Chemical Geology, 107 (1993) 333–336
Elsevier Science Publishers B.V., Amsterdam

Hydroclimatology and biogeochemistry of the Amazon
1. Erosion

Yves Tardy[a,b,c], Jefferson Mortatti[b], Reynaldo Victoria[b], Luiz Martinelli[b], Aristides Ribeiro[b], Carlos Cerri[b], Marisa Piccolo[b], Jener Leite de Moraes[b], Jean Luc Probst[c], Francis Andreux[d] and Boris Volkoff[a]

[a]*ORSTOM, Institut Français de Recherche Scientifique pour le Développement en Coopération, 213, rue Lafayette, F-75480 Paris, France*
[b]*USP, Universidade de São Paulo, CENA, Centro da Energia Nuclear na Agricultura, CP 96, 13400 970, Piracicaba SP, Brazil*
[c]*ULP, Université Louis Pasteur, CGS, Centre de Géochimie de la Surface, 1, rue Blessig, F-67084 Strasbourg, France*
[d]*CPB, Centre de Pédologie Biologique, rue Notre Dame des Pauvres, Nancy, France*

(Received March 17, 1993; revised and accepted March 30, 1993)

ABSTRACT

The Amazon is the largest stream in the world. Its basin covers at least $7 \cdot 10^6$ km^2, which represents ~5% of the global continental area and almost 70% of the area of the continents localized in the equatorial zone, between 5°S and 5°N of latitude. The global tropical moist forest covers ~$9.35 \cdot 10^6$ km^2, so that the Brazilian evergreen rain forest represents at least 50% of this area. At Obidos, the most accessible downstream station for collecting data, the area concerned is $4.619 \cdot 10^6$ km^2.

The purpose of these two extended abstracts is to show how changes and oscillations of climate can significantly affect erosion as well as carbon and nitrogen cycles, and may also mask the degradations of the environment due to deforestation.

1. Hydroclimatology of the Amazon for the last 100 years

For the basin as a whole, climatic and hydrological parameters are given in Table 1. These coefficients are relatively high by comparison with other tropical regions. At Obidos ($4.619 \cdot 10^6$ km^2), the average total runoff (1027 mm yr^{-1}, 4744 km^3 yr^{-1} or 149,700 m^3 s^{-1}) represents 11.9% of the global water discharge (40,000 km^3 yr^{-1}).

For the last 100 years, the average temperature has been decreasing slightly, between 28° and 26°C, while the rainfall and the stream flow have been rising together. Rainfall has been oscillating between 1600 (which, for Amazonia, is relatively dry) and 2800 mm yr^{-1} (which is relatively humid). The total runoff at Obidos exhibits very large interannual fluctuations, around the average of 150,000 m^3 s^{-1}, between 130,000 and 180,000 m^3 s^{-1} (Fig. 1).

For the purpose of modelization, the following linear relationships have been established which allows the evaluation of rainfall (P) and evaporation (E) if the total runoff (D_t) is known, or to evaluate runoff and evaporation if the pluviosity is given. These relationships are valid within the range of values measured during the last 100 years (Table 1):

$$P = -1120 + 3.153 D_t \quad (\mathrm{mm\ yr^{-1}}) \qquad (1a)$$

$$E = -1120 + 2.153 D_t \quad (\mathrm{mm\ yr^{-1}}) \qquad (1b)$$

$$D_t = +355 + 0.317 P \quad (\mathrm{mm\ yr^{-1}}) \qquad (2a)$$

$$E = -355 + 0.683 P \quad (\mathrm{mm\ yr^{-1}}) \qquad (2b)$$

Along the historical series both evapotranspiration and runoff increase together with

TABLE 1

Hydroclimatology of the Amazon basin as a whole: secular averages and extremes interannual characteristics between the most humid and the driest year

	Temperature (°C)	Humidity of the air (%)	Rainfall (mm yr^{-1})	Evapotranspiration (mm yr^{-1})	Runoff (mm yr^{-1})			K_e (%)	K_r (%)
					rapid	slow	total		
1969	26	90	2,646	1,452	414	780	1,194	45	35
Average	26.7	85	2,120	1,093	255	772	1,027	48	25
1919	28	80	1,470	649	58	763	821	56	18

K_e is the runoff coefficient ($=D_t/P$, where D_t=total runoff and P=precipitation); K_r is the surface runoff coefficient ($=D_r/D_t$, where D_r=rapid superficial runoff and D_t=total discharge).

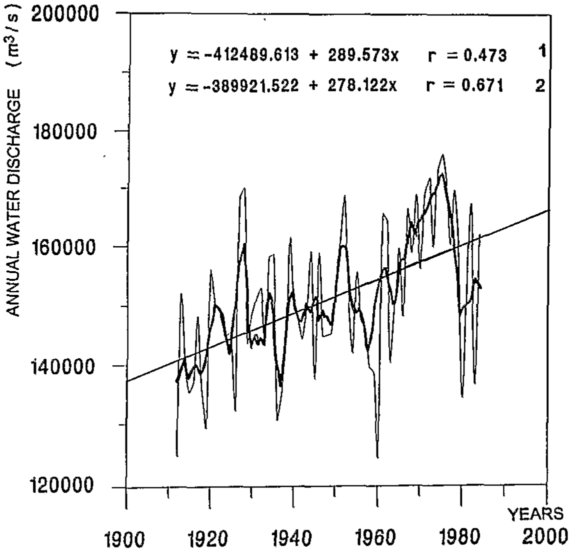

Fig. 1. Secular oscillations of the total water discharge (D_t, in m^3 s^{-1}) of the Amazon at Obidos. Annual discharge (*1*) and 3-year mobile averages (*2*) are presented. It shows that the water discharge oscillates, but rises from the first to the second part of the century.

rainfall. However, it should be noticed that K_e, the runoff coefficient ($K_e=D_t/P=355/P+0.317$), rises when P decreases or decreases when the pluviosity increases. However, if one considers different regions in the world, under a large variety of climates, one observes that K_e increases with rainfall. Further research will determine if the decrease of K_e when rainfall rises is a peculiarity of the Amazon basin or a characteristic of the climatic zone in which it is located.

2. Superficial runoff and mechanical erosion

It seems necessary to recall that the mechanical erosion occurs only in the rapid superficial runoff (D_r) and not in the slow and base infiltered runoff (D_b), while the chemical erosion plays a part in both superficial (D_r) and base water flows (D_b). The total water discharge (D_t), which flows out of the basin, is in fact the sum of the two contributions ($D_t=D_r+D_b$). It is not possible to solve the problems of erosion without solving first the questions of the superficial runoff in which it occurs exclusively.

For large basins, the superficial runoff is undeterminable directly but can be evaluated by models. The model which seemed the most appropriate acts with two water reservoirs (D_r and D_b), of a constant composition, but mixing in different proportions. Analysis of historical series would give simple answers, the accuracy of whose is increasing with the number of data collected and the duration of observations. The data used here, for the evaluation of the two components of the stream flow are those of the seven cruises of "CAMREX", organized between 1982 and 1984 (Jeff Richey, from the University of Washington, Seattle, U.S.A., leader of the project) and are given in Table 2.

Nitrate and sodium are exclusively concentrated in the infiltrating waters. Potassium comes from the two reservoirs but principally

TABLE 2

The runoff model: calculated concentrations of the chemical parameters, characterizing the two types of water flow in the Amazon basin

Runoff		(%)	NO_3	Na	K	POC_f	POC_c	POC_t	SS_f	SS_c	SS_t
Total	D_t	100	12.5	112.4	27	2.24	0.29	2.53	201	29	230
Superficial	D_r	29	0	0	57	5.96	0.82	6.78	582	93	675
Infiltrating	D_b	71	17.6	158.3	19	0.73	0.07	0.80	72	7	79

NO_3, Na and K are ions in solution (μmol l^{-1}); POC*f* and POC_c are the particulate organic carbon (f=fine fraction; c=coarse fraction) (mg l^{-1}); SS_f, SS_c and SS_t are solid suspensions (f=fine, c=coarse, t=total) (mg l^{-1}).

from the surface runoff waters. Organic or mineral suspensions are all — as expected — mostly coming from the surface runoff waters. Other parameters, not listed, are variably distributed in the two types of reservoirs. In the water of the superficial runoff, the concentration of suspended solids is ~100 times greater for the mineral ($SS_t = 675$ mg l^{-1}) than for the organic part ($POC_t = 6.78$ mg l^{-1}). If one defines ME_m and ME_o as the mineral and the organic mechanical specific erosion, respectively (in t km^{-2} yr^{-1}), calculated by multiplying the concentration SS_t or POC_t by D_r, taking 1982 as an example, one obtains:

$$ME_m \ (\mathrm{t\ km^{-2}\ yr^{-1}}) = 675 \times 366 : 1000$$
$$= 247 \ \mathrm{t\ km^{-2}\ yr^{-1}}$$

Data on superficial runoff and mechanical erosion for the Amazon basin at Obidos are presented in Table 3. Mechanical erosion of the Amazon is of the same order as the global erosion (152 t km^{-2} yr^{-1}). The concentration of suspended solids in the total water flow (D_t) decreases when the rainfall increases. However, in the superficial rapid runoff, the concentration is constant. In humid years, the mechanical erosion increases because the superficial runoff rises with rainfall. The model, based on the following linear relationships, is only valid for P values between 1500 and 3000 mm yr^{-1}:

$$D_r = 0.303P - 387 \quad (\mathrm{mm\ yr^{-1}}) \quad (3)$$

$$D_b = 0.014P + 742 \quad (\mathrm{mm\ yr^{-1}}) \quad (4)$$

$$ME_m = 0.205P - 261 \quad (\mathrm{t\ km^{-2}\ yr^{-1}}) \quad (5)$$

and

$$ME_o = 0.00205P - 2.62 \quad (\mathrm{t\ km^{-2}\ yr^{-1}}) \quad (6)$$

D_r progresses significantly with rainfall, while D_b progresses very slowly. This is simply because under humid climates groundwater reservoirs are close to saturation.

It can be shown that the specific mechanical erosion for both mineral and organic materials

TABLE 3

Superficial runoff (D_r) and mechanical erosion in Amazon, at Obidos, for the years 1982–1984

Year	P (mm yr^{-1})	D_t (mm yr^{-1})	K_e (%)	D_r (mm yr^{-1})	K_r (%)	ME_m (t km^{-2} yr^{-1})	ME_o (t km^{-2} yr^{-1})
1982	2,487	1,144	46	366	32	247	2.48
1983	1,834	937	51	169	18	114	1.14
1984	2,377	1,109	47	333	30	225	2.25
Mean	2,233	1,063	48	289	27	195	1.96

Specific erosion is given in t km^{-2} yr^{-1}. ME_m and ME_o are respectively the mineral (m) and the organic (o) mechanical erosion (ME).

TABLE 4

Evaluation of the average annual mechanical erosion in the Amazon for the last 100 years

Years	P (mm yr^{-1})	D_r (mm yr^{-1})	ME$_m$ (t km^{-2} yr^{-1})	ME$_o$ (t km^{-2} yr^{-1})
Less humid (1919)	1,470	58	39	1.05
First part of the century (1912–1932)	1,959	206	139	1.40
Average for the last 100 years	2,120	255	174	1.75
Last part of the century (1964–1984)	2,265	298	201	2.02
Most humid (1969)	2,646	414	279	2.80

ME is the mechanical erosion (m and o denote mineral and organic, respectively).

increases with rainfall in more humid times and decreases in less humid periods. Results of the estimated erosion for the past 100 years are in Table 4.

It can be shown also that the mechanical erosion should have been progressing with the humidity of the climate. If this secular tendency is attributed to deforestation, which in fact began in the 1970's, thus deforestation might also be responsible of an increase of humidity. This conclusion contradicts some ideas commonly expressed.

We believe that an increase of the mechanical erosion could be mostly the effect of climatic oscillations (natural?) which mask the possible effect of human deforestation. The precise knowledge of the rate of erosion will be therefore deferred as long as clearly established strategies will not exist for organizing historical series of observation, i.e. observatories in which data will be systematically collected over long periods of time.

Chemical Geology, 107 (1993) 411–414
Elsevier Science Publishers B.V., Amsterdam

Hydroclimatology and biogeochemistry of the Amazon
2. Geochemical cycles

Yves Tardy[a,b,c], Jefferson Mortatti[b], Reynaldo Victoria[b], Luiz Martinelli[b], Aristides Ribeiro[b], Carlos Cerri[b], Marisa Piccolo[b], Jener Leite de Moraes[b], Jean Luc Probst[c], Francis Andreux[d] and Boris Volkoff[a]

[a]*ORSTOM, Institut Français de Recherche Scientifique pour le Développement en Coopération, 213, rue Lafayette, F-75480 Paris, France*
[b]*CENA, Centro da Energia Nuclear na Agricultura, USP, Universidade de São Paulo, CP 96, 13400 970, Piracicaba SP, Brazil*
[c]*CGS, Centre de Géochimie de la Surface and ULP, Université Louis Pasteur, 1, rue Blessig, F-67084 Strasbourg, France*
[d]*CPB, Centre de Pédologie Biologique, rue Notre Dame des Pauvres, Nancy, France*

(Received March 17, 1993; revised and accepted March 30, 1993)

1. Total water discharge and chemical erosion

Chemical erosion takes part principally in infiltrating waters (D_b) but also in the superficial runoff (D_r) carrying partly immature sediments which are deposited in flooded zones (varzeas). As well as for nitrate and sodium, it is relatively easy to determine what the different concentrations in the two major reservoirs are: D_r and D_b (Table 1).

Potassium, calcium and above all magnesium metabolized and recycled by plants are concentrated in surface waters. The quality of analyses of sulfates and chlorides is poor, so that by the method followed no trend can be really demonstrated for these two variables. However, the electrical balance (S meq cations $-$Alk.$=S^+-S^-$) shows a large variance in waters of surface runoff. This also suggests important quantities of sulfur and chlorine are recycled by plants near the soil surface (Tables 1 and 2).

Results of table 4 of Part 1 (Tardy et al., 1993 in this issue) show that as an average, the mechanical erosion is 174 t km^{-2} yr^{-1}. This corresponds to an ablation of 87 m each 10^6 yr. On the other hand, results of Table 2 show that as an average the amounts of silica are 135 μmol l^{-1}, which corresponds approximately to an alteration of 8.3 m of rocks each 10^6 yr. Mechanical ablation seems 10 times greater than the chemical erosion.

As shown by values of $R_e=(3\text{Na}+3\text{K}+2\text{Ca}+2\text{Mg}-\text{SiO}_2)/(0.5\text{Na}+0.5\text{K}+\text{Ca}+\text{Mg})$, the calculation of a mass balance for chemical weathering in su-

TABLE 1

Chemical composition (in μmol l^{-1}; for Alk, DOC, S^+ and S^-: meq l^{-1}) of dissolved elements in the two major water reservoirs of the Amazon basin

Reservoir	SiO_2	Na	K	Ca	Mg	Alk	NO_3	DOC	(S^+)	(S^+-S^-)
Groundwater	132	158	19	105	26	303	18	22	439	96
Surface runoff	144	0	57	420	135	866	0	24	1,167	277
Total discharge	135	112	27	186	50	439	12	23	611	137

TABLE 2

Weathering and chemical composition of the two major reservoirs of water of the Amazon basin, after correction of the rain contribution

Reservoir	SiO_2 (μmol)	Na (μmol)	K (μmol)	Ca (μmol)	Mg (μmol)	R_e	pH	$\log p_{CO_2}$
Rain contribution	0	10	5	6	2			
Groundwater	132	143	15	102	25	2.89	6.73	−2.44
Surface runoff	144	0	46	388	130	1.68	7.23	−2.48
Total discharge	135	102	22	180	48	2.39	6.85	−2.40

perficial runoff as well as in groundwater is strongly perturbed by the storage of K, Ca, Mg, SO_4 and even Cl in vegetation and soil layers. Therefore, the balance can be accounted for in the total discharge water, where all reservoirs are well mixed.

Careful studies of the chemical and mineralogical compositions of suspended materials and their weathering evolution in the floodplain have shown that Ca- and Na-plagioclases as well as vermiculites and smectites are altered into kaolinite which, along the course of the river, progressively concentrate with quartz. Furthermore, kaolinite and quartz dominate in all the Amazon soils. Thus the molecular ratio $R_e = SiO_2/Al_2O_3$ in soil products, as index of weathering, should reflect the formation of kaolinite and approach the value of 2, instead of 2.39 (Table 2).

The total CO_2 consumed by chemical weathering through photosynthesis and further mineralization of organic matter in soils depends on the contributions of salts, carbonates and silicates in their respective proportions. Data of Table 3 are the result of a modelization which takes into account the different sources of parent-rock materials.

Ca is in Ca-plagioclase ($CaAl_2Si_2O_8$), in calcite ($CaCO_3$), in dolomite ($CaMg(CO_3)_2$) and in gypsum ($CaSO_4$); Mg is in Mg-silicates ($MgAl_2Si_2O_8$) and in dolomite ($MgCa(CO_3)_2$); and Na is in albite ($NaAlSi_3O_8$) or halite (NaCl).

The consumption of CO_2 is for silicates two times greater than for carbonates, so that the total budget of CO_2, consumed by weathering can be evaluated (Table 3). This amount (357 μmol l^{-1}), the result of organic matter oxidized in the soil solution, corresponds to a flux of organic carbon of 4.3, a flux of CO_2 of 15.7 and a flux of organic matter of 10.7 t km^{-2} yr^{-1}, thus 6 times greater than ME_0, the mechanical organic erosion rate.

TABLE 3

Sink-budget of CO_2 (μmol l^{-1}) consumed by weathering calculated in the total discharge of the Amazon at Obidos

Na from NaCl	49; $CO_2=0$
Na from plagioclases	53; $CO_2=53$
Na total	102; $CO_2=53$
Mg from carbonates	28; $CO_2=28$
Mg from silicates	20; $CO_2=40$
Mg total	48; $CO_2=68$
Ca from $CaSO_4$	46; $CO_2=0$
Ca from carbonates	54; $CO_2=54$
Ca from silicates	80; $CO_2=160$
Ca total	180; $CO_2=214$
K from silicates	22; $CO_2=22$

CO_2 from weathering = 357 (82 carbonates, 275 silicates); CO_2 primarily in carbonates = 82; CO_2 total dissolved = 439; alkalinity measured = 439; R_e from silicates = 2.11.

2. Biodegradation and geochemistry of soil solution

Several thousands of chemical analyses of soil solution collected near Manaus have been performed (Tables 4 and 5). In the top soil, compared with samples taken at depth, all ele-

TABLE 4

Chemical composition and characteristics (μeq l^{-1}) of soil solution with depth and of the calculated base flow (groundwater) component (D_b) at Obidos

Position	SiO_2	H	NH_4	Na	K	Ca	Mg	S^+	NO_3	DOC	HCO_3	SO_4	Cl	S^-
20 cm	220	92	40	98	58	64	88	440	110	86	162	50	32	440
120 cm	100	8	10	66	36	40	52	212	46	77	55	20	14	212
Groundwater	132	0	0.5	158	19	210	52	440	18	22	303	62	35	440

TABLE 5

Chemical composition of soil solutions and of the base flow component presented for the calculation of p_{O2} and p_{CO2}

Position	pH	NO_3	NH_4	$\log p_{O_2}$	DIC	$\log p_{CO_2}$	DOC	DIC/DOC	C/N ox
20 cm	4.04	0.11	0.04	−27.35	0.162	−0.03	0.086	1.884	14.7
120 cm	5.09	0.05	0.01	−28.49	0.055	−1.55	0.077	0.714	11
G.W.	6.73	0.022	0.005	−27.70	0.303	−2.44	0.022	13.78	13.8

$\log p_{O_2} = 0.5[-47.154 - 2pH + \log(NO_3)/(NH_4)]$; $\log p_{CO_2} = 7.8 - pH + \log(HCO_3)$; ( ) = ion activity; $(C/N)_{ox} = (HCO_3)/(NO_3)$; G.W. = groundwater component in the total flow; DIC = dissolved inorganic carbon; DIC = HCO_3 or H_2CO_3; DOC = dissolved organic carbon.

ments seem to be concentrated. Apparently these elements are being activley recycled by the vegetation.

As also shown by the evolution of the ratios of ion activities (noted between parentheses): $(NO_3)/(NH_4)$ and DIC/DOC, it seems likely that p_{CO_2} and p_{O_2} decrease from the top to the bottom of the soil profiles. The partial pressure of CO_2 is ~3000 times higher in the soil atmosphere than in the atmosphere itself. Consequently, CO_2 will tend to diffuse from the soil surface: (1) for a smaller part to the deep horizons; and (2) for a larger part to the atmospheric air. Contrarily, the partial pressure of oxygen in the atmosphere is much higher than in the soil, so that O_2 will diffuse from the atmosphere to the depth where it is used for oxidation.

In all cases studied, dissolved inorganic carbon (DIC) is higher either in surface horizons or in surface runoff flow than either in the deep horizons of soils or in the groundwater flow. It indicates that the CO_2 consumed in more humid periods will be higher than in less humid or arid time periods. At any rate, the metabolism of the great evergreen forest is enhanced when climate becomes more humid.

3. Biomass and cycles of carbon and nitrogen

The living phyto-biomass in Amazonia is ~14% of the global continental phytomass, i.e. 270 t ha^{-1}, equal to $2.7 \cdot 10^4$ t km^{-2}, and is equivalent to $1.1 \cdot 10^4$ t km^{-2} of carbon, ~$0.016 \cdot 10^4$ t km^{-2} of nitrogen and $1.6 \cdot 10^4$ t km^{-2} of water. In the organic material of the living rain forest, the ratio C/N (ponderal) is close to 69, while $\delta_{13}C$ is practically equal to −29.6‰. Data for other reservoirs are given in Table 6.

The residence time of C, H, O and N in the phytomass ($C_{80}H_{256}O_{78}N$), with respect to photosynthesis and mineralisation or respiration, is calculated as follows: $2.70 \cdot 10^4/8{,}250 = 3.27$ yr, which represents on age intermediate between that of old trees and young leaves.

The residence time in soils of the same elements constituting the organic matter or humus ($C_{12}H_{20}O_{10}N$) is calculated as follows: 27,000 : 24.8 = 1088 yr. The age of Amazonian

TABLE 6

Size of the organic reservoirs and fluxes of carbon and nitrogen

	$\delta^{13}C$ (‰ vs. PDB)	C/N (ponderal)	(10^4 t km^{-2})		
			CH_2O	C	N
Organic matter reservoir: Characteristics and size					
Living phytobiomass	−29.6	69	2.70	1.10	0.016
Litter	−30	27	–	–	–
Soils up to 150 cm	−27	10	2.92	1.17	0.110
Sediments of flood plain	−28.6	10	2.34	0.94	0.089

	C/N (ponderal)	(t km^{-2} yr^{-1})		
		CH_2O	C	N
Carbon and nitrogen in the Amazon: Characteristics and flux				
Total flux in Amazon, average (1030 mm yr^{-1})	35	24.8	10.00	0.28
Flux in superficial runoff (250 mm yr^{-1})	35	10.6	4.24	0.12
Flux in groundwaters (780 mm yr^{-1})	35	14.2	5.76	0.16
Total flux for 1969, a very humid year	35	28.2	12.68	0.35
Total flux for 1919, a very dry year	35	16.4	6.62	0.18
Primary production	69	8,250	3,300	48

humus, in fact, approaches 1000 yr.

It seems that the transformation of a part of the living phytomass into humus occurs more or less at constant nitrogen concentrations. The C/N ratio in the chain of the relict products, from trees, to litters and finally to humus, is decreasing significantly.

The transformation of 24.8 t km^{-2} yr^{-1} liberates water (dehydration) and CO_2 (decarbonation), but in quantities very small compared to the fluxes of transpiration, oxidation and decarbonation of organic matter previously photosynthesized.

If we assume a steady state and constant organic matter concentration levels in soils, the fluxes of destruction–formation are equal. Consequently, the part which goes from the phytomass to the soil (24.8 t km^{-2} yr^{-1}) each year is equal to the part which is transferred to waters in runoff or infiltration. Therefore, this part is negligible compared to the one which returns to the atmosphere after respiration of living plants or oxidation of the litters (8225 t km^{-2} yr^{-1}).

Furthermore, the amounts of organic matter eroded from soils seem likely to increase in humid periods when rainfall increases and decrease in less humid periods when rainfall decreases. Erosion is more the fact of humidity than aridity.

References

Tardy, Y., Mortatti, J., Victoria, R., Martinelli, L., Ribeiro, A., Cerri, C., Piccolo, M., Leite de Moraes, J., Probst, J.L., Andreux, F. and Volkoff, B., 1993. Hydroclimatology and biogeochemistry of the Amazon, 1. Erosion. In: L.R. Kump (Guest-Editor), Geochemistry of the Earth Surface. Chem. Geol., 107: 333–336 (this special issue).