Geochemistry of the Sahelian Gambia River During the 1983 High-Water Stage

by

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With 8 Figures and 2 Tables

Contents

1. Introduction

Despite recent efforts to fill the gap (Lenoir, 1972 for the Bandama; Gac & Pinta, 1973 and Gac, 1979 for the Chari; Eisma & Cadeé, 1982 and Deronde & Symoens, 1980 for the Zaire; Martins, 1983 for the Niger), our knowledge on the chemistry of African rivers is far beyond those of any other continent. The scarcity of these academic studies is confirmed by the very poor regular water quality surveys made by African countries (see the GEMS Water Programme, Meybeck, this volume). A remarked contribution has been given by Lesack et al. (1984, 1985) for the Gambia River in Senegambia, West Africa. They have studied, during a whole hydrological cycle (July 1980–June 1981), major elements, nutrients and organic carbon species, although on a restricted number of samples (12/year).

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Within the framework of a hydrological study of Gambia, during the high-water stage of 1985 (Ló, 1984), we have reconsidered the geochemistry of this river with three objectives:

– detailed study (daily samples for suspended matter, every 3 days for water chemistry) of the high-water stage (3 months);

– comparison of particulate organic carbon in the Gambia River for 1982, 1983, and in the Senegal River for 1983 with previous measurements of LESACK et al. (1984);

– dissolved and suspended transport budgets; rain contribution to the dissolved solutes.

2. The Gambia Watershed, Sampling and Analysis

Most prominent features of the watershed have already been presented by LESACK et al. (1984) and Lô (1984). Therefore, a short description will only be given here.

The Gambia River originates at an altitude of 1,538 m, in the Fouta Djalon Mountains in Guinea, then flows north in Senegal and reaches the ocean through an extended estuary located in Gambia State (Fig. 1 A). The Gouloumbou
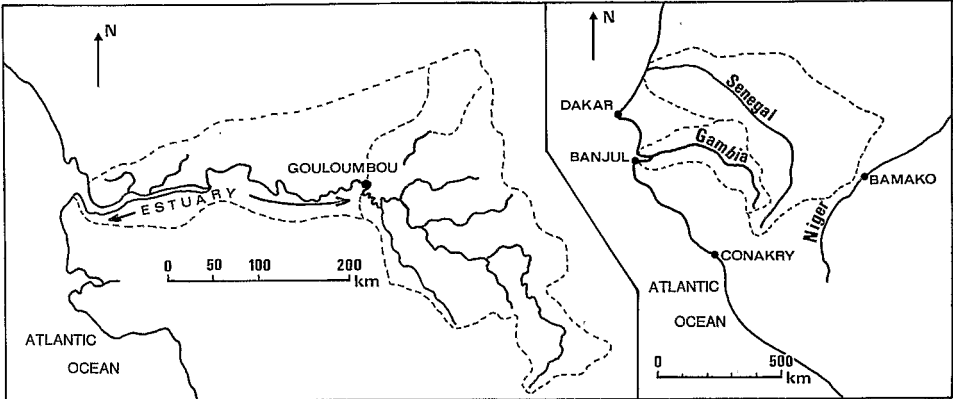

Fig. 1A: The Gambia river basin. Gouloumbou is the gauging station where the study has been realized.

gauging station marks the most upstream dynamic tide influence in the estuary and has been chosen for this reason as the sampling station for fresh water chemistry and for suspended matter (SM). At Gouloumbou, the drainage area is 42,000 km² and the median elevation is 100 m. The greatest part of the watershed rocks are Cambrian schists (few of them calcareous) and quartzites, and cristalline rocks (dolerite, rhyolite, granite) in the upper basin, while sandstones and clayey sands dominate in the lower basin. Probably less than 5 % of the area are covered by calcareous rocks, evaporites were not reported (LESACK et al., 1984).

As for the relief, there is a strong north–south climatic gradient from the herbaceous savanna, characteristic of all the northern part of the Gambia, continued by the forested savanna at the middle reach of the river (Senegal–Guinea border), to the Guinean forest, in the southern basin (altitude exceeding 600 m). Vegetation, and rain distributions are of course very similar (Lô, 1984), and three major climatic sections can be distinguished from north to south (Fig. 1 B): the North Sudanian type (average rain for 1951–1980, from 700 to
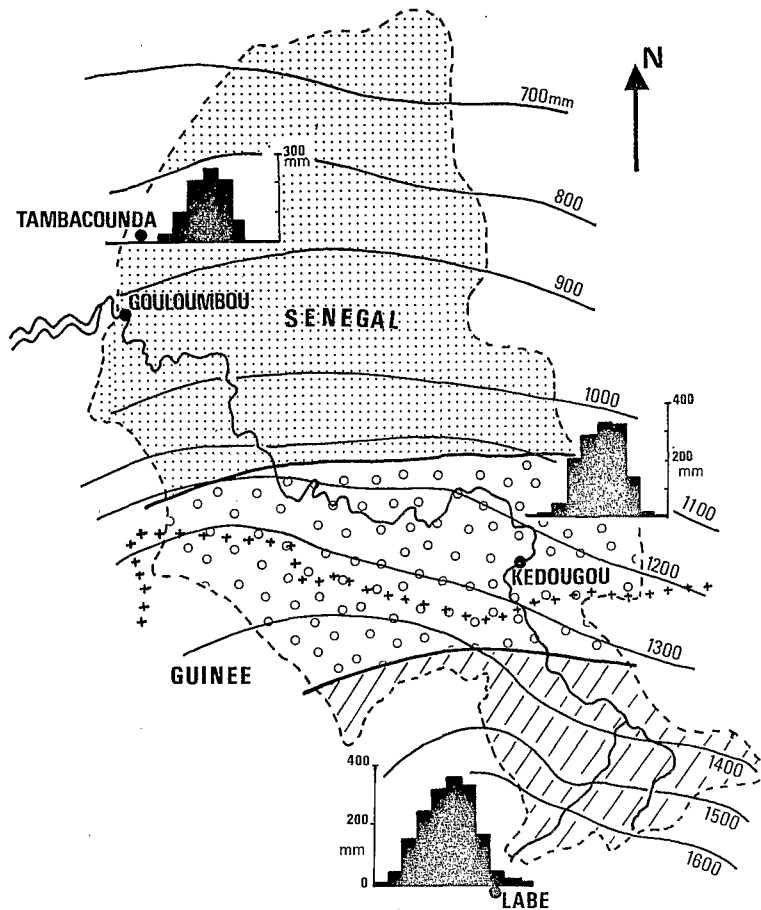
Fig. 1B: Average isohyets (1951-1980) on the continental Gambia river basin (Lô, 1984).
Hatched areas correspond to the 3 major climatic belts, from north to south: North
Sudanian, South Sudanian, and Guinean. Monthly rain variation are given for
Tambacounda, Kedougou and Labé. (Maximum rain in August).

1,100 mm/year), the South Sudanian type (from 1,100 to 1,400 mm) and the
Guinean type (from 1,400 to more than 1,600 mm). The monthly rain variations,
at any station in the watershed, present a well-marked maximum in summer
(maximum rain in August) and a minimum in winter. At the most southern
stations of Labe (in Guinea), the monthly rain varies from 3 mm in February to
355 mm in August (annual average 1,660 mm). At Tambacounda, in the north,
the dry season (less than 2 mm/month) extends from December to April, and the
maximum drops to 246 mm in August (annual average 854 mm).

Monthly temperatures are relatively stable: around 20 °C all through the
year in Labe, from 25 to 30 °C at Tambacounda. The potential evapotranspiration
is therefore also relatively constant (from 100 to 200 mm/month). As a result, the
hydrological regime of the river is directly related to the rain distribution and
the maximum water discharge at Gouloumbou gauging stations is noted in
September. The high-water period extends every year from July to October.
Rainfall distribution and limited ground water storage are responsible for a
marked monthly variation of discharge: at Gouloumbou (1970–1981), the ratio
monthly average/yearly average varies between 0.02 in April and May to 4.28 in

463

September (Lô, 1984). The water discharged by the river at Gouloumbou (1970–1981), from August to October, is 83 % of the total annual volume.

The sampling period has been focused on the 1985 high-water stage, from June 26 to September 27:

– Suspended matter (SM), pH, temperature, conductivity: daily sampling. SM measurements have been realized from a 64 l sample to which 5 cm³ of HCl were added to ease flocculation. After 2 x 24 h settling, the settled particles (about 1 l) were stored and shipped to the laboratory where they were collected by centrifuging.

– Major ions and silica: one sample every 3 days. Samples were filtered in the field, spiked with chloroform, and stored. Samples were analyzed 3 months later, in the ORSTOM Laboratory in Dakar.

– Samples for particulate organic carbon (POC) determination has been filtered every 3 days in the field, on Whatman GFF filters pre-ignited and pre-weighed, stored dry, and determined with a Leco analyzer.

– Rain chemistry has been studied at Gouloumbou, on weekly bulk samples.

POC results will be compared to a limited survey during the 1982 high-water stage (7 samples) at Gouloumbou station, and to a similar survey of the Senegal River at Bakel (see Fig. 1A), from June 24 to October 7, 1983.

The 1983/1984 water year at Gouloumbou has been much dryer than usual, a consequence of the Sahelian drought. The annual average discharges were the following: 1983–84, 59 m³/s; 1953–83, 115 m³/s; 1970–81, 81.4 m³/s. The 1980–81 water year sampled by LESACK et al. (1984) was more representative (86 m³/s) of the last decade than our period. The major difference between 1983/84 and previous years is noted for the high-water stage: the average water discharge for this period is only 34 % of the 1970–1981 value. For 1983–84, the runoff coefficient has only been 6.9 % (Lô, 1984), which corresponds to a specific discharge at Gouloumbou of 1.4 l/s/km². Actually, this water year has been the driest ever recorded at Gouloumbou and would correspond to a 500 year return period on the basis of the 1955–1983 data. However, water discharges for the last 13 years may not have the same distribution as the 1953–1970 period (FAURE & GAC, 1981).

3. Pattern of the Suspended Matter (SM) Transport

The SM daily variation during three months is presented on Figure 2, together with the daily discharge. As frequently noticed in solid transport studies, the first part of the high-water stage is the most turbid one. The striking feature is the relatively high SM level around July 1st, which occurs before any water discharge variation. This first peak could be caused by the first local rains near Gouloumbon. A second peak is linked to the first flood and reaches the highest values on July 10th.

From July to September, the pattern of the SM-water discharge variations (Fig. 3) is characterized by a series of loops with decreasing maximum values. The SM level at the yearly maximum water discharge (363 m³/s) is a factor of two less than the July 10th value (100 m³/s). These loops reflect the highest turbidities observed during the rising stage of floods and are well known for this type of river (GAC & KANE, 1986a; GAC & CARN, 1986). In September, the SM levels are relatively low (less than 50 mg/l for water discharges higher than 200 m³/s) and poorly connected with discharge-variations.
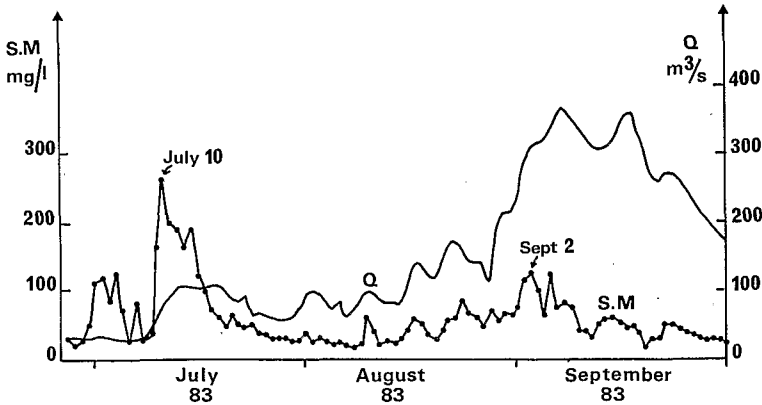
Fig. 2: Water discharge (Q) and suspended matter (S. M.) variations in Gambia river at Gouloumbou during the 1983 high-water stage.
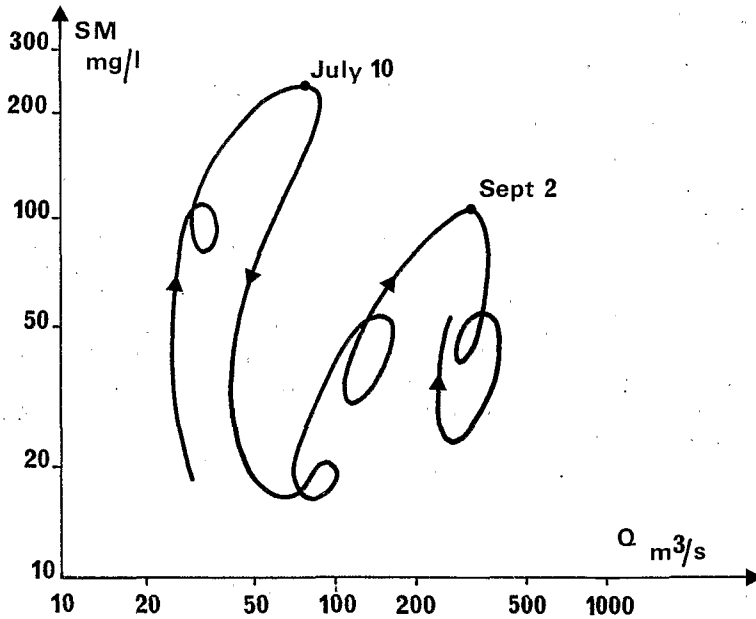

Fig. 3: Schematic loops of suspended matter (S. M.) versus discharge (Q) from July to September 1983 in the Gambia River.

This clearly emphasizes the need for a regular sampling procedure for such rivers based on at least weekly samples. Monthly measurements cannot record such loop patterns.

4. Evolution of Major Ions

As already noted by LESACK et al. (1984), the Gambia River waters are characterized by their low ionic content. The sum of cations (Σ^+) has varied in 1983 from 290 µeq/l to 1,090 µeq/l, and during this high-water stage, 90 % of Σ^+ measurements were between 310 and 560 µeq/l. Bicarbonate is the most abundant anion (95 % of Σ^-), and its variation reflects the stability of the dissolved ions during the flood period (Fig. 4). An example of the concentration versus

465
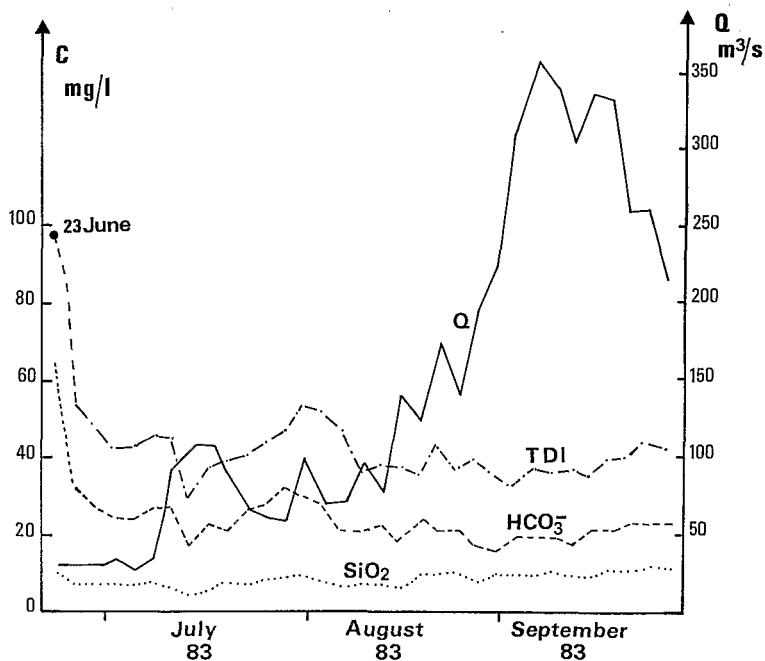
Fig. 4: Variations of total dissolved ions (TDI cations plus anions in mg/l) bicarbonates, dissolved silica, and water discharge, during the 1983 flood period in the Gambia River at Gouloumbou.

discharge variation is given for calcium on Figure 5; it emphasizes a limited dilution of ground water with surface runoff during the flood. This variation is in good agreement with the one previously observed by LESACK et al. for 1980/81.

Fig. 5: Calcium versus water discharge (Q) variations in Gambia river + three months survey during the 1983 flood; ● monthly samples in 1980–1981 taken by LESACK et al. (1984) at the same station.

466

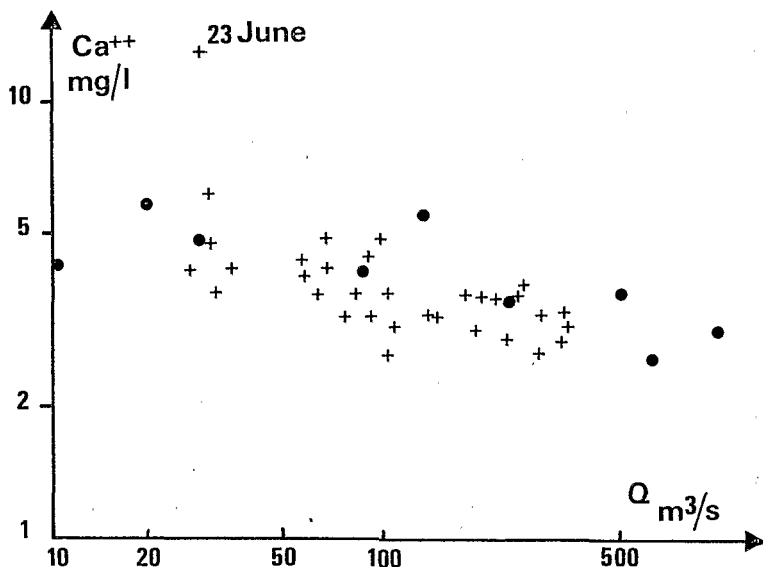The first sample of our study (June 23, 1983) shows much higher ionic contents than usual, but with similar ionic proportions. A contamination remains possible. If not, ist could be attributed to the washout of some evaporitic salts, resulting from the previous dry season, from the river banks and/or soils, during the very first rains. This very short episode cannot be confirmed because of lack of samples.

5. Particulate Organic Carbon (POC) Variations

The POC content of suspended particles varies between 8 and 1.2% (dry weight). This variation is closely linked to the amount of SM (Fig. 6) as already noted by MEYBECK (1982) and confirmed in numerous other studies (MILLIMAN et al., 1984; DEGENS & ITTEKKOT, 1985). The 11 samples taken in 1980/81 by LESACK
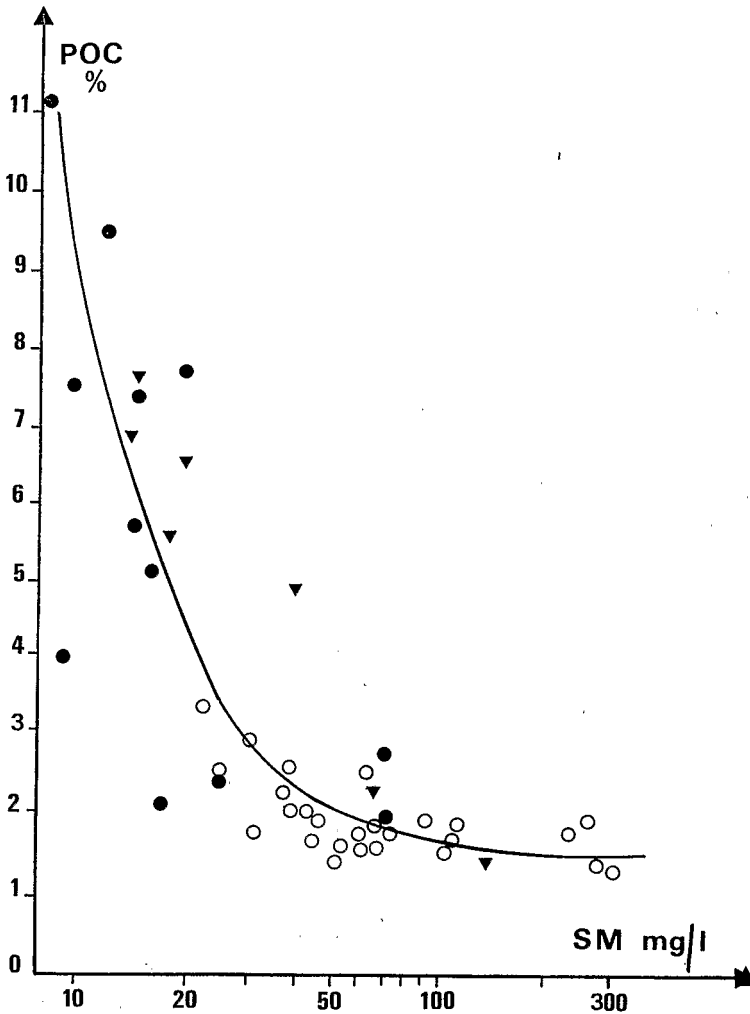

Fig. 6: Particulate organic carbon (POC, in % of suspended matter) versus suspended matter (S. M.) in Gambia River. ▼ 1982, high water stage; o 1983 high water stage; ● monthly syamples 1980–1981 from LESACK et al. (1984).

et al. (1984) fit quite well within the variation observed for the high-water stage in 1982 and in 1983. This general decrease is connected to two processes:

i)   during the low-water period, POC is a mixture of allochtonous and autochtonous matter (phytoplankton, periphyton) while at higher discharges, the terrigenous inorganic material is much more abundant;

ii) POC is mainly allochtonous and originates from soil erosion; during the high-water period, the linear erosion in channels (characterized by low organic matter contents) increases more rapidly than the sheet erosion of soils richer in organics. Actually, both processes may occur simultaneously as observed in the highly eutrophied Loire (see CAUWET & MEYBECK, this volume). A simple means to decipher the origins of POC is to survey the algal pigments (DESSERY et al., 1984) which has not been possible here for lack of freezing possibilities in the field.

6. Discussion

6.1 Water Chemistry

The average dissolved contents (Table 1) of Gambia water have been weighted by the water discharge for the 1983/84 water year considering the 33 samples

Table 1
Average composition (C_i) of Gambia River water during the 1983 flood
(myeq/l for ions, mymol/l for silica)

	SiO_2	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-	% discharge	cation sum	anion sum
Flood period C_i (July to September)	140	170	122	67	21	18	<10	352	71 %	380	<380
Dry period [1] C_i (October to June)	145	251	202	131	27	11	15	(585)[3]	29 %	611	611
Annual average:											
1983/84 C_i	143	194	146	86	23	16	(10)	422	100 %	449	448
% (4)		43	32	19	5.5	3.5	2.5	94			
1980/81[2] C_i	213	84.8	69.5	147	29.9	13.8	3.9	284		332	302
% (4)		26	21	44	9	4	2	94			

1) taken from 1980/81 study of LESACK et al. (1984);
2) LESACK et al., discharge-weighted mean of 12 samples;
3) estimated to fit the ionic balance;
4) ionic proportions of cation and anion sums.

taken during the 3 months flood period studied, and, for the remaining 9 months of the dry period not sampled, on the basis of the average quality observed by LESACK et al. (1984), from November to June.

Our measurements present some discrepancies with the previous study of LESACK et al. (1984) which are due to the greater contribution of relatively more mineralized ground waters in 1983 than in 1980. However, the ionic proportions should have remained similar which is not the case: Na^+ and Ca^{2+} abundances are inverted.

The Gambia water chemistry cannot be fully understood without consideration of the rain input. We are reporting here (Table 2A) the average rain concentration at two stations of the Gambia basin (Gouloumbou and Kedougou, see location on Fig. 1) compared to some Ivory Coast stations. All analyses reflect the limited amount of dissolved matter at these inland stations. The ionic ratio to Cl^- (C_i/Cl^-) are very close from one station to another, except for Ca^{2+}, a highly variable element in continental precipitation.

Average ionic ratios have been determined, and the rain contribution to Gambia watershed has been computed as follows (MEYBECK, 1983):

i) river Cl⁻ is assumed to be only of atmospheric origin which seems reasonable when considering the lack of any evaporitic rocks in the watershed;

ii) rain contributions for other ions C_i have been considered to be proportional to Cl⁻ levels and to the average C_i/Cl⁻ ratio in rain.

The composition of Gambia River chemistry is compared to four other West African rivers – Senegal, Bandama (Ivory Coast), Niger (in Nigeria) and Ouham (in Tchad) – for which a similar rain correction has been applied, with identical average C_i/Cl⁻ ratios. Actually, the rain contribution to the cation transport is generally low (less than 10 %) due to the distance from the coast, which is reflected by the low Cl⁻ levels in any inland rain chemistry station (Table 2A).

Table 2 A
Rain Chemistry

	Ca^{2+}	Mg^{2+}	Na^+	K^+	Cl^-	SO_4^{2-}	HCO_3^-
— Gouloumbou (average of 10 weekly samples, 1983; 380 mm sampled)							
C_i	27	7.5	30	10	41	6	–
C_i/Cl⁻	0.66	0.18	0.73	0.24	1.0	0.15	–
— Kedougou (average of 1981, TRAVI et al., 1986)							
C_i	140	14	28	12	45	12	–
C_i/Cl⁻	3.1	0.31	0.62	0.27	1.0	0.27	–
— Saria (Ivory Coast, LELONG et al., 1984) - Savanna							
C_i	100	20	4	10	10	30	–
— Korhogo (Ivory Coast, LELONG, et al., 1984) Forested savanna							
C_i	100	10	10	10	10	20	–

Average chosen for the Gambia watershed						
C_i/Cl⁻	1.5	0.25	0.65	0.26	1.0	0.2

The five West African river waters in Table 2B have very similar levels of mineralization: the sum of cations (Σ^+) ranges from 346 to 553 µeq/l. These values are found in less than 20 % of the river waters discharged to ocean by major rivers (MEYBECK, 1979), and are characteristic of waters draining crystalline rocks (metamorphic and plutonic) and/or sandstone and non-calcareous shales. Detailed analysis of such rivers performed on monolithologic watersheds in France (MEYBECK, 1986) are given in Table 2C for these two major rock categories. Both ionic levels and proportions of African waters are in between

Table 2 B
West Africa River Chemistry (Rain Corrected)

(all concentrations C_i in my eq/l, except SiO_2 in my mole/l).

— Gambia (1983/84)	SiO_2	Ca^{2+}	Mg^{2+}	Na^+	K^+	Sum⁺[1]	E_d[2]	Q[4]
C_i	143	174	142	76	19	411	1.05	2(197
% [3]		42	35	18.5	4.5			
— Senegal (GAC & KANE, 1986 b)								
C_i	170					346	1.7	3.2
% [3]		33	39	17	10	.		
— Bandama (LENOIR, 1972)								
C_i	(270)					473	3.4	4.1
% [3]		20	37	35	8			
— Niger (MARTINS, 1983)								
C_i	270					553	4.6	5.5
% [3]		44	31	19	8			
— Ouham (GAC and PINTA, 1973)								
C_i	357					380	7.6	8
% [3]		29	29	29.5	12.5			

1) sum of cations; 3) cations in % of cation sum;
2) chemical denudaton in t/km²/a; 4) specific runoff in l/s/km².

469

Table 2 C

Monolithologic Watershed Chemistry in France
(Rain Corrected) (MEYBECK, 1986)

		SiO_2	Ca^{2+}	Mg^{2+}	Na^+	K^+	Sum^+
Plutonic and	C_i	140					185
metamorphic	% (3)		26	24	45	5	
Non calcareous sandstones and	C_i	150					500
shales	% (3)		48	30	18	4.2	

3) Cations in % of cations sum.

these two sets of analyses. This is quite in agreement with the general lithologies of the five watersheds considered, in which evaporites, limestone and volcanic rocks are very scarce. A quick check of the very limited influence of calcareous rocks in these African rivers is the ratio Ca^{2+}/Na^+, which ranges from 0.6 to 2.3 (eq/eq), a level only found in watersheds where limestones are less than 5 % (MEYBECK, 1986). Calcium and sodium proportions in the African waters reported here are variable and may reflect the influence of the dominant feldspar type, as observed in France for the plutonic rock watersheds where two sets of waters, calcic and sodic, have been found. LESACK et al. (1984) also suggest a preferential adsorption of Ca^{2+} and Mg^{2+} in tropical soils. As in any surface water, the K^+ ion is always found in limited proportions. Silica levels in these African waters are usually higher than in the temperate waters studied in France, due to the well-known influence of climate on silicate weathering. Actually, SiO_2 levels found in Gambia and Senegal may even seem low when compared to the other rivers; it could be related to some silica uptake by diatoms within the river.

The chemical denudation rate E_d (t/km²/a) has been computed with the sum (in mg/l) of the transported major cations plus silica (Table 2B). Chloride has been supposed to originate entirely from the precipitations; sulfate is negligible, and bicarbonate is considered to come only from atmospheric and soil CO_2 (limestone dissolution is negligible). Runoff values q, used in E_d computation, are long-term data; their range is much higher (1 to 4) than the one observed for the dissolved load of rivers (1 to 2). For this reason, the chemical denudation is directly linked to runoff, an observation which has already been made on Kenyan watersheds by DUNNE (1978). The E_d levels in West African rivers are among the lowest found for perennial rivers, together with some lower Amazonian rivers for which the dissolved loads are 5 times lower but the runoff much higher (around 40 l/s/km²; STALLARD & EDMOND, 1983).

6.2 POC Levels

When compared to the annual variations of other tropical rivers (Fig. 7), the Gambia River is well within the general range; but its POC levels are 1 to 1.5 % lower than those of Changjiang River, in China, for the highest SM values. The Changjiang pattern is highly scattered and this difference could be due to the occurrence of highly cultivated soils in this river: a third POC origin linked to anthropogenic activities is likely.

The Senegal POC variation during the 1983 high-water stage (Fig. 7) is very similar to the one in Gambia, although at somewhat lower levels. This difference between the average POC levels, at given turbidities, may be linked to the average terrestrial primary productivity of the watershed, a relationship which has been pointed out before for the yearly TOC export rates (MEYBECK, 1982).
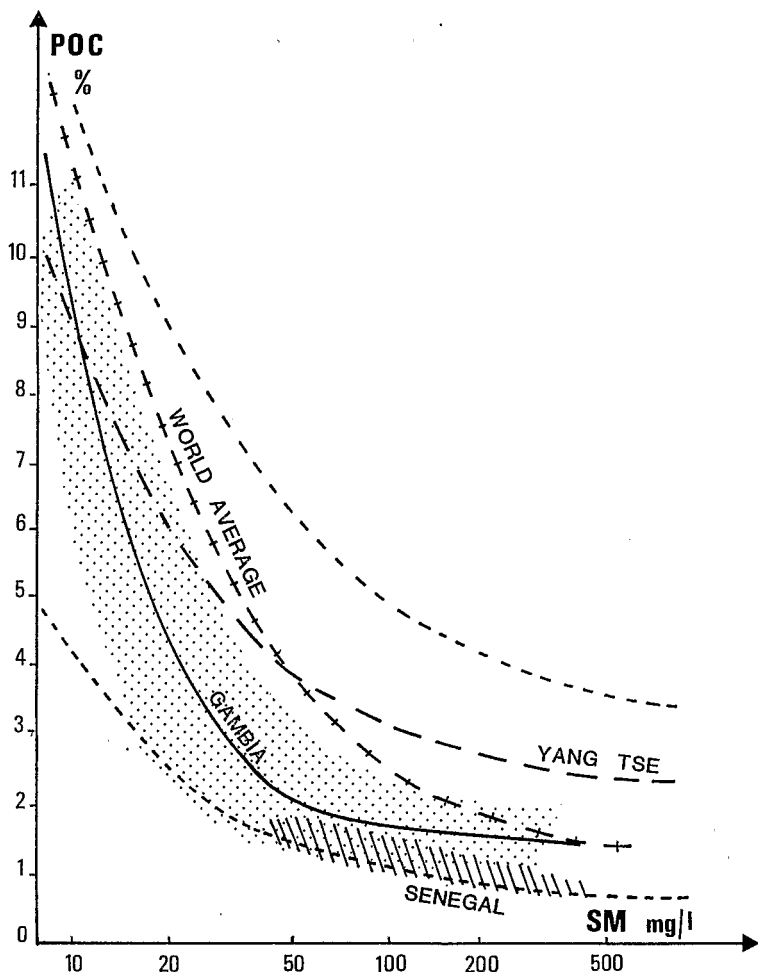
Fig. 7: POC (% of suspended matter) versus suspended matter variations in Gambia (– and grey range), in Senegal for the 1983 high water stage (hatched area) and in the Changjiang (MILLIMAN et al., 1984) (average variation (–––), range…), compared to the world variation set on major rivers (MEYBECK, 1982).

The POC output from the Gambia, for the 1983/84 water year, has been computed with the 29 measurements during the flood period (discharge-weighted average 1.05 mg C/l), combined with the 6 measurements of LESACK et al. during the dry period (average 0.8 mg C/l), which gives an average POC content of 1 mg/l, a load of 1.83×10^3 tC and a specific transport of only 0.043 t/km²/a, a very low level only found in oligotrophic lake outlets. The discrepancy between LESACK et al.'s estimate (0.12 POC t/km²/a) and ours is mainly due to the difference in specific runoff (3.5 and 1.4 l/s/km²), which points out the influence of hydrology on organic carbon export.

6.3 Mechanical versus Chemical Transport

The variation of dissolved and particulate loads (in t/day) are presented on Figure 8. The dissolved load corresponds here to the sum of major ions (cations and anions) plus silica. Even during the flood stage, the dissolved load may exceed, for some days, the particulate load. Generally, this pattern is only found
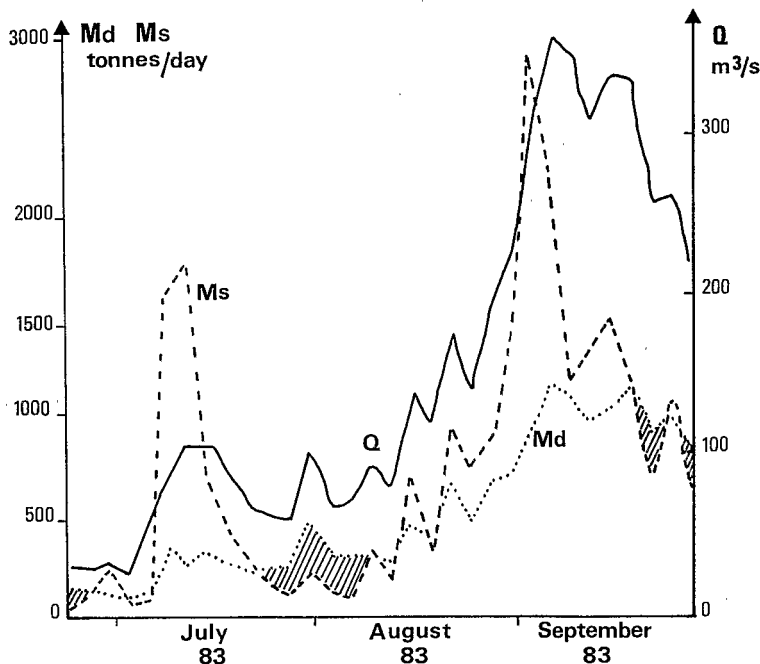
471

Fig. 8: Evolution of daily loads (t/day) of suspended matter (S. M.) and dissolved matter (M_d, sum of major ions plus silica transport) during the 1983 Gambia flood stage. Hatched area corresponds to period of dominating chemical transport. Q = water discharge.

in such rivers outside the flood period (LESACK et al., 1984). The yearly average dissolved content, in 1983/84, of the Gambia River is around 44 mg/l (discharge-weighted), which corresponds to 80,000 t/a; the average suspended matter, for the same period, is of the same order, 47 mg/l and 87,000 t/a. These low transport rates are not at all representative of long-term averages since they are much influenced by the exceptionally dry water-year studied (Q = 59 m³/s, compared to 115 m³/s for the 1953–1983 period). As a comparison, the suspended matter load has been 660,000 t/a in 1974/75 (Q = 110 m³/s), i.e. a 8 fold difference, while the discharge only varied by a factor of two (ORSTOM measurements quoted by LÔ, 1984). This exponential relation between yearly loads of suspended matter and discharge have been described many times. The dissolved load for a "normal" water year is probably around 100,000 t/a. When the long-term averages of specific transport rates (t/km²/a) for dissolved (T_d) and suspended (T_s) matter are considered, the T_s/T_d ratio is around 6 for a specific runoff of 3 l/s/km², a figure quite similar to those found in other dry environments such as the Amu Darya or the Nile (prior to the Aswan High Dam construction). The overall erosion rate of the Gambia (1.25 t/km²/a for the chemical denudation and about 16 t/km²/a for the mechanical denudation) is very low and reflects the stability of this part of the African continent.

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