PIRACICABA RIVER BASIN: MECHANICAL AND CHEMICAL EROSIONS

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ABSTRACT - It was carried out the characterization of the mechanical and chemical erosive processes in the Piracicaba River basin, for the period 1992-1996, in terms of the fluvial transport of dissolved and particulate materials. The mechanical erosion was calculated from the suspended sediment transport in the basin, considering the surface runoff discharge and the respective concentration calculated taking in account the statistical hydrogram separation method employed. The specific physical degradation calculated for the Piracicaba River basin was 90 t/km^2.a, which correspond the velocity of the soil thickness reduction of about 64 m/Ma. The dissolved load of Piracicaba River was corrected due to the influence of the atmospheric inputs, mainly for SO_4^{2-}, Ca^{2+} and Mg^{2+} (79.6; 63.8 and 41.8%, respectively). After the input corrections, it was estimated the total atmospheric/soil CO_2 consumed during the silicate weathering (229 x 10^3 moles/km^2.a) and the total chemical erosion (16.6 t/km^2.a) expressed in terms of the total dissolved solids transported in the basin. The velocity of the silicate rock profile reduction (2.8 m/Ma) was calculated by the fluvial transport of dissolved silica knowing the mean silica concentrations in the parent rock and in the soil profile.
Keywords: Piracicaba River Basin; mechanical erosion; chemical erosion; fluvial transport; physical degradation.

RESUMO - *J. Mortatti, J.L Probst; M.J. Bortoletto Júnior – Bacia do Rio Piracicaba: erosões mecânica e química.* O presente trabalho procurou caracterizar os processos erosivos mecânicos e químicos predominantes na bacia de drenagem do Rio Piracicaba, durante o período de 1992-1996, em termos dos transportes fluviais dos materiais dissolvidos e particulados. A erosão mecânica foi estimada em função do transporte fluvial de sedimentos em suspensão, considerando o escoamento superficial rápido e as respectivas concentrações. O modelo de separação de hidrogramas utilizado foi o estatístico, com o emprego de filtros numéricos. A degradação física específica calculada para a bacia de drenagem do rio Piracicaba foi de 90 t/km^2.a, o que representou uma taxa de redução da espessura do solo da ordem de 64 m/Ma. A carga fluvial dissolvida foi corrigida dos aportes atmosféricos totais, principalmente em termos de SO_4^{2-} (79,6%), Ca^{2+} (63,8%) e Mg^{2+} (41,8%). Após a correção desses aportes foi possível calcular o fluxo específico de CO_2 de origem atmosférica/solo consumido pela alteração de rochas na bacia de drenagem, como sendo de 229 x 10^3 moles/km^2.a, como também a erosão química total (16.6 t/km^2.a) expressa em função dos sólidos totais dissolvidos e transportados fluvialmente. A taxa de redução do perfil rochoso, principalmente ligados aos silicatos, foi estimada em 2,8 m/Ma, sendo calculada a partir do transporte fluvial de sílica e as respectivas concentrações na rocha e nos solos da bacia de drenagem.
Palavras-chave: Bacia do Rio Piracicaba; erosão mecânica; erosão química, transporte fluvial; degradação física.

INTRODUCTION

The evaluation of the erosion balance in a agricultural drainage basin can be achieved with the use of different methodologies, but always associated to the physical-chemical control of the river waters and the transport of dissolved and particulate material associated with the climatic influences occurring in the drainage basin. According to Tardy (1990), the mechanical erosion is related to the suspended sediment transported by river, while the chemical erosion (which precedes the mechanical erosion) correspond to the rock weathering by hydrolysis or dissolution, modifying the internal horizons of the alteration profiles, with a consequent transport to the rivers, as dissolved load.

The chemical erosion is influenced by several factors, and the most important are the temperature, precipitation and the atmospheric/soil CO_2 consumed during the weathering process. The rate of the chemical erosion can be estimated in terms of silica and major ions transported by rivers (Tardy, 1990; Probst et al., 1994; Mortatti et al., 1997). The atmospheric/soil CO_2 consumed during the rock weathering is calculated in function of the HCO_3^- ions produced during the silicate and carbonate weathering processes. The annual mass balances of dissolved and particulate loads transported by rivers are used to characterize and quantify the chemical and mechanical erosion in a drainage basin.

The main objective of this paper is to make a comparison between mechanical and chemical erosion rates for the Piracicaba River basin, in order to indicate whether the soils are in equilibrium under present-day climatic conditions.

STUDY AREA

The drainage area of the Piracicaba River basin, 12,400 km^2, is mainly located at São Paulo State (Brazil) between 22°05'-23°16' S and 45°51'-48°24' W, occupying, in subtropical climate, lands of the Atlantic Plains and Peripheral Depression (Feltran Filho, 1982). Three major rivers compose the main channel of the Piracicaba River: Atibaia, Jaguari and Camanducaia rivers (Figure 1). The eastern headwaters of the Piracicaba River basin are relatively unpolluted, whereas the central and western sub-basins, which have higher population densities, are polluted (due to higher sewage loading and industrial discharges into rivers, Krusche et al., 1997; Ballester et al., 1999).

The agricultural part of the river basin is mainly composed by sugar-cane, citrus fruit and pasture, distributed along the soils (ferralitic and podzolic) formed over the crystalline and sedimentary rocks. The weathering profiles are mainly represented by red lateritic soils which are composed of kaolinite and iron oxides.

In this paper, the CESP/COPERSUCAR sampling station (Figure 1) was considered as the mouth of the basin, with a drainage area of about 8,851 km^2, which was used to calculate the particulate and dissolved loads in the basin.
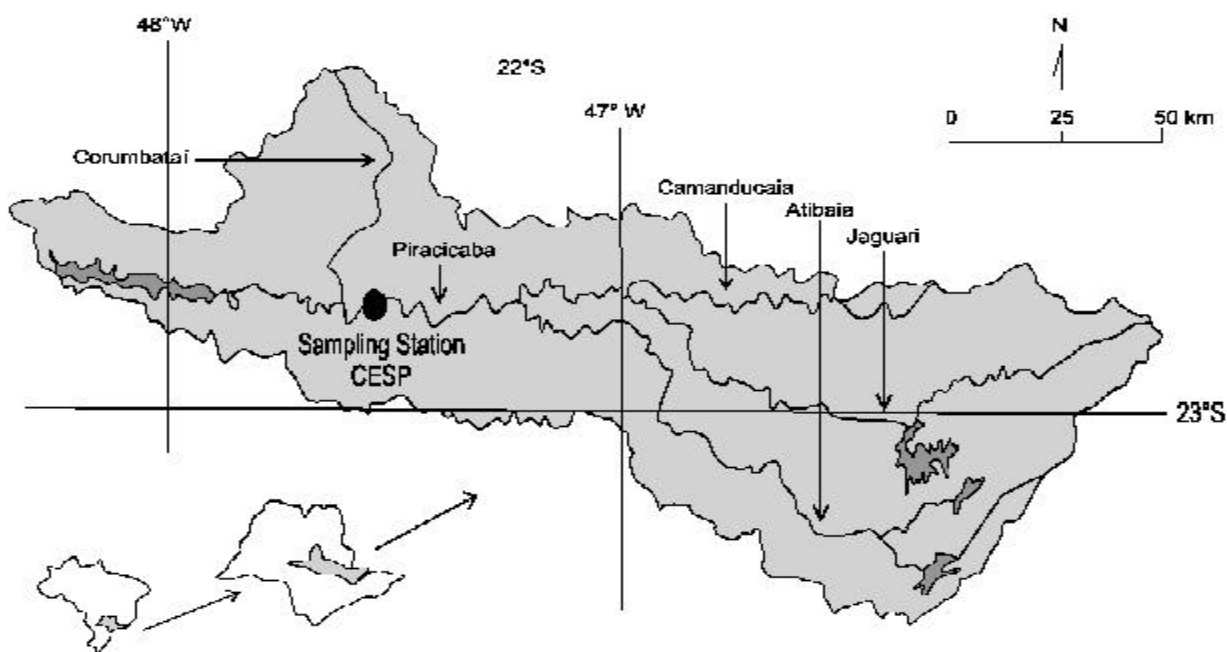

FIGURE 1. Localization of the Piracicaba River basin and the CESP/COPERSUCAR sampling station.

SUSPENDED SEDIMENT TRANSPORT AND MECHANICAL EROSION

During the period 1992-1996, two samples per month of the fine suspended sediment (FSS < 63 µm) were collected on the Piracicaba River, at CESP/COPERSUCAR station, using a simple stage sampler at 1.5 m depth in the current axis. The samples (300 ml) were filtered in pre-weighthed acetate membrane (0.45 ìm), dried at 60ºC and quantified in terms of mg/l. An average FSS concentration of 220.4 mg/l was obtained during the studied period. With the mean discharge value observed during the same period, it was possible to calculate the average flux of FSS for the period 1992-1996 as being 0.76 x 10^6 t/a.

It can be observed in Figure 2 the temporal variation of the suspended sediment and discharge

during the high water period of January 1996. It was possible to verify the remobilization-deposition pattern associated with the high concentrations of suspended sediment during the river flood period.
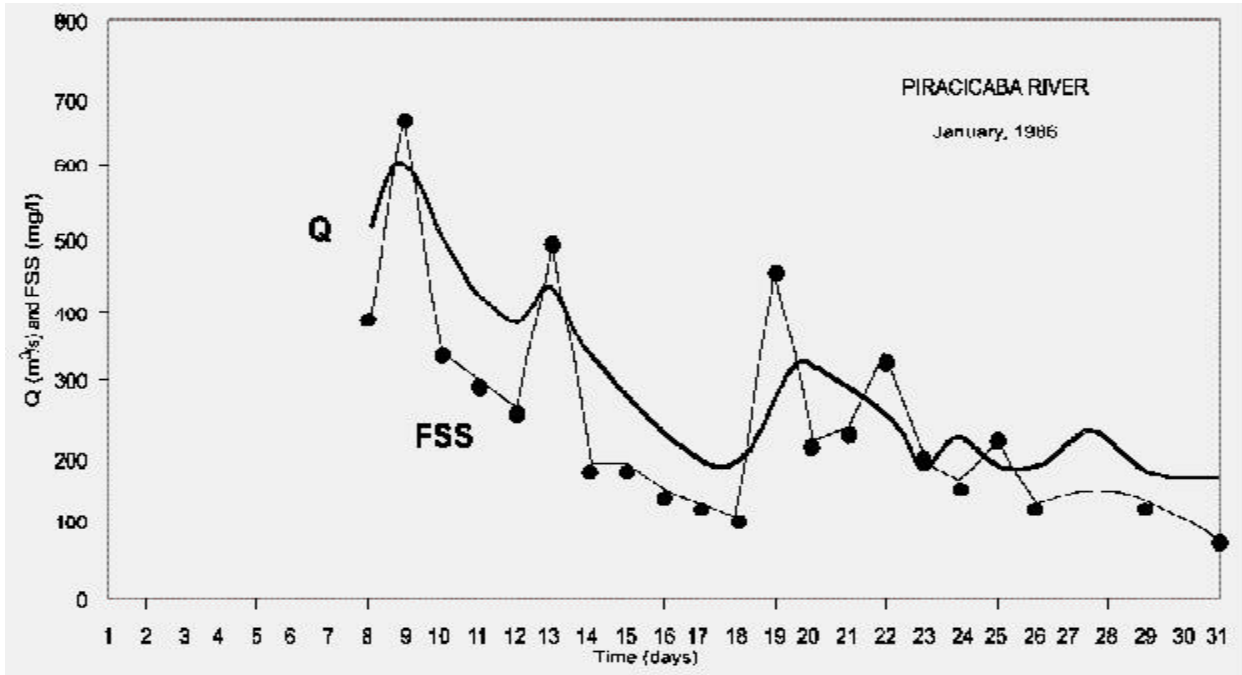

FIGURE 2. Temporal variation of the suspended sediment concentrations associated with the discharge values during the high water period (January, 1996), for the Piracicaba River at CESP/COPERSUCAR station.

The contribution of the surface runoff and baseflow to the total discharge of the Piracicaba River during 1992-1996 period was investigated using a statistical method of hydrogram separation with a numerical filter application, according to Hino & Hasebe (1981), Araújo & Dias (1995) and Mortatti et al. (1997). This method is based in a high-frequency cut-off filter which allows the passage of only the low frequency component of the total river flow, corresponding to the base flow. The high-frequency cut-off filtering of the total river flow time series Q(t), for the first order filter equation is calculated by:

$$Qb(t) = \alpha \, [B \, Qb \, (t-1)] + A \, Q(t) \qquad (1),$$

where Qb(t) is the filtered baseflow, a is the weighting factor chosen to satisfy the condition that the filtered and residual outputs should not be negative. A and B are constants given by:

$$A = e^{(1/T_c)} / T_c \qquad (2),$$

$$B = \frac{\Delta t}{T_c} \qquad (3),$$

where Δt is the time interval and $T_c = f_c^{-1}$ is the separation period which is the inverse of the cut-off frequency.

The separation period T_c can be determined from the order of magnitude of autoregressive coefficients (AR) or by means a periodogram of the discharge time series statistical analysis, in a monthly base data. According to this method, the baseflow (Kb) and surface runoff (Kr) coefficients were determined by equations 4 and 5:

$$Kb = Qb / Qt \qquad (4),$$
$$Kr = Qr / Qt \qquad (5),$$

where Qt is the monthly average discharge for 1992-1996 period, 117 m³/s.

The results obtained by the two reservoir model used show an average contribution of the surface runoff (Kr) of about 27%, while the baseflow (Kb) is responsible for 73% of the total river flow. The complete hydrogram separation for the Piracicaba River during 1992-1996 period can be observed in Figure 3. During the high peak flow the contribution of the baseflow or groundwater was of about 59% of the total discharge.
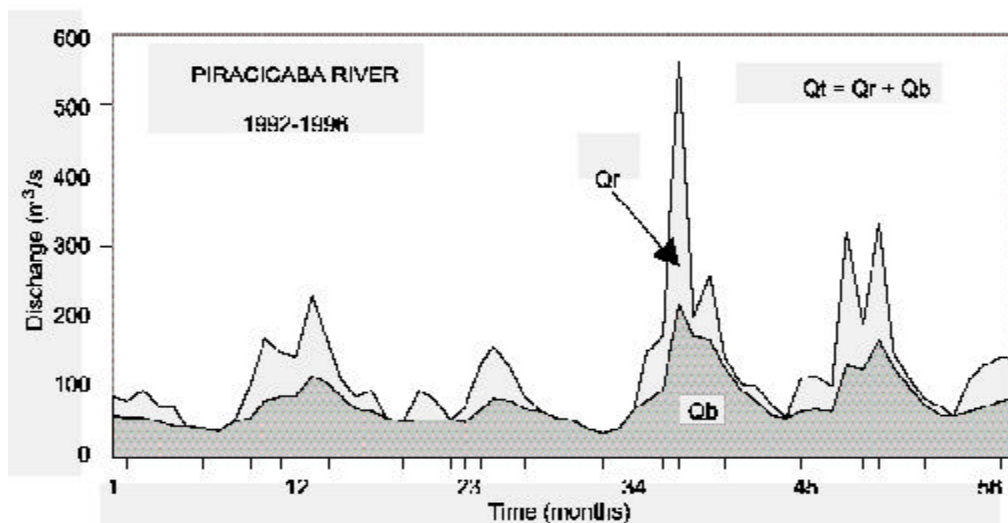
FIGURE 3. Hydrogram separation for the Piracicaba River during 1992-1996, using a statistical method with a numerical filter, in baseflow (Qb) and surface runoff (Qr).

The concentration of the solid material carried out by the surface runoff (Cr) was estimated from the hydrogram separation in terms of the surface runoff coefficient (Kr), according procedure developed by Probst & Sigha (1989), given by equations 6 and 7:

$$Qt.Ct = Qr.Cr + Qb.Cb \qquad (6),$$

where Ct is the average flux of FSS in the Piracicaba River for 1992-1996 period, 220.4 mg/l, and Qr is the surface runoff discharge calculated from equation 5, 31.6 m^3/s.

If we consider that there is no solid material transport given by the baseflow (Cb = 0), we can calculate the concentration of particulates in the surface runoff as being:

$$Cr = (Qt.Ct)/Qr \qquad (7),$$

The result obtained shown to be 0.8 g/l, which was similar the value from Gac (1980) for the Tchad region, in Africa, of about 1 g/l.

The specific mechanical erosion (SME), 90 t/km^2.a, was calculated in terms of the specific flux of the surface runoff (Cr) by equation 8:

$$SME = (Qr.Cr . 31.536) / A \qquad (8),$$

where 31.536 is a constant for unity conversion and A is the drainage basin surface, 8,851 km^2.

The physical degradation rate was estimated, according Mortatti et al. (1997), dividing SME by the mean soil density of the drainage basin (1.4 g/cm^3, obtained from Rodrigues Jr., 1998). The result show an important physical denudation rate for the whole basin of 64 m/My, which corresponds to the soil loss in the drainage basin by mechanical erosion.

FLUVIAL DISSOLVED LOAD

The dissolved load of the Piracicaba River, at CESP/COOPERSUCAR station, was estimated during 1992-1996 period and the original data are reported in Rodrigues Jr. (1998). The concentrations of the main chemical species were compared with the theoretical dilution curves established by Kattan & Probst (1986) expressed, by equation 9:

$$Ci = (Qmin . Cmax) / Qi \qquad (9),$$

where Ci is the model concentration of the chemical specie, Qmin is the minimal discharge observed during the studied period, Cmax is the maximal observed concentration of the chemical specie and Qi is the

discharge value observed during the sampling period.

Figure 4 illustrate the behavior of dissolved Ca^{2+} and Mg^{2+} in the Piracicaba River water during the studied period. Both chemical species were not in accordance with the theoretical dilution curves, which means an additional diffuse input of these species in the body water. For Na^+ and K^+ the theoretical dilution curves were followed, mainly in the Na^+ case (Figure 5). This procedure for hydrochemical characterization is very important in order to identify the several sources of the respective chemical specie in drainage waters, mainly between the atmospheric inputs, pollution and rock weathering releases.
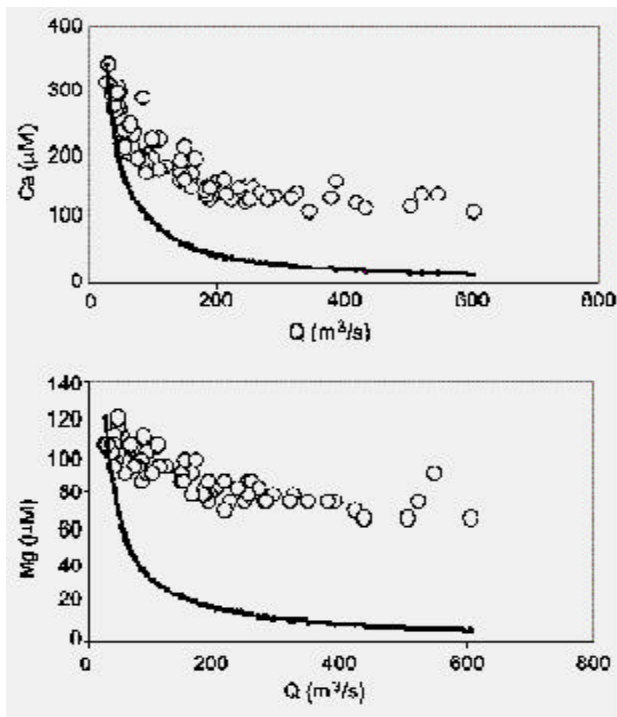
FIGURE 4. Behavior of dissolved Ca^{2+} and Mg^{2+} with the respective discharge values in relation with the theoretical dilution curves for the Piracicaba River during 1992-1996.
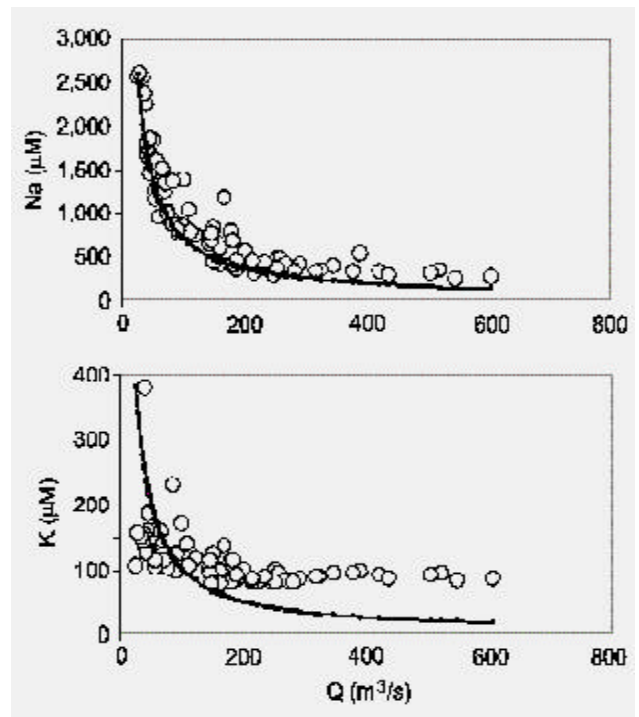
FIGURE 5. Behavior of dissolved Na^+ and K^+ with the respective discharge values in relation with the theoretical dilution curves for the Piracicaba River during 1992-1996.

The average concentrations of the major elements, normalized by discharge values, and the respective fluvial transports for Piracicaba River can be observed in Table 1. It can be verified that HCO_3^-, SO_4^{2-} and Na^+ fluxes are important in the basin, i.e., 124×10^3, 53×10^3 and 44×10^3 t/a, respectively. The specific transports, associated with these chemical species, calculated for whole basin were respectively 14, 6 and 5 t/km².a. The specific transport of the total dissolved solids (TDS_S) estimated for the Piracicaba River was of 35.5 t/km².a.

The influence of the total atmospheric inputs in the dissolved load of the Piracicaba River, which is very important in order to identify the predominant processes of rock weathering in the drainage basin, was verified by means the chemical analysis of the rain water in the basin (sampled at CENA/USP), in terms of the major cations and anions (Ca^{2+}, Mg^{2+}, Na^+, K^+, NO_3^-, Cl^-, SO_4^{2-}, and also SiO_2) from May 95 to July 97. The average concentrations, normalized by daily precipitations, were of 11.7; 100.1 and 14.0 µM for NO_3^-, SO_4^{2-} and Cl^-, respectively. For Ca^{2+}, Mg^{2+}, Na^+ and K^+, the concentrations were, respectively, 53.6, 18.6, 9.2 and 11.7 µM, while in terms of SiO_2, the value was 7.0 µM.

TABLE 1. Average fluvial transport of the main dissolved chemical species for the Piracicaba River at CESP/COOPERSUCAR station, during 1992-1996 period.

Components	Concentration (µM)	River transport (10^3 t/a)	Specific river transport (t/km²/a)
HCO_3^-	585	123.65	13.97
NO_3^-	29	6.23	0.70
SO_4^{-2}	160	53.23	6.01
Cl^-	228	28.00	3.16
Ca^{2+}	155	21.48	2.43
Mg^2	82	6.91	0.78
Na^+	553	44.07	4.98
K^+	99	13.41	1.52
SiO_2	83	17.26	1.95

The contributions of the atmospheric inputs to the fluvial dissolved load shown to be important for SO_4^{2-}, NO_3^-, Ca^{2+} and Mg^{2+} (62.6, 40.3, 34.6 and 22.7%, respectively) and less important for Na^+ and Cl^- (1.7 and 6.1%). The values obtained for K^+ and SiO_2 were similar (11.8 and 8.4 % respectively). Such contributions are mainly related with materials derived from industrial and agricultural activities, mainly related to the burning in the sugar-cane culture.

CHEMICAL EROSION

For the whole drainage basin of the Piracicaba River, the chemical erosion was calculated from the specific transport of total dissolved solid (TDS_S) considering the atmospheric input corrections (ions and CO_2 consumed by the rock weathering) using the equation 10 from Probst et al. (1994):

$$CE = TDS_S - ions - CO_2 \qquad (10),$$

where ions is the atmospheric input corrections for cations and anions species and CO_2 is the correction for the fluvial HCO_3^- from the atmospheric/soil origin.

The atmospheric/soil CO_2 flux consumed (229×10^3 moles/km^2.a) was estimated by the fluvial HCO_3^- flux in its totality, due to the presence of silicate rock in the basin (> 98%, according Rodrigues Jr., 1998). The specific chemical erosion calculated for the Piracicaba River basin was about 16.6 t/km^2.a. These results obtained for the Piracicaba River basin are comparable to the Amazon basin ones (Mortatti et al., 1997) of about 331×10^3 moles/km^2.a for the atmospheric/soil CO_2 consumed during silicate rock weathering and 22.6 t/km^2.a for the silicate chemical erosion.

The mean annual dissolved silica carried out by the Piracicaba River is calculated to be 25.3×10^3 tons, corresponding to specific transport of 2.86 t/km^2.a. The chemical weathering rate of silicates (R_{ch}) was calculated as described by Boeglin & Probst (1998), from the dissolved silica specific transport (F_{SiO2}) knowing the silica composition of granitic rocks (S_o) and the silica of the saprolite (S_s), according to the equation 11:

$$R_{ch} = F_{SiO2} / (S_o - S_s) \qquad (11).$$

Considering 70% of SiO_2 in the tipic granitic rocks (d = 2.65 t/m^3) in the Piracicaba River basin, it was possible to calculate the volumic mass of silica in this rocks as being 1,855 kg/m^3 and for the saprolite (46% of SiO_2, with a mean density of 1.8 t/m^3) of about 828 kg/m^3 (data from Rodrigues Jr., 1998). According the equation 11, the mean chemical weathering rate of silicate rocks (R_{ch}) for the Piracicaba River basin was about 2.8 m/My, which means the silicate rock profile reduction and consequently soil formation.

EROSION BALANCE

With the values obtained for the mechanical and chemical erosions, it was possible to verify the present day conditions of the erosion in the Piracicaba River basin. The results show that the mechanical process of erosion (90 t/km^2.a) is more important than the chemical weathering (16.6 t/km^2.a). If we consider the rate of physical soil denudation (64 m/Ma) in comparation with the rate of silicate rock profile reduction (2.8 m/Ma), the soil loss in the Piracicaba River basin is about 23 times more important than the soil formation. This occurrence can be considered normal due to the agricultural practices carried out in the basin, where the soil is in permanent management.

CONCLUSION

The erosion balance in the Piracicaba River basin could be characterized by means of the mechanical and chemical erosions calculated in the drainage basin. The mechanical erosion was estimated in function of the suspended sediment transport, associated to the surface runoff contribution to the total river flow.

The chemical erosion was evaluated by means total dissolved solids in the fluvial system, corrected in terms of ions and atmospheric/soil CO_2 consumed during the rock weathering. Other geochemical approaches could be used to estimate the chemical erosion in the river basin, based on the dissolution and hydrolysis of the major elements released during the silicate weathering. For the Piracicaba River basin at CESP/COPERSUCAR sampling station, this procedure are resumed by the TDS approach because only the silicates were predominant in this part of the basin.

BIBLIOGRAPHIC REFERENCES

1. ARAÚJO, A.A.M. & DIAS, N.L. Separação do hidrograma de cheias através de filtros auto-recursivos. In: SIMPÓSIO BRASILEIRO DE RECURSOS HÍDRICOS, 11, e SIMPÓSIO DE HIDRÁULICA E RECURSOS HÍDRICOS DOS PAÍSES DE LÍNGUA OFICIAL PORTUGUESA, 2, 1995, Recife (PE). **Anais...** Recife: Associação Brasileira de Recursos Hídricos, 1995, Hidrologia, v. 1, p. 267-272.

2. BALLESTER, M.V.; MARTINELLI, L.A.; KRUSCHE, R.L.; VICTORIA, R.L.; BERNADES, M.; CARMAGO, P.B. Effects of increasing organic matter loading on the dissolved O_2, free dissolved CO_2 and respiration rates in the Piracicaba River basin, Southeast Brazil. **Water Research**, v. 33, p. 2119-2129, 1999.

3. BOEGLIN, J.L. & PROBST, J.L. Physical and chemical weathering rates and CO_2 consumption in a lateritic environment: The upper Niger basin. **Chemical Geology**, v. 148, n. 3-4, p. 137-156, 1998.

4. FELTRAN FILHO, A. **Contribuição à análise fluvio-métrica da bacia do rio Piracicaba**. Rio Claro, 1982. 188 p. Dissertação (Mestrado em Geociências) - Instituto de Geociências e Ciências Exatas, UNESP.

5. GAC, J.Y. **Géochimie du bassin du lac Tchad. Bilan de l'altération, de la érosion et de la sédimentation**. Travaux et Documents de l'Orstom, ,1980, v. 123, p. 1-251.

6. HINO, M. & HASEBE, M. Analysis of hydrologic characteristics from runoff data - A hydrologic inverse problem. **Journal of Hydrology**, v. 49, p. 287-313, 1981.

7. KATTAN, Z. & PROBST, J.L. Transports en solution et en suspension par la Moselle en périodes de crues. Strasbourg, **Journées d'Hydrologie**, p. 143-167, 1986.

8. KRUSCHE, A.V.; CARVALHO, F.P. de; MORAES, J.M.; BALLESTER, M.V.R.; HORNINK, S.; MARTINELLI, L.A.; VICTORIA, R.L Spatial and temporal water quality variability in the Piracicaba River basin, Brazil. **Journal of American Water Resources Association**, v. 33, p. 1117-1123, 1997.

9. MORTATTI, J.; VICTORIA, R.L.; TARDY, Y. Balanço de alteração e erosão química na bacia Amazônica. **Geochimica Brasiliensis**, v. 11, n. 1, p. 2-13, 1997.

10. PROBST, J.L. & SIGHA, N. Estimation de l'écoulement superficiel et de sa charge en suspension sur quelques grands bassins fluviaux du monde. Paris, **Compte Rendu de l'Academie des Sciences**, Série 2, n. 309, p. 357-363, 1989.

11. PROBST, J.L.; MORTATTI, J.; TARDY, Y. Carbon river fluxes and global weathering CO_2 consumption in the Congo and Amazon River basins. Oxford, **Applied Geochemistry**, v. 9, p. 1-13, 1994.

12. RODRIGUES JUNIOR, J.C. Balanço de erosão na bacia do Rio Piracicaba. Piracicaba, 1998. 58 p. Dissertação (Mestrado em Ciências) - Centro de Energia Nuclear na Agricultura, Universidade de São Paulo.

13. TARDY, Y. Erosion. In: **Encyclopedia Universalis**, 1990, v. 8, p. 615-627.