study results yielded a discharge rate of Q = 935.86 m³/h or 0.259961 m³/s, which was added to the runoff hydrograms for the Córrego Seco basin. The influence by the mine sub-basin was assessed, using the most critical of the simulated rainfall events, namely, of 290 minutes duration and 50-year return period. The results of the foregoing rainfall event characteristics are shown in Figure 10.

Figure 11 shows that the runoff originating from Córrego Seco basin is only slightly altered by the pumping from the Capão Xavier Mine SUMP, because initially the total volume of rainwater is accumulated in the open-pit, then pumped continuously until all of the accumulated water has been drawn out, thus amortizing the hydrogram, shown in red in Figure 12. The volume of this rainfall event under assessment, obtained by measuring the area over the hydrogram shown in red, was 1,999.03 m$^3$. Given the sump pumping system's working characteristics, the time it takes to empty the sump is 2.14 hours. In other words, this rainfall event of 290 minutes duration causes a downpour of approximately 405 minutes. The analysis of the sump pumping information shows that pumping is not done continuously but intermittently depending on the duration of a rainfall event, corresponding with the descendant phase of the hydrogram. The green-colored hydrogram represents the sum total of the surface runoff contribution from the mine area (shown in red) plus the contribution from Bairro Jardim Canadá area (shown in blue).

The studies to determine rainwater storage capacity within the pit sump yielded a total of 4551.60m3. However, with regards the isolated rainfall events that were used in the calculations, the volume of accumulated rainfall was not sufficient to fill the open pit. The sump pumping system is activated the instant water begins to accumulate at the bottom of the mine pit. The "lakes" formed in this manner are shown in Figure 12.

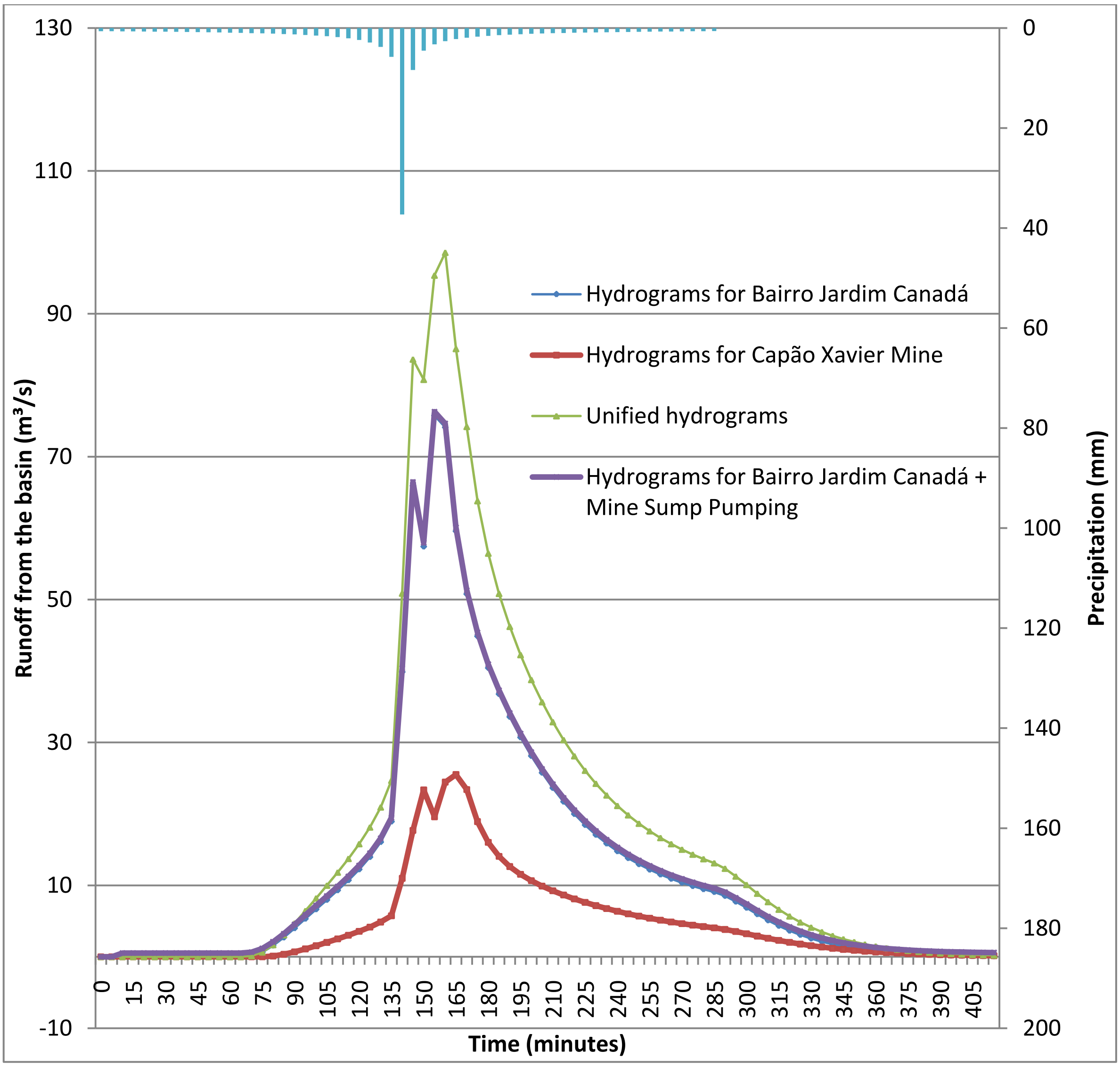


Figure 10 – Runoff conducted to the Capão Xavier Mine's containment reservoir.

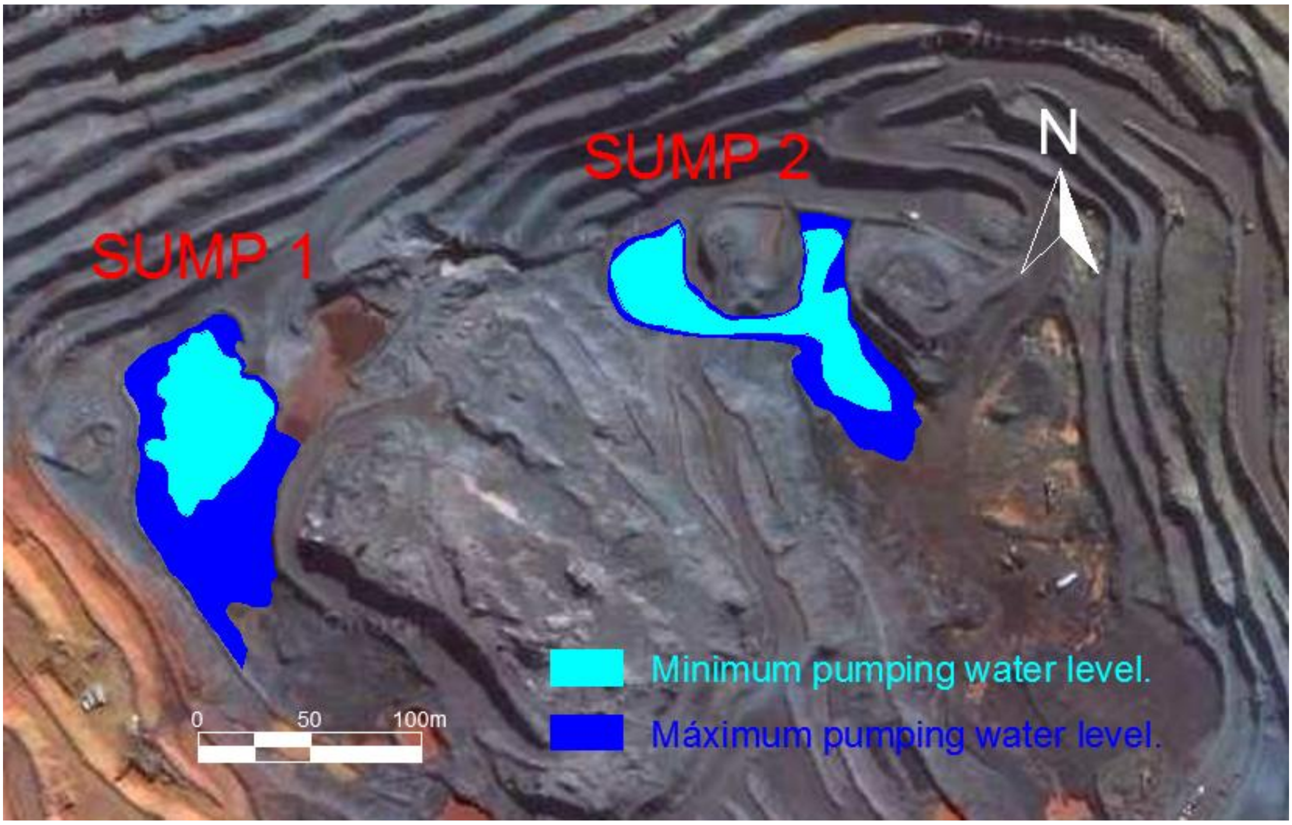


Figure 12 – Accumulated rainfall for removal by sump pumping system at Capão Xavier Mine

Discharge rates from the outlet channel of the aforementioned containment reservoir were simulated on the basis of all the foregoing data. This was done initially only for the accumulated peak discharge from the sump pumping system for the discharge from basin under study. Subsequently, only for the sump pumping system, then finally for the total accumulated measured volume under the hydrogram for the accumulated discharges (hydrogram shown in purple). By applying this volume over the surface area of the containment reservoir, the height increase of the water surface was calculated. This procedure thus led to calculation of the discharge rate into the creek, caused by the downpour. Table 9 shows the results for the referenced rainfall events.

Table 9 – Discharge from the Capão Xavier Mine's containment reservoir into Córrego Seco Creek.

| DISCHARGES (m³/s) | | | WATER LEVEL IN THE OUTLET CHANNEL (m) |
|---|---|---|---|
| BASIN | MINE | TOTAL | |
| 75.764 | 0.260 | 76.024 | 2.016 |
| 0.000 | 0.260 | 0.260 | 0,112 |
| Hydrogram volume | | 0.438 | 0.072 |

The calculations to determine the outlet rate of discharge from the containment reservoir were based on the fact that the rainfall event simulations were specifically for isolated downpours and for the reservoir when full. This involved using calculation procedures related to a long trapezoidal channel, 4.17 m wide with 0.018 m/m declivity fed by a reservoir with a constant water level. Manning's equation (11) and the specific energy equation (12) were used in this calculation method to form an equation system to determine the variables Q, discharge and y, water surface height, which were processed using the Solve function in Microsoft Excel®.

$$Q = \frac{1}{n} R_H^{2/3} A \sqrt{I_0} \qquad (11)$$

$$H = E = y_0 + \frac{Q^2}{2gA^2} \qquad (12)$$

The above-described procedures yielded a discharge rate of 0.438 m³/s and channel water surface height of 0.072 m. The presence of the containment reservoir, formed within the former Magnesita-owned open clay pit is notably of prime importance for controlling discharge into Córrego Seco Creek. To simulate the scenario of the natural state of the entire basin upstream from Highway BR-040 in the absence of the containment reservoir, the downpour hydrograms for both drainage areas (Bairro Jardim Canadá and the mine area, green-colored hydrogram) were united. The resulting sum yielded a peak discharge of 98.563 $m^3/s$, which resulted in water surface level at 2.258 m in the creek.

## CONCLUSION

The assessment of the impacts caused by the occupation of the Córrego Seco micro-basin to the rainfall-runoff transformation processes demonstrates that urbanization causes a very strong impact, even within basins where the permitted degree of urbanization is not significant, as in the case of Córrego Seco basin.

By conducting seepage tests to obtain measurements *in loco*, using double-ring type infiltrometers, data was obtained for three of the model calibration variables. Accordingly, determining the seepage variables simplified the calculation of calibration data, considering that the variables that exert strongest influence on the results are in fact only two, namely, RMAX and $K_{SUB}$.

The hydrological behavior of the urbanized basins, either in their totality or in part, yield diverse responses depending on their characteristics, especially in relation to the removal of vegetation and ground impermeability. The impacts to the hydrology of urbanized basins were worsened by the ground characteristics due to outcropping iron-ore gangue and its presence just under the ground surface. This specific condition within the basin reduces the capacity of the underground reservoir. This fact signifies that the surface runoff during downpours of either very intense or of long duration undergoes a strong increase compared to natural occupation conditions, i.e. non-urbanized. This increased runoff from the basin is responsible for the strong degree of similarity between the runoffs from the non-urbanized basin compared with the urbanized basin.

The presence of Capão Xavier Mine, considering the hydrological cycle, has resulted in the retention of part of the runoff volume within a reservoir formed within the actual mine, which is formed as a necessary part of the mine sump pumping system. Further to the foregoing fact, the rainwater contribution which would runoff directly to the creek in the absence of the mine, are at this juncture collected within the reservoir in the pit for subsequent pumping to the aforementioned containment reservoir. This configuration has resulted in the amortization of the surface runoff from the basin under study to the Córrego Seco watercourse, thus minimizing the risk of flooding downstream from the area in question.

## BIBLIOGRAPHY

ALVES SOBRINHO, Teodorico ET Al. Title: “Water seepage into the ground in direct type and conventional plantation systems”. (“Infiltração de água no solo em sistemas de plantio direto e convencional). Published in: Revista Brasileira de Engenharia Agrícola e Ambiental, Campina Grande, v. 7, n. 2, p.191-196, May 2003. Issued every four months, ISSN 1415-4366. Available at: <http://www.agriambi.com.br>. Acessed: 4th. August 2010.

CASTRO, Leonardo Mitre Alvim de. Title: PROPOSED METHODOLOGY FOR THE ASSESSMENT OF EFFECTS BY URBANIZATION ON BODIES OF WATER”, (PROPOSIÇÃO DE METODOLOGIA PARA A AVALIAÇÃO DOS EFEITOS DA URBANIZAÇÃO NOS CORPOS DE ÁGUA). 2007. 321 f. Thesis (Doctorate) – Sanitation Course Doctorate, Environment and Water Resources, Research Results Department, Hydraulic Engineering and Water Resources Department, at the Federal University of Minas Gerais, Belo Horizonte, 2007.

GREGORY, Justin Haig. Storm water infiltration at the scale of an individual Residential lot in north central Florida. A thesis presented to the Graduate School of the University of Florida in partial fulfillment of the requirements for the degree of Master of Engineering. University of Florida. 115p. 2004.

GERMANO, Andréa; TUCCI Carlos E. M.; SILVEIRA André L. L. Title: “Estimating parameters for the model and IPH II for some Brazilian urban basins”, (Estimativa dos parâmetros do modelo e IPH II para algumas bacias urbanas brasileiras). Published in: Revista Brasileira de Recursos Hídricos. Volume 3. Number 4. Outubro. 1998. P. 103-120.

MINE, Mirian Rita Moro; TUCCI, Carlos Eduardo Morelli. Title: “REAL-TIME FORECAST OF DISCHARGES INFLOWING TO HYDRO-POWER RESERVOIRS”, (PREVISÃO EM TEMPO REAL DE VAZÕES

AFLUENTES A RESERVATÓRIOS DE USINAS HIDRELÉTRICAS). Published in: Revista Brasileira de Recursos Hídricos, Porto Alegre, v. 2, n. 4, p.73-95, 1999. Quarterly issue.

PINHEIRO, Márcia Maria Guimarães; NAGHETTINI, Mauro. Title: "REGIONAL BASIS ANALYSIS OF THE FREQUENCY AND TEMPORAL DISTRIBUTION OF STORMS OCCURRING IN THE METROPOLITAN REGION OF BELO HORIZONTE – RBMH". Published in: Revista Brasileira de Recursos Hídricos, Porto Alegre, v. 3, n. 4, p. 73-88, Oct / Dec / 1998. Quarterly issue.

PINTO, Juliane dos Santos. Title: "Study of hydraulic conductivity of the ground destined for disposal of solid waste in the region of Santa Maria", (Estudo da condutividade hidráulica de solos para disposição de resíduos sólidos na região de Santa Maria). Dissertation presented for the Master's Degree Course for the Civil Engineering Post-Graduate Program, Civil Construction and Environmental Preservation Concentration Area, at Federal University of Santa Maria (UFSM, RS), as a part of the requisites to achieve the Master's Degree in civil Engineering. Santa maria, State of Rio Grande Do Sul. 2005.

TUCCI, Carlos E. M. Title: "Hydrological Models", "Modelos Hidrológicos. Published by: Editora da Universidade / UFRGS – Associação Brasileira de Recursos Hídricos. 669p. Porto Alegre. Rio Grande do Sul. 1998.