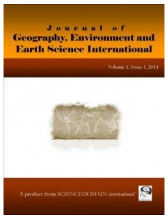

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Assessment of Fluvial Sediments at Serra Azul Stream, Minas Gerais– Brazil

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Authors' contributions

This work was carried out in collaboration between all authors. Author VVMF is the coordinator of the research project. Authors ALO, NMGO and RLMF were responsible for the data treatment and managed the literature searches. Author LMALA was responsible for the chemical analysis and author ROA was responsible for the mineralogical analysis. Author CACF managed the comparison with global values and the statistical analysis. All authors read and approved the final manuscript.

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ABSTRACT

Aims: The goal of this study is to perform the characterization of bottom and in suspension sediments at Serra Azul stream. Chemical, mineralogical and grain size aspects were evaluated, as also the legal issues pertinent to this matter.
Study Design: Hydrosedimentological studies at Juatuba basin.
Place and Duration of Study: Juatuba basin – southeast part of Brazil, between December 2013 and October 2014.

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Methodology: The bottom and in suspension sediments of Serra Azul stream were characterized through different techniques: x-ray diffraction, x-ray fluorescence and grain size analysis (using sieves and laser techniques). The environmental legislation was checked in order to see the values of the allowed concentrations of some heavy metals in the waters. Also, the data of a small hydrometric network were treated in order to obtain the natural flows of the water courses.
Results: Two elements found in the sediments in suspension were not found in bottom sediments: Chlorine and Bromine. Gallium, Lead, Barium and Nickel were not found in the bottom sediments samples in 2013, only in 2014. The concentration values of Chrome, Potassium, Sodium and Silicon became smaller in 2014, however for the other elements that were found, these values became bigger. The bottom sediments collected in the study area present values higher than the threshold above which a probable adverse effect on the biota is expected for Chrome and Nickel, in order of importance. When the global values of the dissolved constituents in surface waters were compared to the ones found at Juatuba basin, it was possible to verify that only for Iron and Aluminum the 2014 found values were bigger than the average elemental composition, according to a variety of sources and authors.
Conclusion: The transport of sediments in the studied area showed that some heavy metals are being transported towards the Serra Azul reservoir in concentrations higher than the allowed ones. Due to a long dry season in the study area, this transport is currently minimized, however the next rain station can generate a serious scenario. It is necessary to implement a permanent program in order to collect and analyze these sediments, inclusive in other parts of the basin. It is also necessary to solve the question concerning to the absence of a legislation for several other chemical elements found in the sediments.

Keywords: Bottom sediments; sediments in suspension; hydrographic basin; environmental legislation.

1. INTRODUCTION

For the last years, many hydrosedimentological studies have been developed at Juatuba representative basin, located 60 km far from the capital of Minas Gerais State – southeast of Brazil, by the hydro resources team of the CDTN – Development Center of Nuclear Technology, an institution from the Ministry of Science, Technology and Innovation. In the last 20 years, the main projects developed at the site were:

- "Application of the technique of tracers to the study of flood hydrographs at Juatuba representative basin" [1,2];
- "Determination of the infiltration and evapotranspiration rates at Juatuba representative basin using artificial tritium" [3,4,5];
- "Study of the formation of the flows using natural tracers at Juatuba basin" [6,7,8];
- "Nucleus of experimental studies in hydrographical basins" [9].

Nowadays, two projects are under execution at Juatuba basin, the first one aims to find sections of water discharge with the help of natural and fluorescent tracers. The goals of the second one are the characterization of the sediments of the Serra Azul stream and the study of the influence of dead zones in the dynamic of sediments using fluorescent and radioactive tracers. It is valid to mention that a major part of these projects were executed in a partnership with the department of hydraulic engineering and hydro resources of the Federal University of Minas Gerais.

The objectives of this work, in the scope of a project under execution, are to characterize the composition of bottom and suspended sediments in Serra Azul stream. The determination of the composition of sediments will be performed by particle size, chemical and mineralogical analysis. Through the implantation of a sedimentometric station in the study area, the concentration of the suspended sediments during a flow event will be obtained. The concentration of the sediments will be compared to the national legislation, aiming to verify if the found values answer the legal parameters established for this kind of scenario.

It is valid to observe that the transport of sediments in watercourses is a key parameter in the management of a river basin. About 90% of this transport occurs in the form of suspended sediments within the liquid mass. The fine sediment (Φ<0.063 mm) basically moves up in suspension and is an important vector in the transport of metals and other pollutants, as well as organic matter in water environment due to the preferential adsorption of these elements to the fine sediment.

2. MATERIALS AND METHODS

2.1 Study Area Characteristics

The Juatuba basin (Fig. 1) is located in the upper part of the São Francisco river, in Minas Gerais State. The Juatuba river is a left tributary of the Paraopeba river, which is a tributary of the São Francisco, and runs 3 km from the meeting of its main tributaries to the point where it flows into the Paraopeba. This watershed covers 442 square kilometers and is located 60 km from Belo Horizonte (capital of the State), covering part of the cities of Mateus Leme, Igarapé and Itaúna. The main streams that form the Juatuba river are the Serra Azul and Mateus Leme streams, which have a drainage area of 265 and 155 square kilometers respectively.

Downstream the Serra Azul stream there is an important reservoir that supplies water for Belo Horizonte and other close cities. The Serra Azul reservoir covers parts of four cities: Mateus Leme, Juatuba, Igarapé and Itaúna. It is located about 55 km far from Belo Horizonte, and its operation started in 1982. Today, the system serves with treated water, about 10% of Belo Horizonte needs, being the third biggest one of the region. It forms, together with the Rio Manso and Vargem das Flores systems, the integrated system of Paraopeba river basin. It is valid to emphasize that currently this reservoir faces a serious situation since the total absence of rains in the southeast of Brazil in the last months generated the worst hydrological crises in the history of the region.

2.2 Sampling of Sediments

As an initial step of this stage, an array of samplers for progressive sampling during a rising stage was constructed. This device was installed in a stretch of the Serra Azul stream at the coordinates N 7,783,184.417 and E 561.850,990 (Fig. 2). The wooden beam had 1.20 meters long and 5 cm thick. As described by [10] this sampler was built based on the "Single Stage Sampler" (Fig. 3), presented by the U.S Geological Survey [11]. The single-stage sampler US-U-59 is not very used in Brazil, despite its simplicity. The same consists of a bottle with siphon tubes, one for sample inlet and other one for the air outlet. These samplers are used in floods that happen very quickly and intermittent watercourses, especially in remote areas – or where the access is very difficult.

The sampler is installed in a predetermined level, on a vertical support, which can be a bridge pillar or a wooden beam, preferably at the center of the watercourse, or close to it. The openings of the tubes must be positioned against the current. One or more samplers can be mounted, one above the other, in a same vertical, to collect sediments at several selected levels [12,13].

The design of the siphon pipe and the positioning of the air outlet nozzles in a direction countercurrent, 3 cm above the sample inlet siphon, is adopted in order to prevent recirculation of the mixture water/sediment, through the bottle, when the equipment is submerged. Thus, if the sampler is not

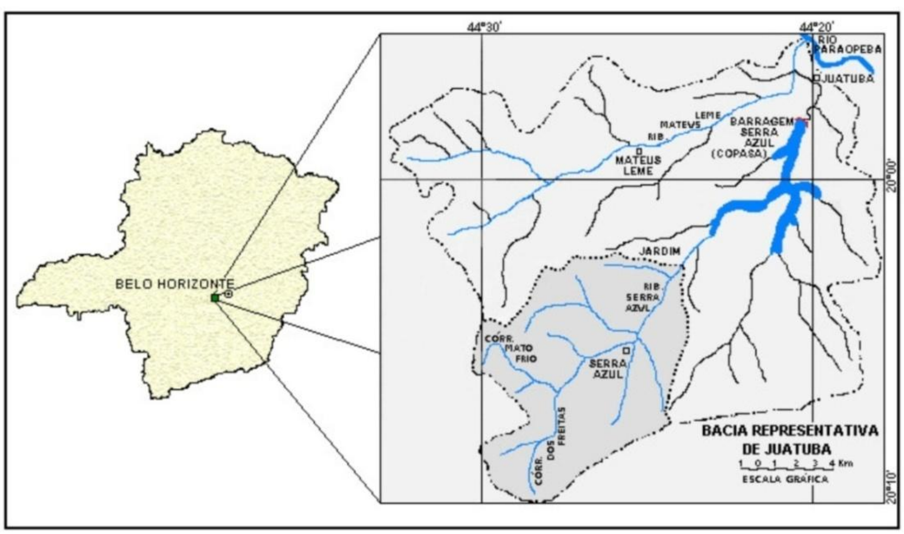


Fig. 1. Location of the Juatuba basin in Minas Gerais State, Brazil

Fig. 2. Location of the section under study-Serra Azul stream

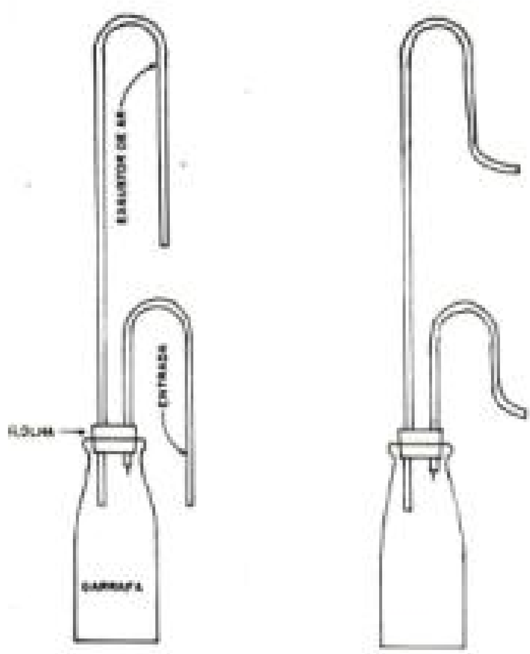


Fig. 3. Single stage sampler US-U-59 [14]

completely filled, there will be no reflux of the material inside the bottle, which would cause a change of it. These samplers were mounted in a vertical position, one above the other, in spacing of about 20 cm between two consecutive water inlets, supported by a wooden beam. This beam was installed in the point where the bottom and suspended sediments were collected, consisting of four samplers with glass bottles of 500 ml capacity.

According to [15], field experiments suggest that the concentration obtained with this type of sampler may not always be representative of the concentration of the watercourse, being necessary to adopt some precautions when using this equipment to obtain the data associated to the concentration of the sediment. However, this sampler has certain disadvantages such as:

- The sample is always taken at the water surface while the water level rises;
- The original sample can be changed by subsequent submersion;
- The speed of water in the inlet of the sampler nozzle is not always consistent with the speed of the stream.

Furthermore, after a heavy rain period (December/2013), besides collecting the bottles of the sampler, the sediments in suspension were collected with the help of buckets, until a 200 liter plastic drum could be filled. A “rock island” collector was also used at the opportunity to get bottom sediments. It is necessary to emphasize here that this was the last rainy period in the study area, and due to this reason the array of samplers did not collect any sediments since then. Thus, the amount of sediments currently in suspension in the watercourse is very low, what made their evaluation during the last year (2014) not feasible.

2.3 Analyses of Sediments

For bottom sediments, due to its bigger size, the grain size analysis was done with the help of sieves. However, since the suspended sediments have a smaller size, it was not possible to analyze them using only sieves. For the major part of the suspended sediments, its particle size distribution was obtained after employing a laser diffraction technique (equipment Cilas 1064L). For all samples, an x-ray diffraction and an x-ray fluorescence was done in order to obtain more information about the composition of the sediments. The equipments used for these analyses were the Rigaku x-ray diffractometer and the ZSX Primus II.

3. RESULTS AND DISCUSSION

3.1 Sediments in Suspension

Tables 1 to 4 and Fig. 4 show the results of the evaluations done in the study area related to sediments in suspension collected in December 2013. Table 1 shows the results of the analysis done to obtain the concentration of the sediments (collected in the array of samplers for progressive sampling). Table 2 presents the values of the final dry mass of the sample after its filtration and sieving process Table 3 shows the results of the laser grain analysis for the suspended sediments. Table 4 shows the results of the x-ray fluorescence, and Fig. 4 for the x-ray diffraction.

A chemical analysis was done for the elements that presented the biggest concentrations in the analyzed sediments. For aluminum and silicon the method used was gravimetry, for iron – titration, and for potassium – flame photometry. Table 5 shows the results.

3.2 Bottom Sediments

Tables 6 and 7, and Fig. 5 show the results related to analysis done in the bottom sediments. It is worth noting that the two elements found in sediments in suspension were not found in bottom sediments: Cl and Br. Also, Ga, Pb, Ba and Ni were not found in the bottom sediments samples in 2013, only in 2014. The concentration values of Cr, K, Na and Si became smaller in 2014, however for the other 14 elements of the table, these values became bigger.

The results of the grain size analysis and x-ray diffraction did not show significant differences from 2013 to 2014.

Table 1. Results of the total solids and volume of the array of samplers

Sample code	Total solids - mg/liter	Mixture volume –ml
1	247±7	440
2	539±14	415
3	528±18	455
4	623±7	430

Table 2. Final mass of the sample

Grain size of the sample and method	Mass (grams)
-400 (passing through the sieve - vacuum filtration)	3.013
+400 (retained in the sieve and then dried)	12.271

Table 3. Results of the laser grain analysis – sediments in suspension

Analysis	Concentration (grams)	Mean diameter (μm)
Sample 1	166.0	10.20
Sample 2	232.0	11.50
Sample 3	239.0	10.53
Mean	212.3	10.74

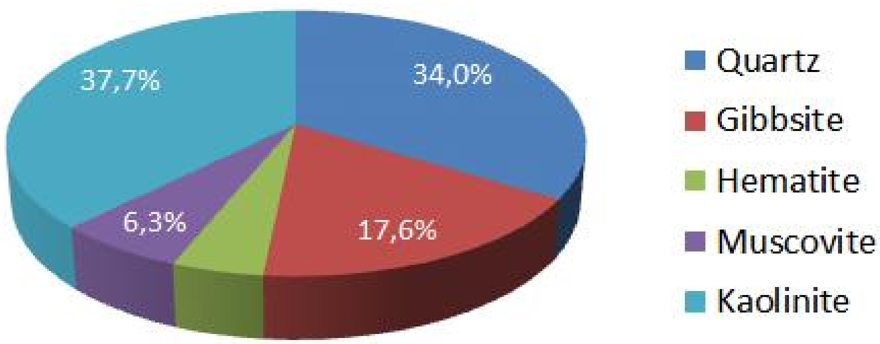


Fig. 4. X ray diffraction results

Table 4. Results of the x-ray fluorescence–sediments in suspension

Number	Chemical compound	Result (mass in %)	Detection limit
1	Na_2O	0.0724	0.0226
2	MgO	0.592	0.0185
3	Al_2O_3	38.0	0.0210
4	SiO_2	41.5	0.0210
5	P_2O_5	0.349	0.0034
6	SO_3	0.123	0.0027
7	Cl	0.0231	0.0038
8	K_2O	1.94	0.0035
9	CaO	0.403	0.0028
10	TiO_2	1.20	0.0084
11	Cr_2O_3	0.0667	0.0048
12	MnO	0.192	0.0036
13	Fe_2O_3	15.3	0.0059
14	NiO	0.0203	0.0023
15	CuO	0.0129	0.0020
16	ZnO	0.0371	0.0017
17	Ga_2O_3	0.0071	0.0019
18	Br	0.0025	0.0011
19	Rb_2O	0.0418	0.0066
20	SrO	0.0074	0.0012
21	ZrO_2	0.00397	0.0089
22	Nb_2O_3	0.0049	0.0015
23	BaO	0.0876	0.0212
24	PbO	0.0132	0.0033

Table 5. Analysis of Al, Si, Fe and K in a sediment sample

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	K (mg/Kg)*
34.45 ± 0.29	31.97±0.24	13.14±0.21	11±1

** - Detection limit (mg/kg) = 0.03*

Table 6. Grain size analysis–bottom sediments (2013)

Tyler (#)	Opening (mm)	Retained weight (g)	wt %	% accumulated above	% accumulated below
16	1	3.25	1.45	1.45	98.55
20	0.81	2.8	1.25	2.7	97.3
28	0.59	10.31	4.61	7.31	92.69
35	0.42	44.15	19.75	27.06	72.94
48	0.297	70.85	31.7	58.76	41.24
65	0.21	52.7	23.6	82.36	17.64
100	0.149	23.6	10.5	92.86	7.14
150	0.105	8.55	3.82	96.68	3.32
200	0.074	3.11	1.39	98.07	1.93
270	0.053	2.28	1.02	99.09	0.91
325	0.044	0.62	0.28	99.37	0.63
400	0.037	0.15	0.07	99.44	0.56
Below 400	-	1.124	0.51	99.95	0.05

Table 7. Results of the x-ray fluorescence–bottom sediments

Number	Chemical compound	Result (mass in %) December 2013	Result (mass in %) December 2014	Detection limit
1	Na_2O	0.194	0.12	0.0142
2	MgO	0.0884	0.62	0.0120
3	Al_2O_3	7.21	34.3	0.0096
4	SiO_2	87.2	43.9	0.0255
5	P_2O_5	0.0638	0.30	0.0032
6	SO_3	0.0215	0.12	0.0031
7	K_2O	2.48	2.2	0.0037
8	CaO	0.0690	0.45	0.0025
9	TiO_2	0.198	1.5	0.0074
10	Cr_2O_3	0.0826	0.062	0.0040
11	MnO	0.0642	0.28	0.0033
12	Fe_2O_3	2.32	15.9	0.0033
13	NiO	0.0074	0.016	0.0019
14	CuO	0.0047	0.017	0.0016
15	ZnO	0.0042	0.027	0.0013
16	Rb_2O	0.0063	0.011	0.0010
17	SrO	0.0028	0.0055	0.0011
18	ZrO_2	0.0131	0.037	0.0012
19	Ga_2O_3	-	0.0054	0.0019
20	PbO	-	0.0091	0.0033
21	BaO	-	0.074	0.0212
22	Nb_2O_5	-	0.0022	0.0015

3.3 Water Level

Fig. 6 shows the water level at Serra Azul stream, at the point where the sedimentometric station was installed. It is possible to see that the water level did not show much variation, due to the absence of rains, from May/2013 to October/2014. There are 4 rain stations installed at the study area. The obtained data show that except for December/2013, where during a few days the four pluviometric stations installed at the basin registered a brief rainy period, the Juatuba basin was marked by a long dry season, what took the Serra Azul reservoir to its minimum operational capacity since its inauguration [16].

3.4 Legal Values

The obtained results were compared to the values exposed in the Resolution 454/2012 of the Environment National Council (CONAMA), which establishes the general guidelines and the minimum procedures for evaluating the material to be dredged in Brazilian waters [17]. Since in Brazil there is no specific legislation for the concentration of sediments in fluvial waters, this Resolution has been used to analyze several scenarios [18,19], including some similar to the studied one for bottom sediments [20,21].

Chemical characterization, according to CONAMA, shall determine the concentrations of pollutants in the sediments (heavy metals, total organic carbon and nutrients). Regarding to the current study, and considering that CONAMA has reference values for 8 elements (Cd, Cr, Cu, Ni, Zn, Pb, Hg and As), Table 8 shows that the bottom sediments collected in the study area present values higher than Level 2 (threshold above which a probable adverse effect on the biota is expected) for the elements Cr and Ni, in order of importance.

Considering the Level 1 (threshold below which a low probability of adverse effects to biota is expected), the value found for Cu was slightly greater than CONAMA value in 2013, but much higher in 2014. The sample shows, for Zn, levels smaller than Level 1 in 2013, but much bigger in 2014. For Pb, the value is also bigger than Level 1 in 2014. It is valid to observe that CONAMA reference values are presented in the last two lines of Table 8. The other elements (Cd, Hg and As) were not present at the sample.

Further investigations are under execution in other parts of the basin in order to verify the concentration of these metals. The goal is to investigate if the high values of Cr and Ni can be considered a natural characteristic of the region, otherwise it will be necessary to find out which are the possible causes of these high values, as also to inform the pertinent environmental authorities. It is valid to observe that according to [22], the main sources of Cr are metallurgical and chemical industries, tanneries and plating vehicles. The presence of Ni is commonly associated to metal casting, mining activities, fossil fuels and asphaltenes.

3.5 Comparison with Global Values

Table 9 presents the value of dissolved constituents in surface waters [23] compared to the ones found at Juatuba basin. It was possible to verify that only for Fe and Al the 2014 found values were bigger than the average elemental composition of dissolved and suspended matter in surface water, according to a variety of sources and various authors. For S, Nb and Zr, also found at Juatuba basin, these average global values are not available.

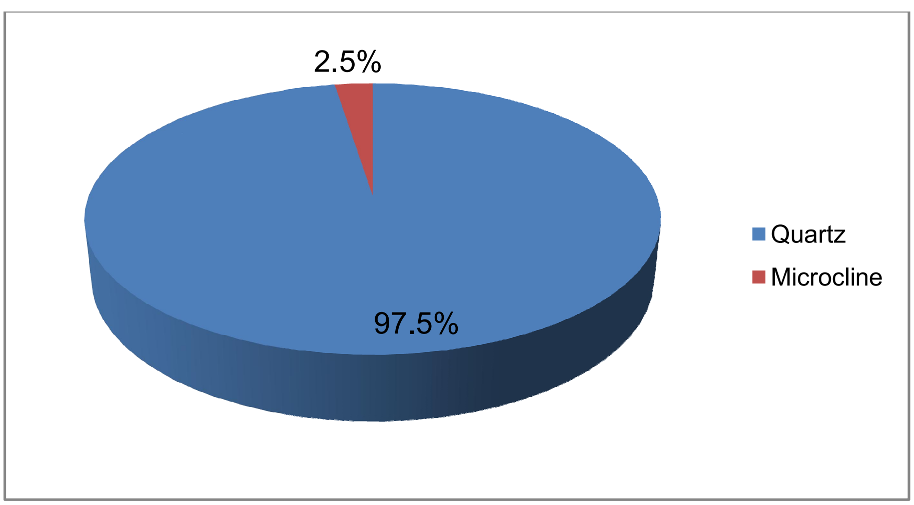


Fig. 5. Results of the x-ray diffraction–bottom sediments (2013)

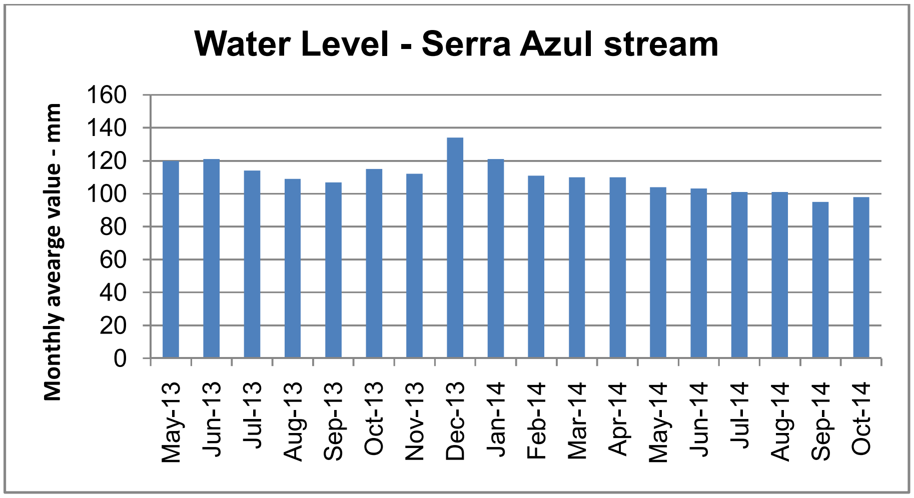


Fig. 6. Water level at Serra Azul stream–monthly average value

Table 8. Concentration of heavy metals (bottom sediments)

Chemical element	Cd mg/kg	Cr mg/kg	Cu mg/kg	Ni mg/kg	Zn mg/kg	Pb mg/kg	Hg mg/kg	As mg/kg
Concentration found in the sample (2013)	-	565.15	37.55	58.14	33.72	-	-	-
Concentration found in the sample (2014)	-	424.20	135.81	125.73	216.92	84.47	-	-
CONAMA 454/2012 Level 1 threshold (fresh water)	0.60	37.3	35.7	18	123	35	0.17	5.9
CONAMA 454/2012 Level 2 threshold (fresh water)	3.50	90	197	35.9	315	91.3	0.486	17.1

3.6 Data Analysis

Fig. 7 shows the relation between bottom and in suspension sediments. It is possible to verify that the concentration of 14 of the 18 chemical compounds that appear in both sediments are bigger in the suspended ones.

The software ORIGIN was used to analyze the data pertinent to concentration of bottom sediments at the actual stage of the project. The results can be seen in Fig. 8 (log scale).

3.7 Hydrometric Network

Besides the sedimentological studies, a hydro monitoring at the Juatuba basin was done. In a previous project, the area upstream the place where the sediments were collected, was divided in six sub-basins whose drainage areas range from 0.8 to 2.3 km^2. In each sub-basin, a fluviometric station was installed in order to obtain the natural flows of the water courses. In the stations there is a weir where a stream gauge records continuous values of water level and temperature. It is valid to observe that the station number 7 is located at the outlet of the basin, where the flows correspond to the total values of the sub basins.

The location of the stations in each sub-basin was chosen considering, among other factors, the proximity of the outlet of the sub-basin, an easy access and the configuration of the cross section of the stream in order to facilitate the construction of the weirs [7]. Once a month, the data are downloaded, and after a math treatment, the water level (recorded every 10 minutes) is transformed in daily values of flows for each one of the stations. It is valid to observe that new gauges were installed at the basin in April 2014.

The water level is converted into flow, at stations 2, 4 and 5, applying the Francis formula (flow through a supressed rectangular weir - equation 1):

$$Q = 1.83 * L * H^{1,5} \quad (1)$$

where Q = flow in m^3 / second;
L = width of the weir (in meters);
H = water level above the crest of the weir (in meters). At station 1 the weir has two lateral contractions and the flow can be obtained by equation 2:

$$Q = 1.83 * (L - 0.2H) * H^{1.5} \quad (2)$$

At station 3 the flows are obtained with the help of equation 3 (triangular weir):

$$Q = 1.4 * H^{2.5} \quad (3)$$

At station 7 there is no weir, and the measurement of the liquid discharges is done through the equation of the local key curve (equation 4). It is valid to emphasize that since 1976 there are monthly measurements at this point.

$$Q = 2.42 * (H – 0,03)^{2.43149} \quad (4)$$

At station 6 there is a Parshall flume, but due to some technical questions, this device is not operational – due to the long dry season there is almost no water at this point. Table 10 presents some data related to this hydro monitoring network.

Figs. 9 to 11 shows the results of the natural flows. The gauge installed at station 1 presented some missing data, and mathematical tools - least squares method and correlation analyzes, will be used to fill the gaps.

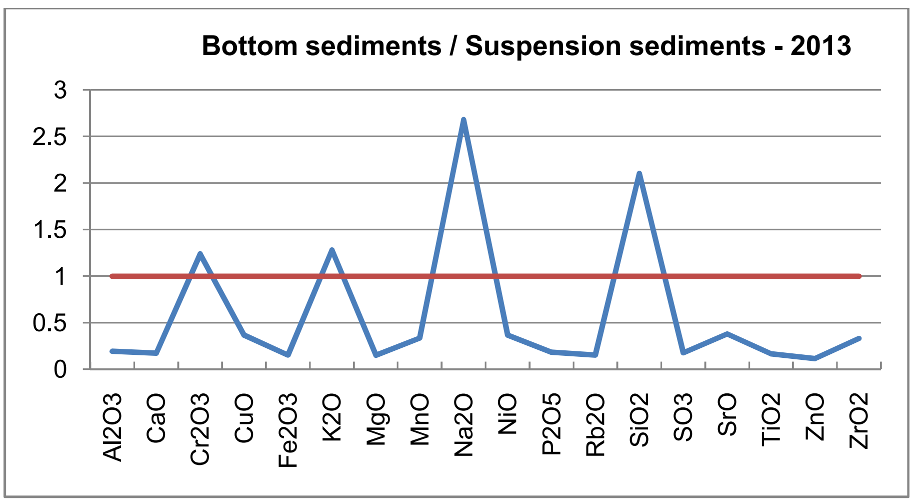


Fig. 7. Relation between bottom and in suspension sediments

Table 9. Comparison between the obtained and global values

Element	Concentration – µg/l		Growth rate 2014/2013	Average elemental composition* - µg/l
	2013	2014		
Al	38.16	181.55	4.76	50
Ca	0.49	3.22	6.52	13,300
Cr	0.57	0.42	0.75	1
Cu	0.04	0.14	3.62	1.5
Fe	16.23	111.20	6.85	40
K	20.59	18.26	0.89	1,500
Mg	0.53	3.74	7.01	3,100
Mn	0.50	2.17	4.36	8.2

Element	Concentration – µg/l		Growth rate 2014/2013	Average elemental composition* - µg/l
	2013	2014		
Na	1.44	0.89	0.62	5,300
Ni	0.06	0.13	2.16	0.5
P	0.28	1.31	4.70	115
Rb	0.06	0.10	1.75	1.5
Si	407.57	205.19	0.50	5,000
S	0.09	0.48	5.58	-
Sr	0.02	0.05	1.96	60
Ti	1.19	8.99	7.58	10
Zn	0.03	0.22	6.43	30
Zr	0.10	0.27	2.82	-
Ba	-	0.66	-	60
Ga	-	0.04	-	0.09
Nb	-	0.02	-	-
Pb	-	0.08	-	0.1

** - average elemental composition of dissolved and suspended matter in surface water from a variety of sources and various authors*

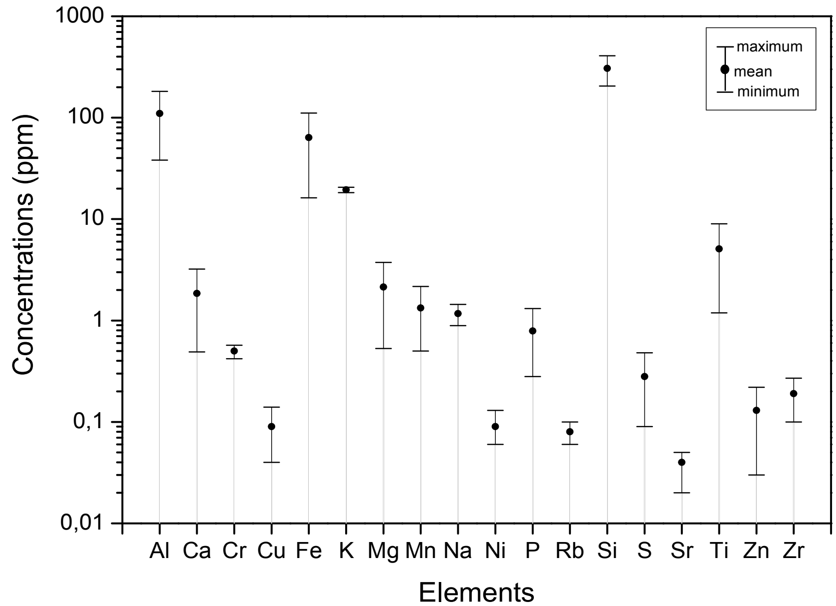


Fig. 8. Results of the analysis done with the software origin

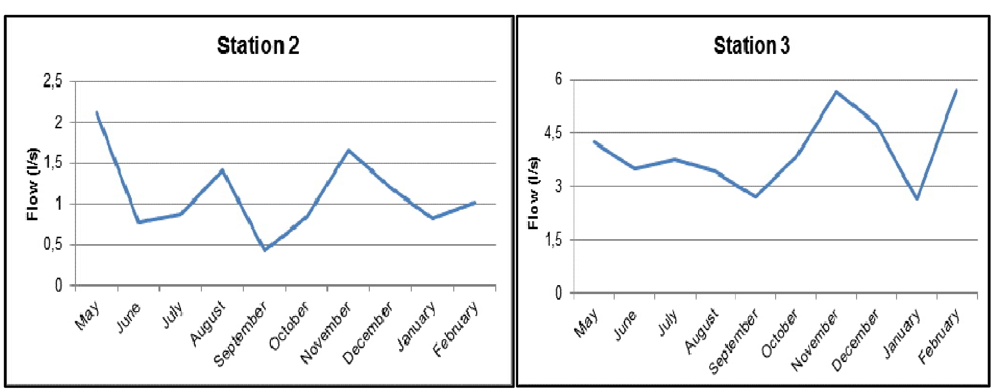
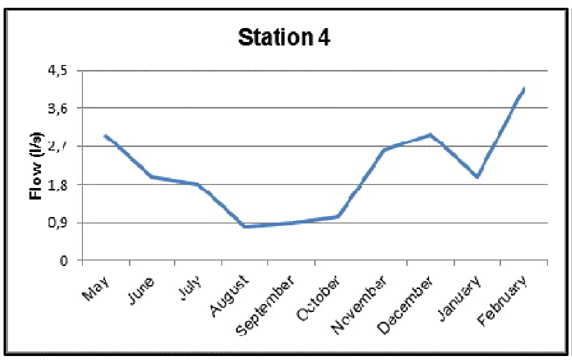


Fig. 9. Stations 2 and 3: natural flows

Table 10. Hydrometric network

Station	Coordinates*	Weir characteristics	Installation date
1	N 7.778.731, E 552.431	Rectangular – wood - without channel, with two side contractions. Sill width: 1.0 m. Inner sill height: 0.40 m. Maximum height: 0.59 m.	October 2006
2	N 7.778.630, E 552.300	Rectangular – concrete - channel without side contractions. Channel width: 0.78 m. Inner sill height: 0.19 m. Maximum height: 0,76 m.	October 2006
3	N 7.778.300, E 552.950	Triangular (metal sheet)- concrete	May 2012**
4	N 7.777.800, E 553.000	Rectangular – wood - channel without side contractions. Channel width: 0.80 m. Channel length: 3.0 m. Inner sill height: 0.10 m.	October 2006
5	N 7.777.240, E 554.100	Rectangular – wood - channel without side contractions. Channel width: 0.80 m. Channel length: 3.0 m. Inner sill height: 0.20 m. Maximum height: 0.48 m.	October 2006
6	N 7.776.640, E 553.389	Parshall flume (nominal width: 15.24 cm). Maximum height: 0.45 m.	October 2006
7	N 7.777.165, E 554.130	There is no weir. The gauge is installed in the natural bed of the stream and the measurements of the water level are carried out through the linimetric ruler.	October 2006

** DATUM: SAD 69 – 23S, ** - the original one was made of wood and installed at October 2008, but due to some heavy rains in 2011 it was partially destroyed. Another one was built at the same place*



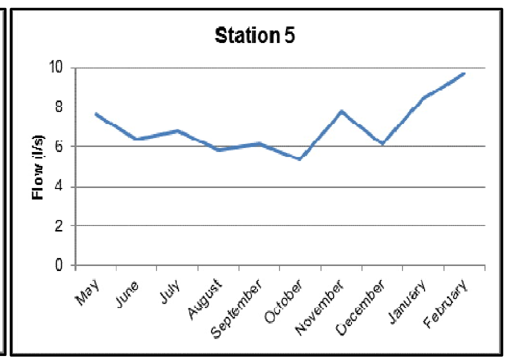


Fig. 10. Stations 4 and 5: natural flows

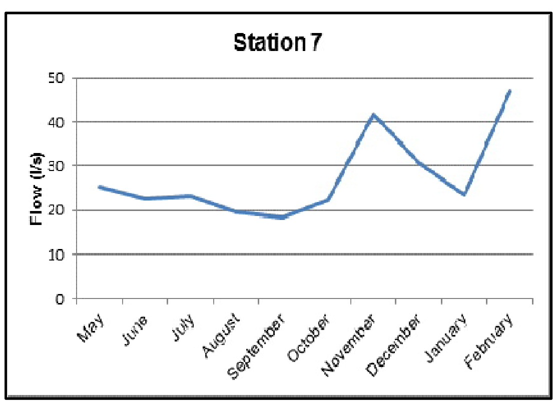


Fig. 11. Stations 7: natural flows

4. CONCLUSION

This work showed some questions regarding the transport of sediments towards Serra Azul reservoir. Regarding to the heavy metal content, bottom sediments collected in the study area present values higher than the threshold above which a probable adverse effect on the biota is expected for the elements Cr and Ni. For the threshold below which a low probability of adverse effects to biota is expected, the values found for Cu, Pb and Zn did not answer the allowable limits. Two elements found in the sediments in suspension were not found in bottom sediments: chlorine and bromine. Four elements were not found in 2013 samples, only in 2014: gallium, lead, barium and niobium. For Fe and Al, the 2014 found values were bigger than the average elemental composition of dissolved and suspended matter in surface water, according to a variety of sources and authors.

Due to a long dry season in the study area, the transport of sediments is currently minimized, however the next rain station can generate a serious scenario. It is necessary to implement a permanent program in order to collect and analyze these sediments, inclusive in other parts of the basin. It is also necessary to solve the question concerning to the absence of a legislation for several other chemical elements found in the sediments. Also, the results can help the management of the hydro resources and sediments by the utility responsible for the water supply at the study area.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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