INTERFERENCE OF THE LAND USE ON FLOODING IN AN URBAN AREA

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ABSTRACT:. The first populations have settled near the rivers and as they have expanded there was an increase of impervious areas, and the suppression of floodplain areas. This fact contributes to changes in river hydrology and hydraulics and to the increased floods. Thus, this work aims to verify the interference of land use on floods in the urban area of the Servidão stream basin, Rio Claro (SP), in different scenarios, i.e., pre- and post-occupation scenarios. For this, the Soil Conservation Service model based on the land use characterization for all scenarios were evaluated, thus permitting to measure the variation on hydrograms and flow peaks. The results indicated that increasing the waterproofing, for the growth of the Rio Claro city, was responsible for the first event of flooding of the city. The government has been doing some engineering work and transferring most of the problems with flooding to downstream areas, where floodings still occur.

Key Words: Land use; urban area; flooding

1. INTRODUCTION

Cities have historically developed along riverbanks where populations have access to food and water for survival. Consistent with this human settlement pattern, the majority of Brazilian cities have developed adjacent to rivers. These urban areas have grown over time, causing expansions of impermeable surface areas and populations near rivers that have contributed to increased flood events.

In 2008, more than 1,000 Brazilian municipalities were affected by floods; approximately 60 were located in southeastern São Paulo, Brazil (MCT, 2009). The total damage included 200,000 houses destroyed, 100,000 houses damaged and 500,000 people adversely affected. According to the Brazilian Department of Science and Technology, flooding causes damages of approximately one billion (US$) annually in Brazil (MCT, 2009).

This work presents a typical example of flooding, potentially increased by urban occupation, in a mid-sized urban area in the interior of São Paulo, Brazil. It represents a case study of an urban area in the Servidão Stream basin located in the Rio Claro municipality. The natural characteristics of the studied area, as well as human land use patterns, are presented. In addition, precipitation conditions were obtained using hydrological models that allow for the evaluation of excessive rain conditions and run-off into canals. The goal of this work is to analyse hydrological behaviour to assist flooding dynamics comprehension in urban area of the Rio Claro municipality.

2. THE SERVIDÃO STREAM BASIN

The Servidão Stream basin is located in the Rio Claro municipality in east-central São Paulo, Brazil (Figure 1). In this study, terrains of the high- and mid-watershed were evaluated since these areas have been subjected to intense urbanisation and have persistent flooding problems since 1970´s. The watershed shape is oblong in the north to south direction, with a maximum width of approximately 4 km and length of 5.1 km.

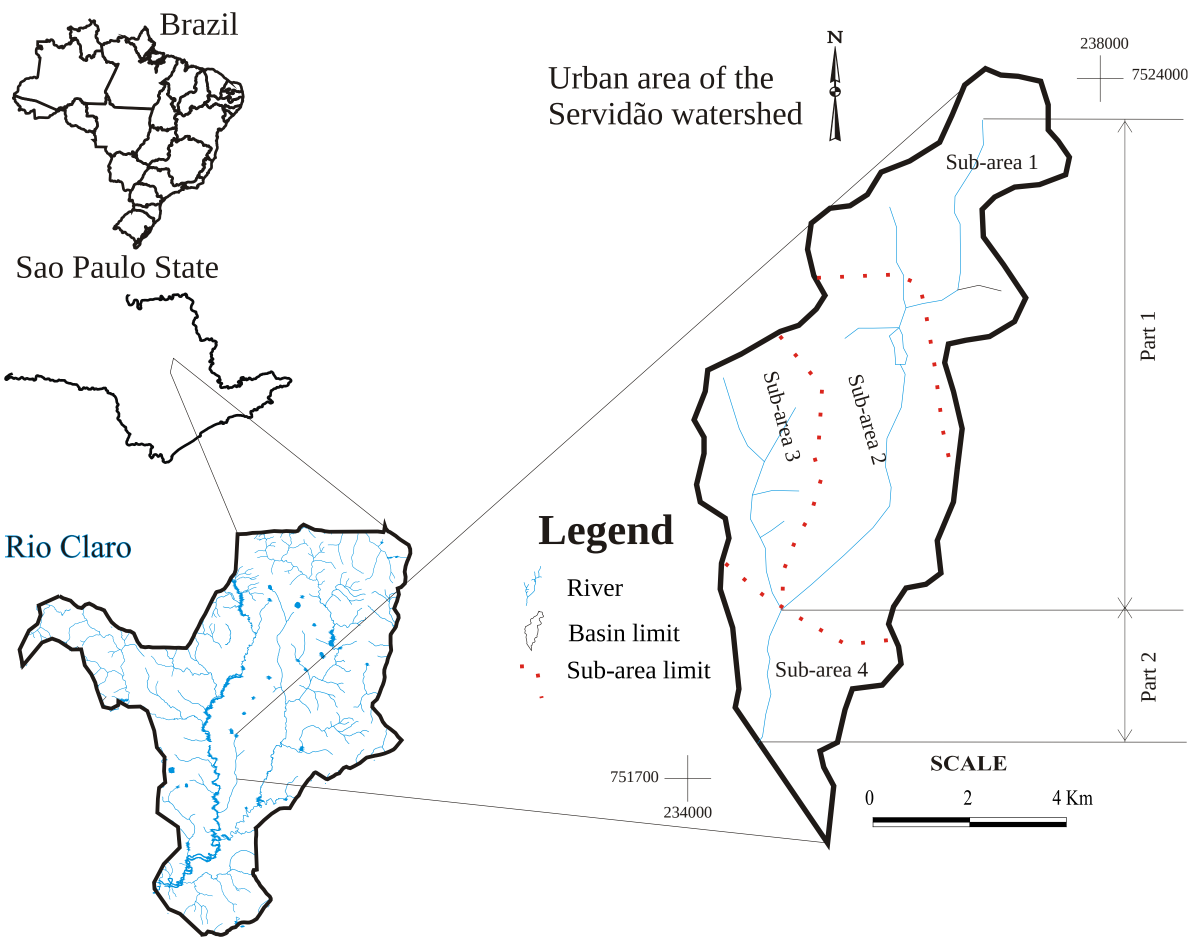


Figure 1 – Location of the Servidão Stream basin in the urban area of the Rio Claro municipality in São Paulo, Brazil

Rio Claro has a population of 190,000 people (average of density of 370 inhabitants.km^{-2}) and is situated nearly 170 km northeast of São Paulo, with road access via the Washington Luiz (SP-310) highway and Anhanguera-Bandeirantes toll road system, as well as by a railway network. This watershed is situated in two Environmental Protection Areas (EPA); this categorisation as an Environmental Conservation Unit was constituted by Federal Law 6.902 on April 27, 1981, under the Corumbataí and Piracicaba EPAs.

The area is part of the Paulista Peripheral Depression (Almeida, 1974), which is an erosion zone located between cliffs of the Cuesta zones, which denote the eastern border of the basaltic flow and Planalto Cristalino. In terms of local geomorphology, the elevation of the canal in the Servidão Stream basin is much higher than surrounding valleys. The studied watershed is also characterised by its gentle topography with roughly 110 m of oscillating altitude. Soils encountered here are sand-rich from the Rio Claro Formation, which include the densely built tops of this watershed.

These petrological characteristics are reflected in the density of the Servidão Stream basin, which possesses an annual flow rate of approximately 0.21 m^3/s at its mouth. The canal of the Servidão Stream basin has two direction changes in the mid course and lower course in northeast and southwest orientations, suggesting structural geological control. This watershed is characterised by low drainage density, which implies favourable soil permeability. Based on methods by Christofoletti (1980), the circularity index of the Servidão Stream basin is only 0.21, which signifies the reduced possibility of concentrated rainwater flow (Schwab et al., 1966).

The Köeppen classification of the Servidão Stream area climate is ‘CWa’ (where, C = hot moderate climate; W = dry season in winter; a = hot summer). Specifically, this area is tropical and rainy; it is characterised by rain in the summer with dry winters and average monthly temperatures >18°C with the hottest month exceeding 22°C. Precipitation in the month of maximum rain is ten times greater than that in the driest month (Conceição & Bonotto, 2004). The area is controlled by tropical and equatorial masses that dominate more than 50% of the year and are accompanied by winds from the south and southeast. In terms of annual rainfall distribution, the climate is tropical, with the following two well-defined seasons: April to September is the dry season with average rainfalls of 30 to 90 mm per month; and October to March is the wet period with average rainfalls of 120 to 260 mm per month. The total monthly rainfall averages result in 1,505 mm of rainfall per year (Conceição & Bonotto, 2003).

Elevated precipitation, combined with the geological substrate, generates well-developed soils in the Servidão Stream basin. The soils found in this watershed are composed of red-yellow Latosols corresponding to the Coqueiro and Laranja Azeda units (Oliveira & Prado, 1984). The red-yellow Latosol of the Coqueiro unit is characterised by average texture along its profile with sand levels that are responsible for its high friability and low plasticity. The red-yellow Latosol of the Laranga Azeda unit contains clay deposits superior to the Coqueiro unit despite maintaining an average texture along its profile.

In this area, the plain terrains of the Servidão Stream basin were the first to be developed, giving rise to the city of Rio Claro. Currently, field and cadastral maps indicate a predominance of urban residential (79%) and industrial (21%) land uses. These land usage characteristics produce a typical Portuguese arrangement pattern of colonization known as chessboard pattern. This land use system of squares follows the direction of the slope, which in tropical climates, maximizes the velocity of pluvial flows. Furthermore, despite the soil characteristics and topography, substantial rainwater infiltration occurs. Urban centres, as currently organised, must be considered as important factors influencing flooding events recorded in recent years. Generally, the process of urban occupation in Brazil is different from those in developed countries mainly in terms of density and illegal occupation of land, whether public or private. The urban dynamic can be simplified by then the follow: i) the buildings are settled nearby the natural canal, as at ancient times, ii) a principal road is installed just beside the river path and, finally, iii) the natural canal is transformed into an artificial canal in order to increase the flow magnitude.

3. EVALUATION OF PRE- AND POST-OCCUPATION SCENARIOS FOR FLOODING IN THE URBAN AREA OF THE SERVIDÃO STREAM BASIN

Evaluation of the pre and post-occupation of the urban area of the Servidão Stream basin was performed by means of differential use and occupation conditions for each sub-area (Figure 1). This evaluation considered the type C soil hydrological group for the antecedent moisture condition (AMC II) in accordance with the Soil Conservation Service (SCS, 2004). Hydraulic and hydrological models were used, in combination with the Methodology of Oriented Modelling of Objects applied to Systems of Hydraulic Resources (Viegas Filho, 2000), and employing the computational program denominated IPHS1 (Tucci et. al., 1989). The SCS model (SCS, 2004) was employed for conversion of rain-flow and for propagation of excessive rain. The non-linear, Muskingum-Cunge model was adapted specifically for closed channels for propagation of flooding in canals and Pulz model for propagation in reservoirs.

The Equation of heavy rain events for the Rio Claro municipality were obtained by applying the mean of non-linear regressions and applying the algorithm proposed by Marquardt (1963) to data on maximal rainfalls presented by Moruzzi and Oliveira (2009). The equation was used in this paper for rainfall definition.

The Servidão Stream urban area was first divided into 4 sub-areas that conformed to the division presented in Figure 1. The principle characteristics of each sub-area are presented in Table 1. For this division, occupation, locations of interest and civil hydraulic works were considered. Decline in terrain was obtained using the average of declivity calculated in cross sections established according to the equidistance variation of level curves on topographic maps with scales of 1:10,000. The decline of the canal was calculated using the length and relative altitudes for each section.

Sub-area 1 corresponds to the spring region of the Servidão Stream basin, which is composed of the retention reservoir, Lago Azul (Figures 1). This reservoir has an area of approximately 400 m by 80 m, and a spillway length of 2 m with a crest located 0.5 m above the maximum water storage level. The maximum storage volume of the Lago Azul reservoir is located 2 m depth from the water level. Sub-area 2 begins where the water leaves the retention reservoir and extends to the confluence of the Servidão Stream stream with the Córrego Wenzel stream. Sub-area 3 is comprised of the area contributing to the Córrego Wenzel. Sub-area 4 is the region after the confluence of the Servidão Stream and Córrego Wenzel at the mouth of the Servidão Stream urban area in the Rio Claro municipality.

The principle canal was divided in two consecutive stretches (Figure 1). Stretch 1 of the stream is represented by the Servidão Stream and extends from the retention reservoir to its meeting with the Córrego Wenzel. Stretch 2 is comprised of the Servidão Stream from its meeting with the Córrego Wenzel to the mouth of the Servidão Stream basin. The simulated sections are piped and closed with a constant rectangular cross section. The section 1 piping is 3,626 m in length and drops 25 m, with cross-sectional diameters of 3 m in height and 4 m in width. The Manning coefficient (n) is 0.03, which corresponds to dredged channels under regular conditions (Porto, 1998). The section 2 piping is 1,514 m in length and drops 10 m, with cross-sectional diameters equal to that of section 1 with n values of 0.04 linked to the accumulation of transported sediments (Porto, 1998). For both sections, the excess runoff was assumed to be transported to the streets using an n value of 0.013, consistent with cement gutter surfaces (Porto, 1998).

Table 1 – Principal characteristics of the areas that comprise the urban area of the Servidão Stream basin.

Sub-area	**Area (km^2)**	**Slope of the terrain (%)**	**Slope of the rain canal (%)**	**Pre-Occupation condition**	**Pos-Occupation condition**
1	4,22	0,89	0,79	Forest	16,3% - industrial area; 4,1% - available spaces; 79,6% - households area.
2	4,33	1,27	0,68		2,5% - industrial area; 3,2% - available spaces; 94,3% - households area.
3	2,72	1,58	1,5		5,5% - industrial area; 7,7% - available spaces; 86,8%- households area.
4	2,34	2,46	0,66		24,0% - crops; 2,9% - available spaces; 73,1% - households area.

The concentration time of the sub-areas was calculated according to Equation 1, proposed by Chow et al. (1988).

$$tc = 57\left(\frac{L^3}{H}\right)^{0.385} \tag{1}$$

Where: t_c = concentration time (min); L = length of the principle water line (km); H = difference in elevations of the thalweg between the most distant point and the reference section of the watershed (m)

Equations 2 and 3 present the algorithm employed to obtain the excess rain according to the SCS (2004) for six time intervals of 600 s each.

$$Q = \frac{(P - 0.2.S)^2}{(P + 0.8.S)} \quad (2)$$

Where: *P* = precipitation; *S* = maximum storage potential of the soil for an initial loss corresponding to 20% of storage capacity

$$S = \frac{25{,}400}{CN} - 254 \quad (3)$$

Where: *CN* varies between 0 (infinite hydraulic conductivity) and 100 (totally impermeable watershed)

Equation 6 presents the Pulz model for reservoir propagation. This model considers storage variation over time as a function of input and output flows from the reservoir. The left hand term considers the unknowns, which are established by storage and output from the reservoir in time (t_2).

$$\frac{S_2}{\Delta t} + 0.5.O_2 = \frac{.S_1}{\Delta t} - 0.5.O_1 + 0.5.(I_1 + I_2) \quad (4)$$

Where: I_i = inlet flows; O_i = outlet flows; *Si* = accumulation for $t_1 \leq i \leq t_2$.

Since there are two unknowns, Equation 5 is applied to obtain the outlet flow at each interval. This estimate can be obtained by determining the relationship of height versus volume for a given reservoir, and by establishing the relationship of flow versus height, which depends on the spillway type.

$$O_2 = f.\left(\frac{S}{\Delta t} + 0.5.O_2\right) \quad (5)$$

Equation 6 presents the Muskingum model of propagation in canals, proposed by McCarthy (1938). In the simulations presented in this study, excess flow was extended to the street, utilising a non-linear version of the Muskingum-Cunge model adapted specifically for closed ducts, which allows distributed lateral contributions.

$$\frac{dS}{dt} = I - O; S = K\left[X.I + (1 - X).O\right] \quad (6)$$

Where: I_i = inlet flow; O_i = outlet flow; *Si* = accumulation; *K* and *X* are denominated adjustment parameters of the canal that representative the displacement time and influence of the inlet and outlet flows of the section as storage functions

Figure 2 presents the rainfall graphs, generated from the IDF of Rio Claro for the conditions of pre and post-occupation over different return times (TR of 5, 20, 50 and 100 years), and the excess rain obtained by Equations 4 and 5. By analysis of the rainfall graphs, the excessive flow generated by post-occupation conditions is evident when compared to pre-occupation conditions.

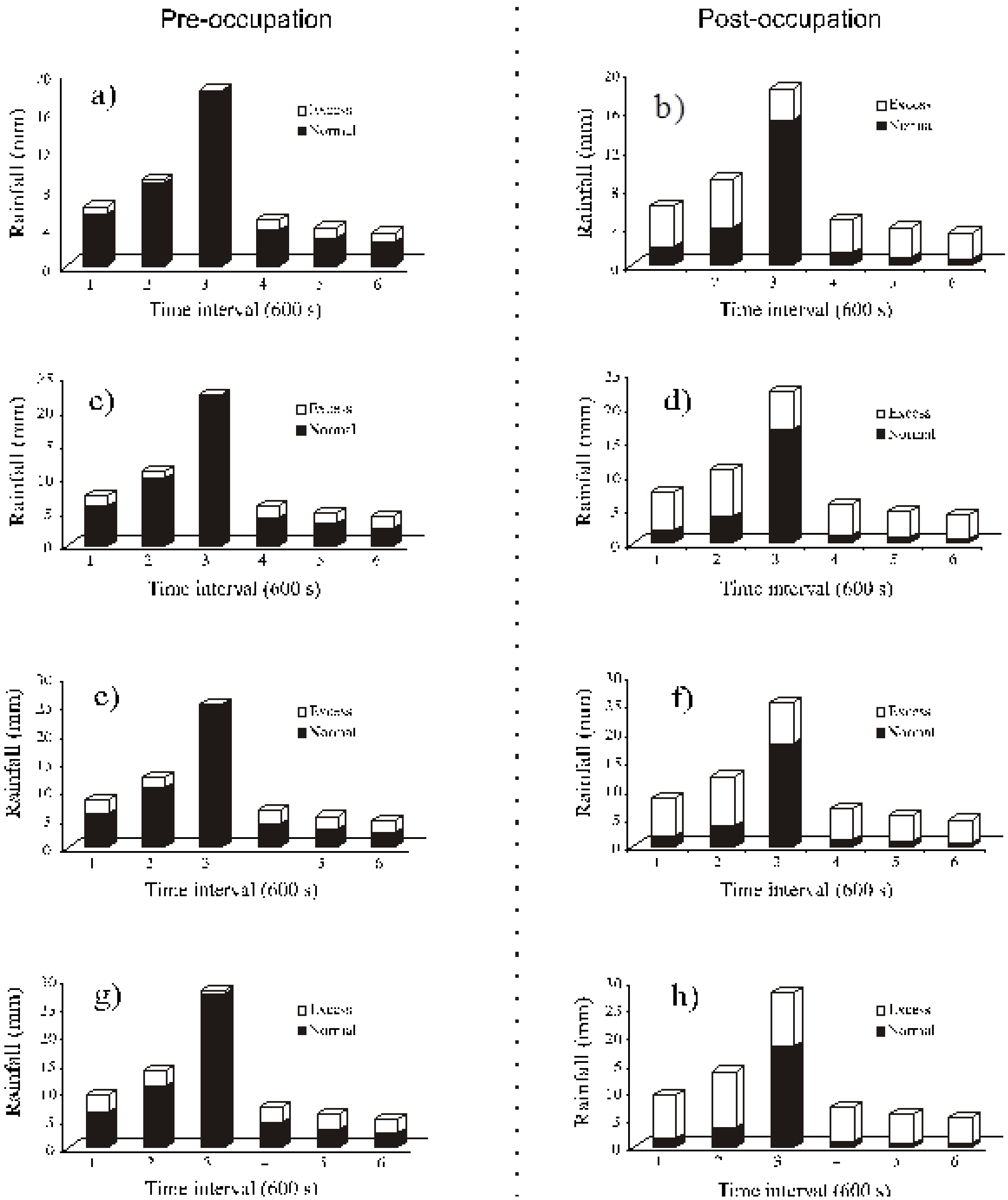


Figure 2 – Disaggregated and reordered design rainfall data that were generated using the IDF of the Rio Claro municipality that considered the pre-occupation (graphs on the left) and post-occupation (graphs on the right) scenarios of excess rainfall calculated using the SCS (2004) algorithm for different return period (TR) storms (i.e., with TR(s) of 5 (a, b), 20 (c, d), 50 (e, f) and 100 years (g, h).

Each generated rainfall graph was propagated in the sub-areas comprising the Servidão Stream basin, and was shown to be drained by means of the principle rain canal (Table 1). Figures 3 to 6 presents the run-off for pre-occupation condition, considering the period of return of 5 years, in each one of the four considered sub-areas.

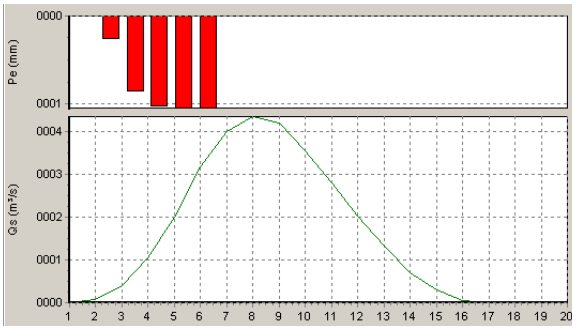


Figure 3 Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with intervals of 600 s for the sub-area 1 in pré-occupation conditions.

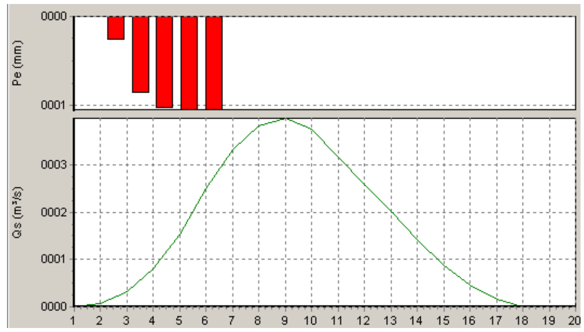


Figure 4 Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with intervals of 600 s for the sub-area 2 in pré-occupation conditions.

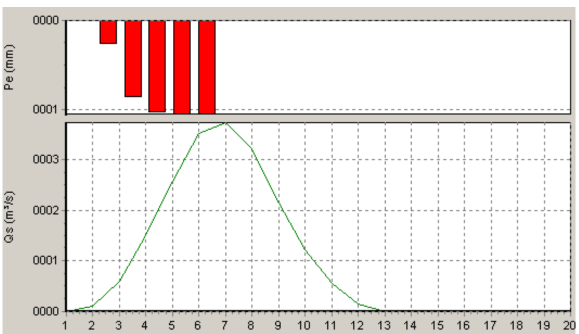


Figure 5 Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with intervals of 600 s for the sub-area 3 in pré-occupation conditions.

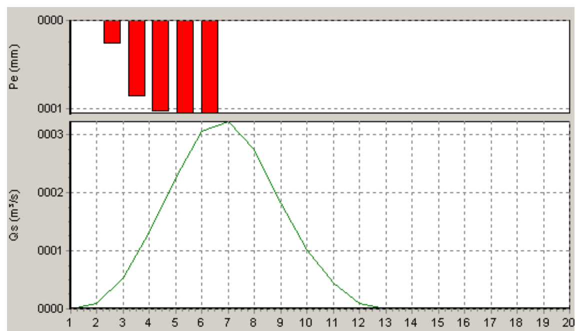
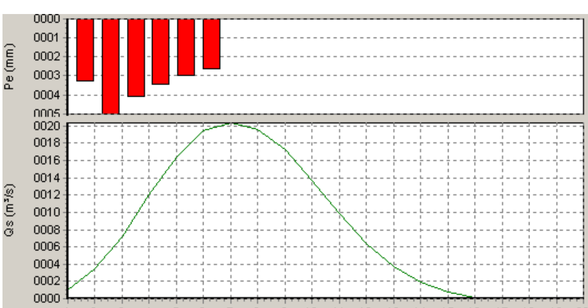


Figure 6 Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with intervals of 600 s for the sub-area 4 in pré-occupation conditions.

The peak flow can be confirmed to be roughly 3 or 4 $m^3.s^{-1}$ before occupation, considering CN 70 for all investigated sub-areas. These conditions were drastically altered by soil occupation and impermeability as illustrated in Figures 7 to 10 presenting the hydrograms of the same sub-areas for the same projected rains under actual human habitation conditions (CN 89). Peak increases were on the order of 4-5 times elevated in comparison to pre-occupation conditions, making evident the urban effect on run-off.



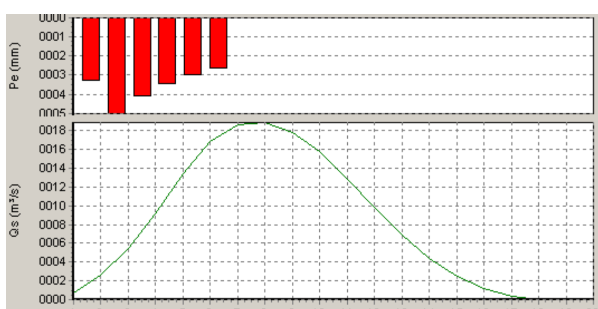


Figure 7- Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with

Figure 8- Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with

intervals of 600 s for the sub-area 1 in current occupation conditions. Source: Moruzzi et al. (2009).

intervals of 600 s for the sub-area 2 in current occupation conditions. Source: Moruzzi et al. (2009).

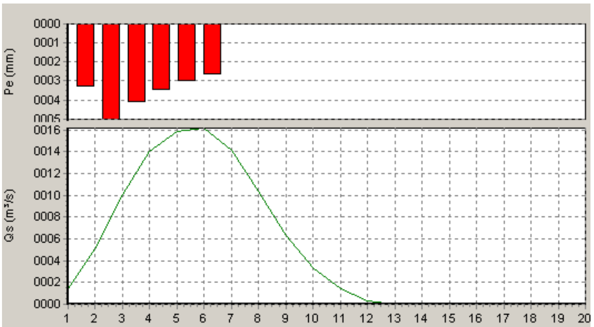


Figure 9- Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with intervals of 600 s for the sub-area 3 in current occupation conditions. Source: Moruzzi et al. (2009).

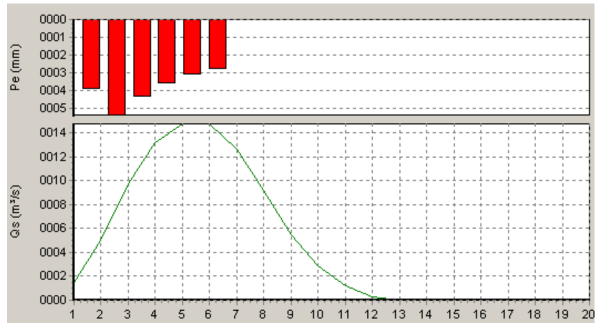


Figure 10- Hydrogram resulting from outlet (Qs) for TRs of 5 years of rainfall excess (Pe) and with intervals of 600 s for the sub-area 4 in current occupation conditions. Source: Moruzzi et al. (2009).

Figure 11 and 12 presents the hydrograms of floods for conditions of inlet and outlet from the reservoir, considering return times of 5 and 20 years, respectively, verified in the natural reservoir downstream of sub-area 1. The effects of peak dampening and flow retardation can be verified by the analysis of simulation results. It is clear that the retention reservoir is quite important on flow attenuation. However, the simulations suggest that the hydrogram of the reservoir outlet propagated by the part 2 of the principle canal in post-occupation conditions was responsible for some flooding conditions (Figure 13). This was evident even when considering the dampening effect of the reservoir and for return times of 20 years (see Figure 14 which shows flood photos in the studied watershed after a 20 years rainfall). Of course, the problem becomes even worse in the case of less frequent rainfall (higher values of period of return - TR). For this reason, we chose to terminate the analysis of the spread of excess with the value of TR for 20 years. The flood was not observed for the simulations performed in the same conditions considered to be natural by pre-occupation.

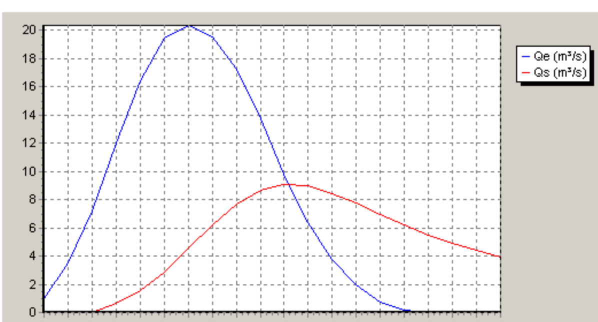


Figure 11- Hydrogram resulting from inlet (Qe) and outlet (Qs) for TRs of 5 years and with intervals of 600 s for the retention reservoir located at the head of the Servidão Stream basin for current occupation conditions. Source: Moruzzi et al. (2009).

Figure 12- Hydrogram resulting from inlet (Qe) and outlet (Qs) for TRs of 5 years and with intervals of 600 s for the retention reservoir located at the head of the Servidão Stream basin for current occupation conditions. Source: Moruzzi et al. (2009).

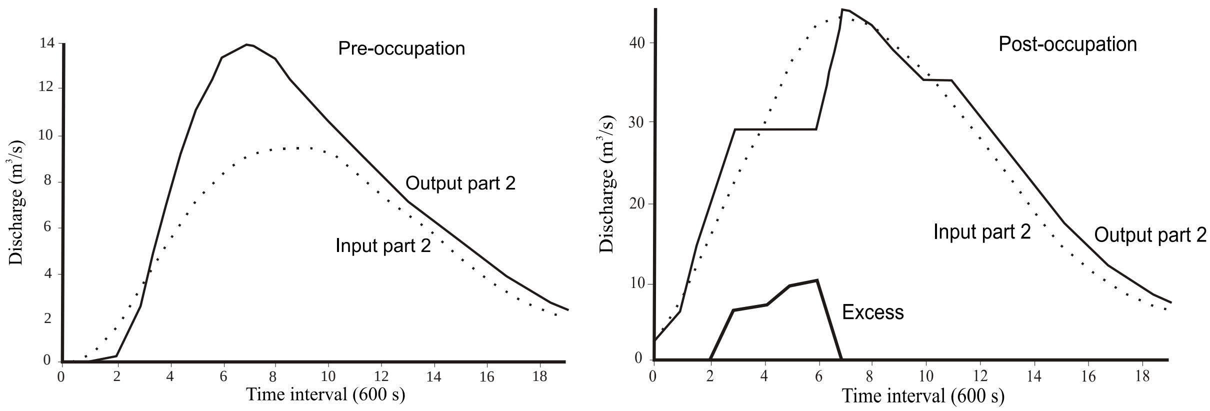


Figure 13- Hydrogram resulting from propagation of flow and excess in section 2 of the canal of the Servidão Stream for TRs of 20 years and with intervals of 600 s for pre- and post-occupation conditions. Source: Moruzzi et al. (2009).

Figure 14 – Flooding photographs in the Servidão Stream main canal after a 20 years rain.

Further, flow accumulation was determined by multiple direction flow using digital terrain model (Quinn et al., 1991). Flood areas were also determined by means of hydrologic model in order to obtain the runnof and the drainage system capacity.

Data of flow accumulation and hydrologic model were overlaid in order to obtain the results presented in Figure 15. In some sectors, the model pointed out that the overflow occurs downstream, in consonance with the flow accumulation study. Also, the reservoir was responsible for minimize the flooding effect in some areas.

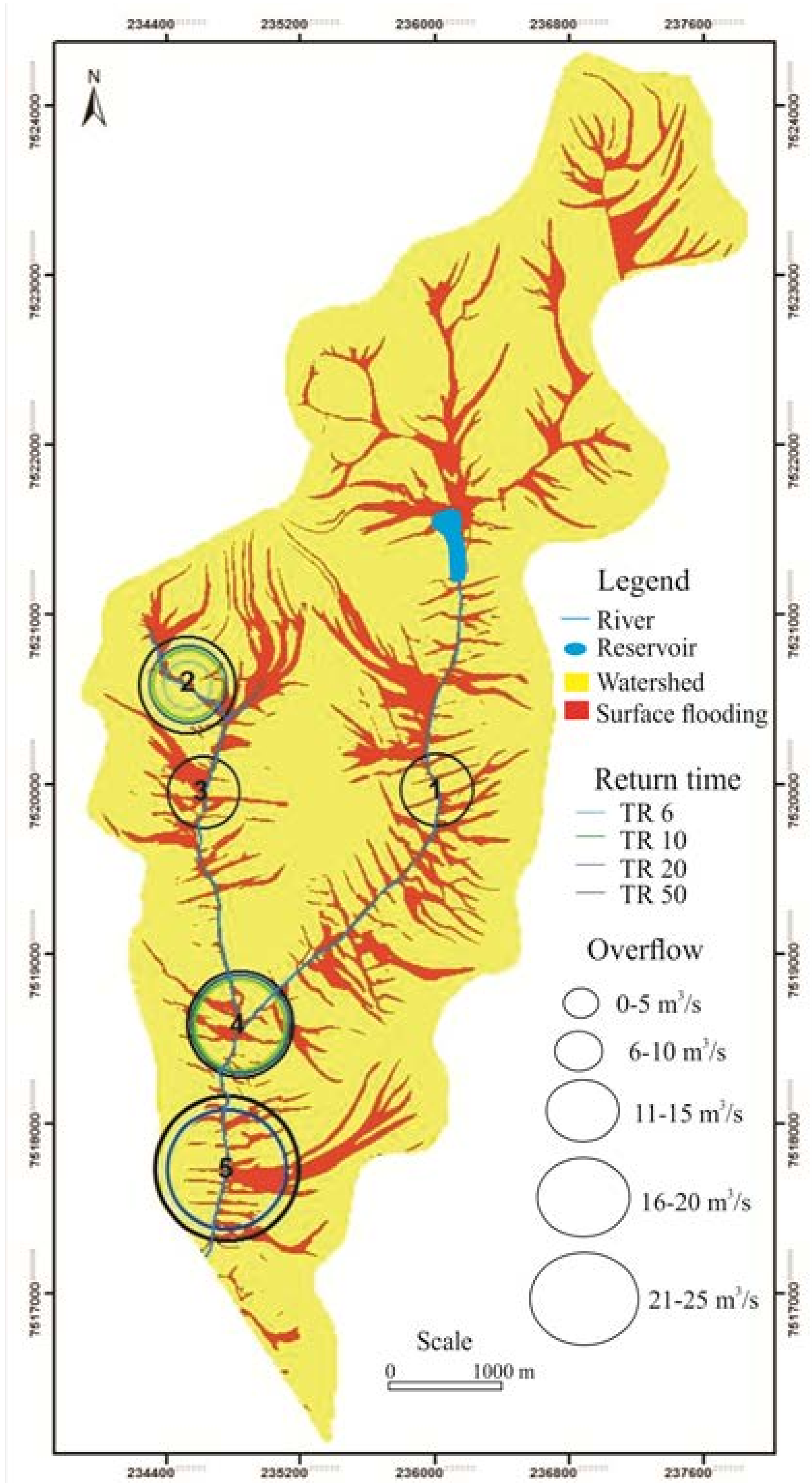


Figura 15. Spatial distribution Overlay of flood regions, according to flow concentration criteria and hydrologic models.

4. CONSIDERAÇÕES FINAIS

The Servidão Stream basin possesses an oblong format that is different from conventional standards. This fact is proven by the circularity index of the watershed, which reaches values of only 0.21 that signifying less probability of concentrated flows of pluvial water. However, the natural characteristics of the Servidão Stream basin are compromised by haphazard occupation.

The plain terrains of the Servidão Stream basin were the first to be occupied by urban construction, resulting in the city of Rio Claro. The principle land uses in this region were urban residential (79%) and industrial (21%). Land use was organised according to a typical arrangement pattern of Portuguese colonisation, known as the chessboard, resulting in a system of square arrangements that follow the direction of the declining topography that increase the velocity of pluvial flows.

Long periods of rain associated with intense and disorderly urban habitation, as well as implementation of disjointed operations from the dynamic hydraulics and hydrology of the watershed are responsible for aggravated flooding problems in the Servidão Stream basin. These problems seem to worsen as the occurrence of rains decline (greater TR values). For this reason, we chose to limit our analysis of excess propagation to TR values less than 20 years.

Therefore, it is evident that urban floods become more common in rainy periods, even for frequent events, and cause great damage to local populations. The solution to the urban flooding problem must be measured not only by enhancing hydraulic capacity of drainage structures, but also by reducing flows in urban lots and public areas. In some cases, removal of the population from high-risk areas should be considered.

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