INFLUENCE OF SEDIMENT TRANSPORT ON FLOW CONDITIONS IN THE VIDOCA RIVER WATERSHED, SÃO JOSÉ DOS CAMPOS-SAO PAULO-BRAZIL

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ABSTRACT – *The aim of this study is to analyze how the transport of sediments interferes with flow conditions in the Vidoca River basin, which has an area of 60.08 km^2 and is located in São José dos Campos,State of São Paulo, Brazil. The urban growth process in the city, an industrialized area, has contributed to an increase in flood frequency. The Vidoca River, an important tributary of the Paraiba do Sul River has been subject to erosion along its sides, with losses of culverts and bridges over the three last decades. Flow and sediment transport data for the watershed did not exist, so it was necessary to acquire them. The hydraulic data were measured during 12 field campaigns, from 2010 to 2013 in two sections. The velocities of flow were measured using either a MLN-07 current meter, or a smaller current meter, the FP101-FP201, and the water levels were measured with staff gauges. Samples of suspended sediments were collected using USDH-48 and USDH-49 samplers. The particle size analysis of solid samples of the background material and the analysis of concentration of total solids were performed in Institute of Aeronautical Technology (ITA) laboratories. The data were obtained through monitoring of liquid flow ($Q_{líq}$), suspended sediment concentration (C_{ss}), precipitation (P), water level (h), topography, and particle size, which were used to obtain the discharge and the relationships for rating curve and sediment yield curve. The results showed that Senhorinha Creek, a tributary located in the upper watershed, presents supercritical flow for Froude numbers ranging from 2.05 to 0.8 in the upper stretches, provoking bank and bottom erosion, thus leading to an increase in the sediment transport. Discharge and water level data were analyzed to establish the rating curve; the discharge varied from 0.50 to 64.52 m^3/s. The sediment yield curve showing liquid discharge flow and solid discharge flow presented a coefficient of determination equal to 0.94*.

Key-words: Urban water, sediment yield, floods

1. INTRODUCTION

An important step in the environmental management of a river basin is to understand the processes related directly or indirectly to the behavior of the water - how, for example, to understand its hydro-sedimentological cycle. Hydro-sedimentological study of a basin is important in verifying whether the production and transport of sediments are within the normal range or are showing variation in time and space, thus it is an indirect way of monitoring conditions of use and occupation of land and thus of climate change as well. Hydro-sedimentological monitoring is indicated in setting guidelines to solve problems and minimize agents having impacts that cause soil erosion and can cause soil sterility, due to inadequate conservation practices. It is fundamental to detect changes that may be occurring in the hydro-sedimentological cycle in order to use the knowledge gained as a basis for making decisions more efficiently.

According to Carvalho (2008) the study and application of sedimentology covers various social areas, such as hydropower generation, navigation, irrigation, soil mechanics, agriculture, road construction, general construction, environment and others; this is why, knowledge of these areas is so important in the planning and development of a country . For guaranteeing continuity of progress and security of life, guidelines must be set in order to control the extent of the problems, so that they do not take on unwanted or even irreversible dimensions . A policy of sustainable development does not slow progress, but creates awareness of its consequences, so that natural resources may be made use of as equitably as possible, taking into consideration the environment and the well-being of future generations. According to Yang (1996), the amount of suspended sediment can be estimated by equations of sediment transport, by calculating its rate of transport or by measurements at flow and sediment measuring stations. Indirect measurement by means of equipment such as instant samplers, by integration or by pumping are also used. According to international criteria, sediment yield can be considered high when greater than 1.75 t / ha year, moderate if it is between 0.70 and 1.75 t/ha year, and low when less than 0.35 t/ha year. These values can be taken as the parameters for comparison studies (Lima et al. 2000).

In the present work, we analyzed the sediment transport in the Vidoca River, for which until now no hydro-sedimentological information was available, due to the lack of the necessary measurements of streamflow and sediment concentrations. Results are presented for the rating curve for sediment transport for the catchment area of the Vidoca River, which is a sub-basin of the the of the Paraíba do Sul River basin. The Vidoca basin is predominantly urban. It was settled in a rather disorganized manner via several points of invasion, and some unsuitable areas were occupied. The study of this basin is important because it is a tributary of the Paraiba do Sul and its mouth is located upstream of major catchments of public water supply.

2. OBJECTIVES

The objectives of this study are to investigate the relationships between: precipitation and liquid discharges, liquid discharges and water levels, liquid discharges and sediment concentrations and liquid and solid discharges for a section of the Vidoca River upstream of its entry into the Paraiba do Sul River

3. METHODOLOGY

3.1 Characterization of the Creek Senhorinha

Senhorinha Creek is the main tributary of the Vidoca River. The physiographic characteristics of the basin are: area, 9 km^2; perimeter, 16 km; axial length, 7.5 km; average slope for the basin, 45m/km, and for the stream,16m/km . According Vendrame, et al., 2000, the basin has undergone an accelerated process of urbanization, and in recent years some new subdivisions were constructed, which, besides making the area impermeable, releases additional garbage into the stream in question, further aggravating the flooding problem. This replacement of areas previously covered with vegetation, with impermeable areas significantly reduces the volume of water infiltration into the soil and the time needed for runoff, thus generating a significant increase in the total volume of water drained in a relatively short time after the onset of rain. Moreover, as a result of erosive processes that have been taking place in the basin, there is a large generation of sediment transport that can be observed a short distance beyond the confluence of the creek with the Vidoca River. This sediment has been the object of successive dredgings. Since the slope of the bed is steep, the flow is torrential over most of its sections, with Froude numbers ranging from 2.05 to 0.80. The drag forces on the bottom and the banks are high, higher than the critical stresses for alluvial soil, causing erosion and sediment transport.

As a result, during the period 2000-2010, the bed of Senhorinha Creek was modified by the Municipality of São José dos Campos, by the installation of small retention basins along its route to reduce flooding problems and minimize deposition of sediments and silting beyond its confluence with the Vidoca River. Figure 1a shows the existing bridge on Guadalupe Street and repair work on the side slopes and stream detention basin located downstream from the bridge, on 5 March 2011. Figure 1b shows the same section shortly after the occurrence of heavy rain, on 23 March 2013, which resulted in damage to the structure of the bridge and caused a return to the bed's original features, destroying the existing detention basin at that site and leading to the fall of the bridge. Damage to this bridge because of the occurrence of heavy rains has been recurrent since March 10, 1999, the day that a rainfall of 102.7 mm occurred, causing damage estimated at 1.5 million reals in the Senhorinha basin, due the burning of power transformers, damaging of phone lines, rupturing of water mains, and the washing away of bridges and culverts.

Figure 1.a - View of detention basin on Guadalupe Street, showing Senhorinha Creek, 05/03/2011.
Figure 1.b - Bridge on Guadalupe Street with damaged Senhorinha Creek showing the return of the stream channel to its original form, 23 Mar, 2013.

3.2 Description of the Vidoca River

The Vidoca River has an area of approximately 60.08 km^2 located mostly in the southern part of São José dos Campos, state of São Paulo. Its headwaters lie at an altitude of 730 meters, in the Atlantic plateau region, near the border between the municipalities of Jacarei and São José dos Campos (Cunha, Alessandra M., 2012).

The Vidoca River basin is predominantly urban. It was settled in a rather disorganized manner via several points of invasion, and some unsuitable areas were occupied. It exhibits a high rate of environmental degradation, which further accentuates the frequency of flooding, silting and erosion on the banks of rivers and streams. The study of this basin is important because it is a tributary of the Paraiba do Sul and its mouth is located upstream of major catchments of public water supply.

3.3 Data Acquisition

The sediments in hydrographic basins can be set in motion or have their movements altered by the action of natural forces or by human actions. The natural causes can include the action of rain, liquid currents, winds, waves, swell and tides in estuaries and seas. Anthropogenic actions may occur in the riverbed and the basin and add to the effects of natural events. The actions may include mining and agricultural activity, sports and tourism activities, construction of dams and other hydraulic structures, deforestation, dredging operations, introduction of domestic and industrial wastes, etc.

The hydraulic variables were recorded during twelve campaigns of field measurements. They considered rainy and dry periods occurring between November 2010 and April 2013. Following the recommendations of Carvalho (2008) for measurements of selected variables and collection of samples, three sections were chosen for monitoring: P1 – Senhorinha Creek; P2 – Vidoca River/Colinas; and P3 - Vidoca River/ EEE (Figure 2). The sections were located in straight stretches with well-defined banks and were free of the effect of curves, to avoid perturbations in the flow.

Staff gauges were installed in the three sections to be measured (P1, P2, and P3), to obtain the water level h. Knowing the water level and having at hand the rating curve for the liquid discharge rates ($Q_{Líq}$), it was possible to estimate the discharge rates for different water levels. Knowing the liquid discharge and using the rating curve for the solid discharge rates (Q_{ss}), which are correlated (Q_{ss} vs. $Q_{Líq}$), we can estimate the amount of sediment outflow for the basin.

To measure the velocities of the river waters, the MLN-7 was used windlass accompanied by a digital pulse counter, and a micro-reel FP101-FP201. When the level and speed did not allow the measurement of velocity at the ford, or when it was not recommended to use the MLN-7 windlass from bridges, we used the technique of measurement by floats (Lobo, 2002) was applied. In these cases the collection of liquid samples was taken from the bridges.

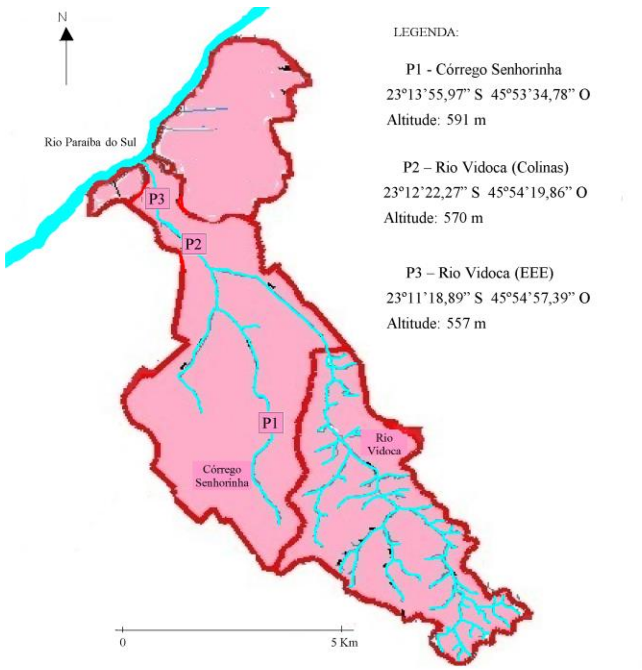

Figure 2 – Basin of the Vidoca River showing the location of the three monitoring sections (SÃO JOSÉ DOS CAMPOS - DVD Cidade Viva, 2011), adapted by the authors.

The collection of liquid samples from the river was done with DH-48 samplers (depths up to 1.5 m and velocities up to 2.75 m/s) and DH-49 samplers (depths up to 6.0 m and speeds of 2.75 m/s). The choice of the most appropriate equipment was determined according to the velocity and the water level at the time of collection. Water samples were sent to the laboratory of the Chemistry Department of ITA for analysis of the concentrations of suspended sediment. To collect the material from the bottom, a bottom sampler of the Petersen type was used. The solid flow calculation was performed using the Colby equation,

$$Q_{ss} = \sum C_{ss} \, Q_{Liq} \quad [1]$$

where Q_{ss} is the discharge rate of solids in suspension (kg s^{-1}), C_{ss} is the concentration of suspended solid sediments (kg m^{-3}) and $Q_{Líq}$ is the flow ($m^3 s^{-1}$). The rainfall data were extracted from the FUNCATE site (2012), which has operated since 1982 in the region. From among the stations that monitor the region of São José dos Campos, data from the meteorological stations of INPE and UNIVAP were used. The organization of data and preparation of the graphics were done with the aid of Excel® 2010 and AutoCaD ® 2012 software.

4. RESULTS

4.1 **Characterization of Section P2**

In section P2 it was possible to perform a greater number of measurements, due to its ease of access, so its results are the ones analyzed in the present paper. The section is located 42 meters from the existing bridge at the intersection of Avenues Jorge Zarur and São João, next to Shopping Colinas in São José dos Campos and 50m from the mouth of its main tributary, Senhorinha Creek. As can be seen in Figures 3.a and 3.b, the banks consist of retaining walls in poor condition, a,rectangular section to a height of 2 m, where there begins a slope with a gradient of 1:2.20 m, covered with grass. The vegetation in the summer consists of tall grass. The stretch upstream of the P2 section is straight . The staff gauge consists of three units with the maximum height at 2.70 m. In Figure 3.a it can be seen that the material at the bottom is quite sandy, but becomes compacted clay and organic clay near the center of the river, and there are also stones fallen from retaining walls in disrepair. The stretch located immediately downstream of the measurement section forms small sandy dunes along the bottom . Figure 3b shows the surroundings of the Vidoca River along section P2, on the left bank of the river. The surroundings are very urbanized, and the slope of the streets toward the river is quite pronounced.

Figure 3.a - Banks and bottom of the Vidoca River at point P2.(10 September, 2011). Figure 3.b - Vidoca River at in section P2, showing urbanized area.(Cunha, Alessandra M.,2012).

4.2 Obtaining the Rating Curve Relationship

The Discharge rates were obtained applying Equation 2:

$$Q= \sum q_i \quad [2]$$

Where: qi are the flows in each catchment area A_i in which the wet section was discretized. Figure 4 shows the variation of the flows with the levels observed on the gauge. Equation 3 was fitted to the pairs h,Q with a coefficient of determination equal to 0.95.

$$Q=15.80\ (h – 0.40)^{1.298} \quad [3]$$

Where: Q is the liquid discharge in m^3s^{-1} and h is the water level in m.

4.3 **Relationship Between Liquid Discharge and Suspended Sediment Concentration**

The relationship between liquid discharge and suspended sediment concentration is presented in figure 5. Equation 4 was fitted to the observed data at section P2 located in the Vidoca River, showing a linear fit for C_{ss} vs. $Q_{Líq}$ for those points. The point showing the largest sediment concentration, 2236.5 mg L^{-1}, was disregarded in this analysis since it was considered an outlier. A linear equation represented the best relation between liquid discharge and suspended sediment concentration and gave a coefficient of determination equal to 0.67.

$$C_{ss} = 0.144\ Q_{Liq} - 5.753 \qquad [4]$$

here C_{ss} is the suspended sediment concentration in mg L^{-1} and Q_{Liq} is the liquid discharge in $m^3\ s^{-1}$.

The suspended sediment concentration, however, tends to reach a saturation value indicating that this linear relationship has an upper limit. From Figure 5, it can be seen that the four highest suspended sediment concentrations occurred in the months of January and March of 2013 because the monthly total precipitation for March of 2013 was higher than the average precipitation over the previous nine years, as shown in Figure 6.

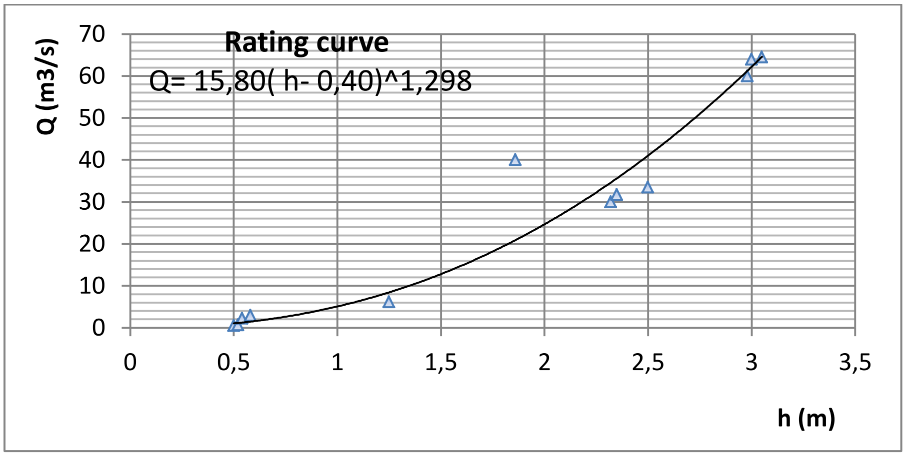

Figure 4 - Observed values of water level (h) and liquid discharge (Q_{Liq}) , for section P2, in the Vidoca River, São José dos Campos, São Paulo, Brazil, from Nov/2010 to Mar/2013.

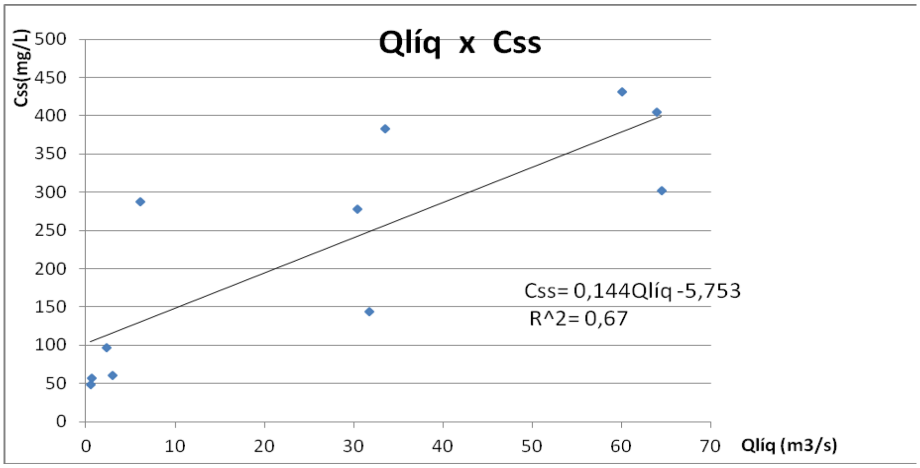

Figure 5 - Relation between observed values of liquid discharge (Q_{Liq}) and suspended sediment concentration C_{ss} for section P2, in the Vidoca River, São José dos Campos, São Paulo, Brazil,from Nov, 2010 to Mar,2013.

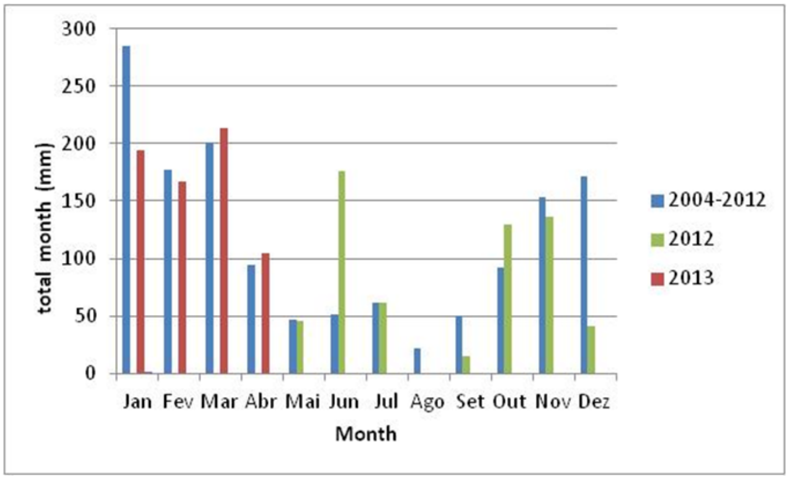

Figure 6 - Mean monthly precipitation(mm) for the period 2004-20012 and precipitation registered for the months of May to December of 2012 and January to April of 2013, at the meteorological station at INPE, São José dos Campos-SP, Brazil.

4.4 Relationship Between Liquid Discharge Flow and Solid Discharge Flow

The sediment yield curve was obtained, relating liquid discharge (Q_{Liq}) to solid discharge (Q_{ss}) data as shown in Figure 7. The best sediment yield curve fitted to the data collected in section P2 in the Vidoca River is an exponential equation (Equation 5) for which the coefficient of determination was equal to 0.94.

$$Q_{ss} = 29.99\,(Q_{Liq})^{\mathbf{0.629}} \qquad [5]$$

Where: Q_{ss} is the solid discharge in t day^{-1} and $Q_{Líq}$ is the liquid discharge in $m^3\,s^{-1}$.

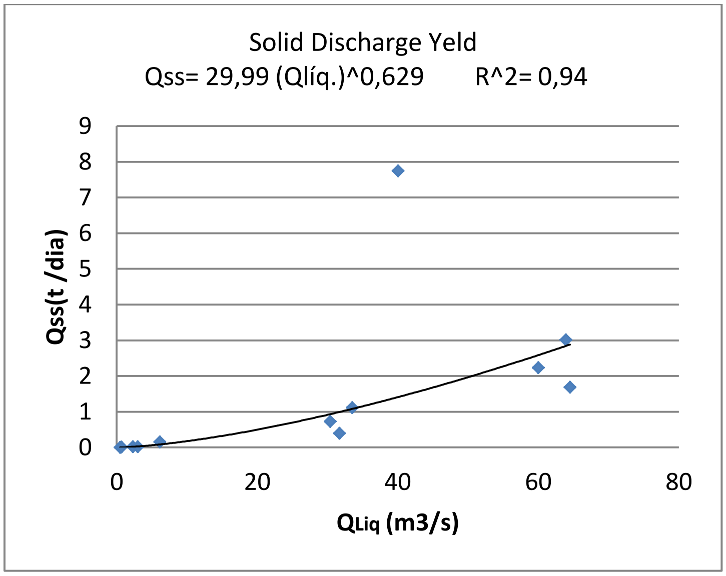

Figure 7 -Yield sediment curve (Q_{SS} vs. Q_{Liq}) at section P2, in the Vidoca River, São José dos Campos, São Sediment Paulo-SP, Brazil, from Nov,2010 to Mar,2013.

5. DISCUSSION OF RESULTS AND CONCLUSIONS

The sandy soil found in the watershed is naturally vulnerable to sediment transport. The bathymetry performed to obtain speed measurements considered water level values below and above the height of the berm, at which the cross section becomes a compound trapezoidal section. The fitted rating curve relationship can be used in future hydrological researches to transform water level into flow rates. The rating curve must be checked periodically to ensure that the relationship between the discharge and gauge height will remain constant, since scouring of the stream and river bed or deposition of sediment can cause the rating curve to change so that the same recorded gauge height may produce a different discharge**.** Nevertheless it is important to continue measurements to consider discharges in the range 10 to 29 $m^3 s^{-1}$ and in the range 41 to 50 $m^3 s^{-1}$ so as to add more reliability to Equation 3 and to improve fluvial sediment monitoring in the city of São José dos Campos. The creek and the river show many points having severe erosion on the sides and bottom of the banks, mainly in urbanized areas without vegetation. Along many stretches of the creek and the river, the protection offered by the riverbank forest has been lost, with buildings constructed in its place. The large sediment load of Senhorinha Creek produced due to its high tractive forces was deposited along years between the channel sides and the Guadalupe bridge pillars, thus decreasinsing the flow cross section and making the waters surpass the bridge and flood the area. The large sediment load of Senhorinha Creek produced is deposited at its outflow point into the Vidoca River near section P2. The largest solid flow reaching 7.74 t day^{-1} was registered on 11/11/2011 as a result of earth-moving work close to the river bed. The other three largest registered solid flows occurred in March 2013, which was the month showing rainfall greater than the March mean over the previous nine years. The sediment yield curve presented a coefficient of determination equal to 0.94 for section P2 and may be used to estimate the solid flow associated with a given liquid discharge flow.

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