Research Article

Mechanical Erosion in a Tropical River Basin in Southeastern Brazil: Chemical Characteristics and Annual Fluvial Transport Mechanisms

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This study aims to evaluate the mechanical erosion processes that occur in a tropical river basin, located in the São Paulo state, southeastern Brazil, through the chemical characterization of fine suspended sediments and the transport mechanisms near the river mouth, from March 2009 to September 2010. The chemical characterization indicated the predominance of SiO_2 , Al_2O_3 , and Fe_2O_3 and showed no significant seasonal influences on the major element concentrations, expressed as oxides. The concentration variations observed were related to the mobility of chemical species. The evaluation of the rock-alteration degree indicated that the physical weathering was intense in the drainage basin. The fine suspended sediments charge was influenced by the variation discharges throughout the study period. The solid charge estimate of the surface runoff discharge was four times higher in the rainy season than the dry season. The transport of fine suspended sediments at the Sorocaba River mouth was $55.70 \text{ t km}^{-2} \text{ a}^{-1}$, corresponding to a specific physical degradation of 37.88 m Ma^{-1} , a value associated with the mechanical erosion rate that corresponds to the soil thickness reduction in the drainage basin.

1. Introduction

The mechanical erosion processes that occur in a drainage basin tend to reduce the thickness of the soils and the volume of the bedrock, by which dislocated and degraded particles are exported by the rivers to the sedimentation areas (lakes and oceans). The sediment production, transport, and deposition at the drainage basin scale are principally controlled by natural processes that may be intensified due to human activities, mainly agriculture and urbanization [1]. It is now recognized that in areas where urbanization grew drastically during the last century, the contribution of urban-originated sediments to the suspended particulate matter of water bodies is significant [2].

Soil erosion and its impacts on agricultural productivity, water quality, and siltation in rivers and reservoirs have been

frequently discussed with regard to sustainable management of the services that these ecosystems deliver to the population [3]. In this context, the knowledge of mechanical erosion processes that occur in a tropical river basin is of outmost importance. It is now essential to reduce the loss of surface soil layers in agricultural areas and to anticipate the accumulation of deposited sediments at the industrial/urbanized areas. The intensity of mechanical erosion in a drainage basin can be assessed by monitoring the fine suspended sediments (FSS) dynamic in a given period [2].

This study aims at evaluating the main aspects of the mechanical erosion processes that occur in the Sorocaba River basin, located in the São Paulo state, southeastern Brazil, through the chemical characterization of fine suspended sediments and mechanisms of river transport close

FIGURE 2: Average monthly discharge (Q) and precipitation (P) in the Sorocaba River basin for the 1984–2008 period.

The region of the headwaters, in Atlantic Plateau, is better preserved (60% with original vegetation) and the Peripheral Depression region concentrated agricultural and urban areas, with 70% and 10% of its total area, respectively [8].

According to Koppen classification [9], the climate is Cwb in the upstream part and Cwa in the Peripheral Depression area, both indicating the predominance of summer rains and dry winters. Figure 2 illustrates the annual variability of the precipitation and the river discharge for the 1984–2008 period. The average calculations were performed from daily data (personal communication DAEE/CTH in 2009) for the limnometric station 4E-001 Entre Rios (23°01'S, 47°48'W) and the pluviometric station E4-019 Iperó (23°20'S, 47°41'W), located in the central region of the drainage basin. The annual averages calculated for the 25-year period were 63.1 m³ s⁻¹ for the discharge and 1243.1 mm for the precipitation, with a higher monthly average discharge in February (122.1 m³ s⁻¹) and the lowest discharge in September (37.5 m³ s⁻¹).

3. Material and Methods

The fine suspended sediments (FSS) transported by rivers are usually characterized as particles smaller than 63 μm [10], whose composition is a complex mixture of organic and inorganic particles originating from various sources, such as atmospheric deposition, eroded soil and rock, and domestic and industrial sewages [11]. Eighteen FSS samples were collected at the Sorocaba River basin mouth station, from March 2009 to September 2010. The FSS concentrations were determined from 1000 mL of river water composite samples, collected in the left and right margins of the river and in the main axis of the current river at a 1.5 m depth using a single-stage sampling point [12]. From these composite samples, 300 mL were filtered through previously weighed cellulose membrane filters (0.45 μm), and the FSS obtained plus the

membrane filters were dried at 60°C to constant weight. The FSS concentration was quantified gravimetrically according to (1):

$$C_{\text{FSS}} = \frac{(m_f - m_i)}{V_L}, \quad (1)$$

where C_{FSS} is the FSS concentration (mg L⁻¹), m_f the final mass of the filter (mg), m_i the initial mass filter (mg), and V_L the volume filtered (L).

The average FSS concentration normalized by the discharge (C_{MNQ} , in mg L⁻¹) was calculated according to the procedure established by Probst [13], as shown in (2):

$$C_{\text{MNQ}} = \frac{\sum(Q_i \times C_i)}{\sum Q_i}, \quad (2)$$

where Q_i is the discharge measured on the sampling day (m³ s⁻¹), C_i the FSS concentration for the sampling day, and $\sum Q_i$ the sum of all discharges measured on the sampling days (m³ s⁻¹).

Additionally, river water composite samples were collected from the left and right margins of the river and in the main axis of the current river. 30 L of water samples are stored in polypropylene containers to obtain sufficient FSS mass for chemical characterization. After the settlement of the FSS, the recovered sediments were air-dried and sieved using a 63 μm nylon mesh. The sediments retained in the sieve (>63 μm) were separated and with a portion of FSS (<63 μm) reserved for mineralogical analysis. Other portions of the FSS samples were calcinated at 1000°C to remove all the organic matter and were digested using the alkaline fusion method proposed by Samuel et al. [14]. 100 mg of the sample was mixed with lithium tetraborate and lithium metaborate (2:1) in a platinum crucible and heated at 1000°C for 30 minutes. After cooling, the melt was dissolved in 20 mL of HCl (1 M) under agitation and heating at 40°C, and the volume completed to 50 mL with MilliQ water. This analysis was performed in triplicate using the inductively coupled plasma optical emission spectrometry (ICP-OES). The limits of detection, in mg L⁻¹, were Si (0.020), Al (0.020), Fe (0.020), Mn (0.002), Ca (0.050), Mg (0.050), Na (0.050), and K (0.050). We controlled the purity of the chemical reagents and the blanks with bank ground measurements below the precision limits. To control the quality of the extraction process and the chemical analyses, we used the international reference material Soil-7 of the International Atomic Energy Agency (IAEA). We obtained the following average % of recovery for the extraction and analysis in triplicate: Si (91.7%), Al (90.1%), Fe (107.3%), Mn (101.2%), Ca (92.3%), Mg (89.7%), Na (89.2%), and K (91.0%).

4. Results and Discussions

4.1. Chemical Characterization of the FSS. The chemical characterization of the FSS showed a predominance of SiO₂ (48.60%), Al₂O₃ (21.05%), and Fe₂O₃ (8.23%) for the analyzed elements (Table 1). Analysis of the FSS mineralogical

TABLE 1: Major element concentrations (expressed as oxide %) for the FSS sampled at the Sorocaba River basin mouth during the study period.

Sampling date	Discharge (m ³ s ⁻¹)	Major element concentrations (expressed as oxide %)							
		SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	CaO	MgO	Na ₂ O	K ₂ O
Mar-10-09	51.50	41.22	19.69	9.82	0.54	0.83	0.86	0.44	2.06
Apr-07-09	59.30	45.74	22.45	10.47	0.49	0.74	0.89	0.40	2.15
May-12-09	46.83	46.03	19.44	7.92	0.39	0.71	0.82	0.38	2.02
Jun-17-09	37.47	42.12	19.50	9.30	0.40	0.70	0.74	0.39	2.02
Jul-21-09	43.71	44.60	23.48	7.61	0.31	0.55	0.81	0.38	2.30
Aug-25-09	123.23	47.80	21.43	6.83	0.23	0.56	0.81	0.32	2.22
Sep-22-09	99.84	43.20	20.26	6.99	0.31	0.57	0.78	0.31	2.07
Nov-10-09	170.01	49.17	18.74	5.97	0.16	0.51	0.88	0.33	2.03
Dec-12-09	363.35	48.95	19.65	6.33	0.22	0.52	0.82	0.34	2.14
Jan-15-10	279.15	51.65	21.35	7.71	0.34	0.68	1.04	0.37	2.46
Jan-20-10	366.47	49.71	21.72	7.03	0.21	0.54	0.97	0.28	2.17
Feb-23-10	184.04	53.23	20.01	7.60	0.50	0.64	0.85	0.37	2.45
Mar-30-10	151.30	56.55	21.61	6.65	0.20	0.56	0.86	0.33	2.38
Apr-27-10	107.64	50.48	22.78	8.37	0.48	0.67	0.87	0.34	2.59
May-27-10	70.21	52.07	22.92	10.46	0.51	0.76	0.90	0.39	2.68
Jun-24-10	42.15	46.48	23.05	12.32	0.69	0.93	0.86	0.35	2.35
Jul-27-10	54.62	47.81	24.23	9.22	0.53	0.75	0.86	0.34	2.58
Sep-01-10	26.56	57.98	16.53	7.61	0.73	1.08	0.80	0.46	2.05
Average (%)	48.04	47.12	21.26	9.42	0.51	0.78	0.84	0.39	2.25
SD	12.76	5.16	2.56	1.57	0.14	0.15	0.05	0.04	0.25
Average (%)	205.00	50.08	20.84	7.05	0.29	0.58	0.88	0.33	2.28
SD	105.13	3.69	1.25	0.74	0.12	0.06	0.08	0.03	0.20
CV (%)	85.9	9.5	9.3	20.6	41.9	22.3	8.1	12.3	9.7

The average and the standard deviations (SD) are shown for two periods, low water and high water, and the coefficient of variation (CV) for the study period (all samples). The bold font represents the low water period and the light face font represents the high water period.

TABLE 2: Mobility estimation of the elements during the rock-alteration process in the Sorocaba River basin.

Element	Crust	Sorocaba River Basin	
	Ct (%)	Ct (%)	% loss (–) or gain (+)
Al	6.93	11.14	0
Fe	3.59	6.40	11
Mn	0.07	0.31	177
Na	1.42	0.27	–88
Ca	4.50	0.49	–93
Mg	1.64	0.52	–80
K	2.44	1.88	–52
Si	27.50	22.71	–49

composition, performed by X-ray diffraction, confirmed this predominance, because a significant amount of quartz, kaolinite, and magnetite was found in the fine fraction (<63 μm), and quartz, potassium feldspar, and plagioclase were found in the larger fraction (>63 μm). The concentrations of Fe and Al in the FSS are attributed to the presence of oxides that originated from the red lateritic soils that cover the basin. This observation was also verified for the Piracicaba River basin [15], another important tributary of the Tietê River.

The coefficients of variation showed a greater dispersion for Mn (41.9%), Ca (22.3%), and Fe (20.6%) and around 10% for other elements. These results reflect an apparent seasonal influence, which may be linked to the different origins of the FSS [16]. Some studies showed that the chemical composition of river sediments can provide information about the rock alteration processes and particularly the origin of the FSS particles. This chemical information may indicate element mobilities during the weathering process at the drainage basin scale [16–18].

In the Sorocaba River basin, this mobility is estimated considering the ratio between the FSS chemical composition (Ct) and the mean composition of surface rocks of the crust, described by Martin and Meybeck [16]. We applied a normalization, by the respective concentrations of Al, assuming its conservative behavior during the rock-alteration processes [19], according to (3):

$$\left\{ \left[\frac{(Ct/Al)_{\text{sed}}}{(Ct/Al)_{\text{crust}}} \right] \times 100 \right\} - 100. \quad (3)$$

The results in Table 2 indicate a conservative behavior for Fe and a significant gain for Mn. Oxides and hydroxides secondary minerals of Fe and Mn may be formed after the rock-alteration processes, especially when predominant land use is agriculture [19]. Na, Ca, Mg, and K levels indicate

reductions from 49% to 93% and illustrate a high degree of mobility that can be related to silicate-alteration processes [19]. Such processes release these elements in the same range that is already found in the alteration process of carbonates and evaporites, which are more easily weathered [20]. For instance, Si, the main element in the alteration of silicate rocks, showed a significant reduction of 49%. This may be related to the solubilization in the rock-alteration process where the mass loss in rocks is associated with Si removal [21].

During the rock-alteration process in the drainage basin, the evolution of primary to secondary minerals is associated with a relative enrichment in Al and Fe and depletion in Si. The increase in Al_2O_3 and Fe_2O_3 concentrations to the detriment of SiO_2 provides an indication of the rock-alteration degree, expressed by the R index, according to (4) [22]. The R index allows comparison of the rock alteration intensity between drainage basins a lower R value indicates a higher rock-alteration process in the drainage basin [23]:

$$R = \frac{\text{SiO}_{2(\%)}}{(\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3)_{(\%)}}. \quad (4)$$

The R value calculated for the Sorocaba River basin was 1.7, indicating an intense rock-alteration process when compared with other drainage basins, such as the Patagonia rivers (2.9 to 4.3) in Argentina, the Ill (3.1) and Garonne (5.1) rivers in France, and the Sebou river (2.8 to 4.8) in Africa [23]. However, this result was similar to that observed for the Piracicaba River basin (1.8) [24], another important tributary of the Middle Tietê basin.

This rock-alteration process was also assessed by the chemical maturity index (ChM), established by Konta [25], which relates the Al with the cationic bases (5). The longer a rock is altered, it becomes more mature and the higher the ChM index:

$$\text{ChM} = \frac{\text{Al}_2\text{O}_{3(\%)}}{(\text{Na}_2\text{O} + \text{MgO} + \text{CaO})_{(\%)}}. \quad (5)$$

The ChM index, calculated for the Sorocaba River basin, was significant (11.1) and similar to the one reported by Mortatti and Probst [15] for the Piracicaba River basin (10.4) and higher than that observed for the Patagonia rivers (2.0 to 4.8), the Ill (4.6), the Garonne (5.1), and the Sebou (3.4 to 5.3) rivers [23], confirming the high rock-alteration degree determined by R index.

4.2. Estimate of the Suspended Load of Quick Surface Runoff. The quick surface runoff is directly associated with mechanical erosion processes that occur in a drainage basin. It is responsible for the transport of particulate matter into the river channel throughout the drainage basin. The particulate matter load that reaches the river channel by quick surface runoff is diluted by river waters from the subsurface and hypodermic and underground compartments, whose particulate matter load can be considered negligible [22]. The relationship responsible for the mechanical erosion between the surface and subsurface reservoirs can be described according to (6) [22, 26]. Using the relationship between total discharge

TABLE 3: Estimation of the particulate matter load of quick surface runoff (Cr , mg L^{-1}) depending on the total concentration of FSS (Ct , mg L^{-1}) and the respective total discharge (Qt , $\text{m}^3 \text{s}^{-1}$) observed at the Sorocaba River mouth, in the study period, with respective averages and standard deviations.

Sampling date	Qt ($\text{m}^3 \text{s}^{-1}$)	Ct (mg L^{-1})	Cr (mg L^{-1})
Mar-10-09	51.50	16.33	43.11
Apr-07-09	59.30	20.67	54.24
May-12-09	46.83	25.33	67.16
Jun-17-09	37.47	14.33	38.46
Jul-21-09	43.71	46.50	123.69
Aug-25-09	123.23	54.33	139.90
Sep-22-09	99.84	45.33	117.21
Nov-10-09	170.01	145.00	371.56
Dec-12-09	363.35	87.17	221.86
Jan-15-10	279.15	47.67	121.54
Jan-20-10	366.47	101.50	258.33
Feb-23-10	184.04	37.83	96.85
Mar-30-10	151.30	178.00	456.84
Apr-27-10	107.64	51.00	131.66
May-27-10	70.21	22.67	59.25
Jun-24-10	42.15	14.50	38.64
Jul-27-10	54.62	28.83	75.92
Sep-01-10	26.56	17.67	48.60
Average (%)	126.52	73.55	188.41
SD	108.62	44.96	114.67

and quick surface runoff presented by Fernandes et al. [27] for the 1984–2008 period (7), it has been possible to estimate the particulate matter load transported by the Sorocaba River associated with the quick surface runoff (Table 3):

$$Ct \times Qt = Cr \times Qr, \quad (6)$$

where Ct is the total concentration of FSS transported by the total discharge (Qt) and Cr is the particulate matter load concentration transported by quick surface runoff (Qr):

$$Qr = 0.3952 Qt - 0.8423. \quad (7)$$

During dry periods, both preceding the rise of the water level (March–July 2009) and after the recession (May–September 2010), the flow-weighted average concentrations calculated for Cr were similar, with values of 64.61 and 57.97 mg L^{-1} , respectively. In the flood period, from December 2009 to January 2010, the flow-weighted average concentration was approximately four times higher (231.03 mg L^{-1}). It should be emphasized that the highest Cr concentration occurred in March 2010 (456.84 mg L^{-1}), during the receding period of Sorocaba River, being associated with erosion processes of the river banks, which is difficult to document.

4.3. Dynamics of Fine Sediments in Suspension. The FSS concentrations seem to be influenced by the variation of the Sorocaba River discharge during the study as illustrated in

FIGURE 3: Temporal variability of the FSS concentration (mg L^{-1}) and respective discharges (Q , $\text{m}^3 \text{s}^{-1}$) at the mouth of Sorocaba River basin.

FIGURE 4: Logarithmic correlation between the FSS concentration (mg L^{-1}) and the respective discharges (Q , $\text{m}^3 \text{s}^{-1}$) at the Sorocaba River basin mouth.

Figure 3. We emphasize that during the rise of the water level (November 2009) and low river levels (March 2010), the highest FSS peaks are observed in the Sorocaba River.

The relationship between the suspended sediment concentration (C) and stream discharge (Q) can be evaluated with the use of the logarithmic model ($C = aQ^b$) [28], where the a and b values vary between drainage basins, reflecting the different physical, climatic, and hydrological characteristics of each basin contribution area. For most rivers of the world, the b exponent is positive, indicating the increase in suspended sediment concentration caused by an increased discharge [29]. The logarithmic correlation model established for the Sorocaba River, using our sampling strategy, was significant at 1% (Figure 4).

The b exponent values obtained for the Sorocaba River (0.7431) were lower than those observed in the literature, which range between 1 and 2, according to the drainage basin characteristics [22]. This difference is confirmed when compared to the results obtained for the Tietê (1.7788) and the Piracicaba (1.4954) Rivers, two other rivers in the Middle Tietê basin region [30].

Although the annual hydrological regime, with the seasonal distribution of precipitation and discharge, as well as the land use (predominantly agricultural) of the Sorocaba River is similar to Tietê and Piracicaba Rivers [31], the comparison of the b exponent indicates a different distribution pattern of the suspended sediment concentration according to the discharge variation of these three rivers, which can be partly explained by distinct physical characteristics of the drainage basins, mainly associated with the relief and the arrangement and contribution of the tributaries. The dispersion of points observed in Figure 4 indicates the possible influence of the dynamic processes on the remobilization and sedimentation, characteristic to small and medium sized rivers [2, 22, 29, 32].

4.4. Transport of FSS. The sediment load carried by the river is evaluated in terms of the FSS, assuming that suspended load represents approximately 90% of the total sediment river flow [33]. Thus, the total transport of river sediments (T , in t a^{-1}) was estimated considering the average FSS concentration normalized by the discharge (C_{MNQ} , in mg L^{-1}) and the average discharge of the study period (Q_m , in $\text{m}^3 \text{s}^{-1}$), using the stochastic method [34], according to (8):

$$T = C_{\text{MNQ}} \times Q_m \times f, \quad (8)$$

where the f factor corresponds to the mass and time correction in the calculation of total transport for results in tons per year and is equal to 31.536.

The total transport of FSS calculated for the Sorocaba River mouth was $293 \times 10^3 \text{ t a}^{-1}$, which corresponds to a specific transport of $55.70 \text{ t km}^{-2} \text{ a}^{-1}$. This value is in accordance with that reported for the Tietê and the Piracicaba Rivers, 59.60 and $55.50 \text{ t km}^{-2} \text{ a}^{-1}$, respectively [30]. Compared to international drainage basins of the same magnitude, the specific transport of FSS observed for the Sorocaba River is similar to the Chena River, USA (5125 km^2 and $54.75 \text{ t km}^{-2} \text{ a}^{-1}$) and the Chaudiere River, France (5805 km^2 and $56.58 \text{ t km}^{-2} \text{ a}^{-1}$) [35].

4.5. Specific Physical Degradation. The physical degradation degree of a drainage basin, understood as the mechanical erosion rate in meters per million years, can be evaluated as a function of specific transport of FSS (F_{FSS} , in $\text{t km}^{-2} \text{ a}^{-1}$) and mean density of soils (d , in t m^{-3}) of the basin studied [36], according to (9):

$$\text{EM} = \frac{F_{\text{FSS}}}{d}. \quad (9)$$

The mean density of the Sorocaba River basin soils was determined by the classical method reported by Blake and Hartge [37], the core method, considering three distinct portions of the drainage basin established in accordance with the distribution of predominant soil types. In the headwater region, where the red-yellow Latosol prevails, the mean density soil was estimated at $1.24 \pm 0.02 \text{ t m}^{-3}$; in the middle part, with the predominance of red Podzols the mean density for this soil was $1.65 \pm 0.01 \text{ t m}^{-3}$; and at the downstream part of the basin, with a predominance of red Latosols, the mean density soil was $1.53 \pm 0.01 \text{ t m}^{-3}$. The mean density calculated from the Sorocaba River basin soil was $1.47 \pm 0.01 \text{ t m}^{-3}$.

The mechanical erosion rate calculated for the Sorocaba River basin is 37.99 m Ma^{-1} . Compared to other drainage basins with similar areas and land use predominantly agricultural, the physical degradation degree of the Sorocaba River basin was similar to that observed by Bortoletto Junior [30] for the Tietê (42.6 m Ma^{-1}) and the Piracicaba (37.0 m Ma^{-1}) Rivers, five times higher than the degradation of the Congo River, with 7.4 m Ma^{-1} [38], and thirteen times higher than the degradation of the Niger River, with values ranging from 2.4 to 3.4 m Ma^{-1} [39]. These differences could be related to land use processes in the respective drainage basins, particularly the agricultural practices of each region, such as soil management and types of crops, and other human activities developed there.

5. Conclusions

A focus of this study is to derive a better understanding of the mechanical erosion processes that occur in a tropical river basin of southeastern Brazil, where the predominant land use is agricultural, with increased urbanization in the past decade. The FSS load is influenced by the variation in discharge river during the study period, with the same seasonal effect. This situation is emphasized by suspended matter load associated with the quick surface runoff, which

was four times higher in the high water period than in dry periods.

However, the FSS chemical characterization for major oxides does not indicate that seasonal influence and the variability of concentrations observed during the study period were related to the mobility of these elements during rock weathering process. The mechanical erosion in the Sorocaba River basin was $55.70 \text{ t km}^{-2} \text{ a}^{-1}$, representing a physical degradation rate of 37.88 m Ma^{-1} , in the same magnitude of the other two major rivers that comprise the Middle Tiete basin.

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