Journal of Hydrology, 92 (1987) 59–76
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

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SUSPENDED SEDIMENT LOAD AND MECHANICAL EROSION IN THE SENEGAL BASIN — ESTIMATION OF THE SURFACE RUNOFF CONCENTRATION AND RELATIVE CONTRIBUTIONS OF CHANNEL AND SLOPE EROSION

Z. KATTAN[1], J.Y. GAC[2] and J.L. PROBST[1]

[1] *Centre de Sédimentologie et de Géochimie de la Surface, Institut de Géologie, 1 Rue Blessig, 67084 Strasbourg Cedex (France)*

[2] *ORSTOM (Institut Français de Recherche Scientifique pour le Développement en Coopération) Centre de Hann, BP 1386, Dakar (Senegal)*

(Received October 22, 1986; revised and accepted January 12, 1987)

ABSTRACT

Kattan, Z., Gac, J.Y. and Probst, J.L., 1987. Suspended sediment load and mechanical erosion in the Senegal Basin — Estimation of the surface runoff concentration and relative contributions of channel and slope erosion. J. Hydrol., 92: 59–76.

The main purpose of this paper is to propose a method to better understand the suspended sediment dynamics in the Senegal Basin, and the behaviour of the river particulate load at Bakel gauging station (218,000 km^2) during the period 1979–1984.

The method is based on the estimation of surface discharge using a simple hydrological model which allows separation of the different flow components of the annual hydrograph. Then the suspended sediment loads can be correlated with the surface discharge. During the study period, the mean annual flow (330 $m^3 s^{-1}$) represented only 46% of the mean long-term flow (1903–1984), and the mean yearly particulate load carried by the Senegal River was about 1.9 million tons. Two approaches are used to estimate the different contributions to the river's suspended sediment transport. The main contribution originates from slope erosion, which supplies 50–80% of the total sediment transport and the second originates from channel erosion. The suspended sediment concentration in the surface runoff, primarily calculated by a global annual method, ranges from 0.9 to 1.6 $g l^{-1}$ and averages 1.3 $g l^{-1}$. After correction for channel erosion input, this concentration is reduced to 1.1 $g l^{-1}$.

INTRODUCTION

Since the beginning of the 20th century, many hydrological research investigations have been devoted to the African continent. Most of these studies have been carried out by ORSTOM researchers who have developed an important hydrological network in several African countries.

Among these studies, the dissolved and suspended loads carried by African rivers have been of great interest to better understanding upland erosion and

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ORSTOM Fonds Documentaire
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the sedimentation processes. Many works have been devoted to these subjects in the African continent: Martins (1982, 1983) for the Niger, Soliman (1982, 1983) and Kempe (1983) for the Nile, Hart (1982, 1983) for the Orange, Clerfayt (1956), Nkounkou and Probst (1987) for the Congo, Pias (1962, 1968), Billon (1968), Billon et al. (1969), Carre (1972), Chouret (1973), Carmouze (1976) and Gac (1980) for the Chari, Mandin (1957), Michel (1968, 1973), Gac and Pinta (1973), Kane (1985), Gac and Carn (1986) and Gac and Kane (1986) for the Senegal, Olivry (1982) and Lô (1984) for the Gambia, Nouvelot (1969, 1972) and Olivry (1977) for the Cameroon, Mathieu (1971), Lenoir (1972) and Monnet (1972) for the Ivory Coast rivers, and finally, Grove (1972), Lisitsin (1972) and Walling (1983, 1984) for several African rivers.

The purpose of this study is to give a review of the hydrological and geochemical characteristics of the Senegal River and to present a method to better understand the suspended sediment load dynamics and mechanical erosion in the Senegal Basin. The data used in this study have been collected by Gac, who has led the ORSTOM research program of the Senegal River hydrogeochemistry at Bakel gauging station, during the period 1979–1984.

STUDY AREA CHARACTERISTICS

The Senegal Basin lies between 10°.20 and 17°.00 N and between 7°.00 and 16°.20 W. It covers an area of about 268,000 km^2, and includes parts of four countries: Guinea, Mali, Mauritania and Senegal. The mean elevation is about 300 m.

The Senegal River is the main stream of the basin. It is about 1800 km long and drains the western slopes of Guinea. It crosses the western part of Mali and the rest of its course forms the border between Mauritania and Senegal, until it flows into the Atlantic Ocean at St. Louis (Fig. 1).

The study area occupies the upstream part of the Senegal Basin and it covers, above Bakel gauging station, about 218,000 km^2, which represents about 81% of the total basin surface. The mean annual temperature ranges from 20 to 35°C. The geological substratum can be divided, in order to simplify, into the following three main formations (Rochette, 1974) from oldest to youngest: (1) the ancient, pre-Paleozoic bedrock, composed of metamorphic rocks, such as schist, micaschist, quartzite and basic rocks transformed into greenstones; (2) the Paleozoic, composed widely of sandstones, quartzites, pelites and limestones; and (3) the Cenozoic, mainly composed of clayey sandstones.

The annual rainfall ranges from 250 to more than 2000 mm; however the annual average rainfall was not more than 900 mm, for the period 1931–1960 preceding the drought of 1973–1974 (Rochette, 1974). Assuming that this drought period was taken into account, the estimation of mean annual rainfall, which has been carried out by Sow (1984) was about 818 mm yr^{-1} over the period 1951–1980, while our estimate is 650 mm, i.e. $142.10^9 m^3 yr^{-1}$, according to the data published by Olivry (1982).

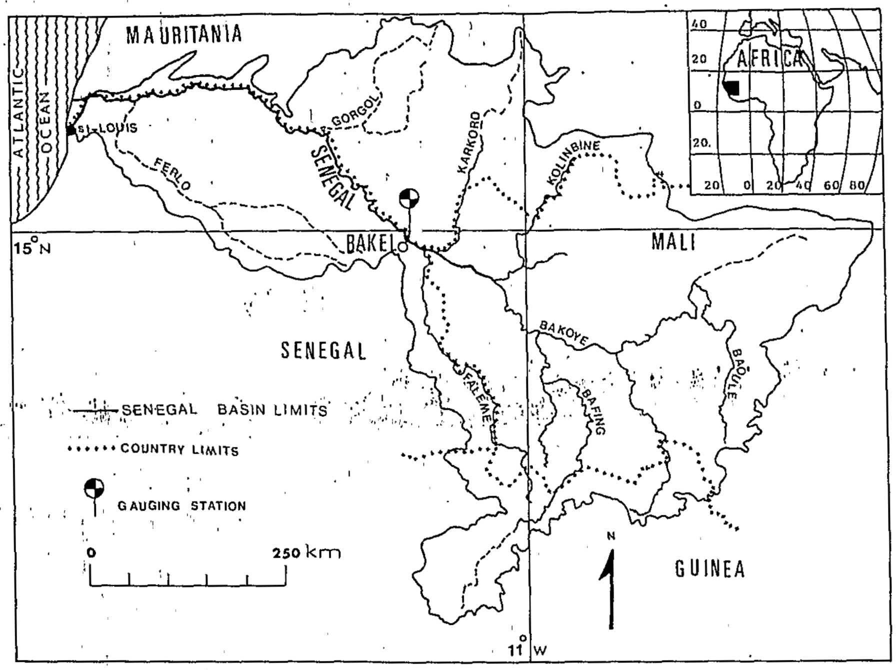

Fig. 1. General situation of the Senegal Basin.

Five annual water years have been investigated during the period May 1979–November 1984. The mean monthly discharges at Bakel gauging station are summarized in Table 1. The values range from 0.19 to 2000 $m^3 s^{-1}$, and the mean interannual discharge was about 330 $m^3 s^{-1}$, i.e 10.4 × $10^9 m^3 yr^{-1}$. Approximately 83% of the annual runoff was discharged during the warm months (August, September and October). Olivry (1982) noted that the Senegal River discharge decreased greatly during the last 15 yr, as a result of the drought, as we can see in Fig. 2. The mean annual runoff, which is about 330 $m^3 s^{-1}$ for the study period (1979–1984) represents only about 46% of the mean long-term

TABLE 1

Average monthly discharges of Senegal River at Bakel gauging station ($m^3 s^{-1}$)

Years	M	J	J	A	S	O	N	D	J	F	M	A	Module
1979/80	1.68	42.3	308	991	1263	573	293	96.0	43.2	17.3	4.2	1.43	303
1980/81	0.56	21.6	317	1620	2000	476	191	83.3	38.1	15.4	4.5	1.28	402
1981/82	0.35	34.8	441	1889	1680	639	222	84.4	42.9	16.6	5.1	1.43	423
1982/83	0.57	0.34	250	1165	1322	540	217	65.7	34.0	14.3	3.9	1.31	303
1983/84	0.19	77.7	390	697	817	425	135	53.6	23.9	8.2	2.4	1.20	218
Average	0.67	35.3	341	1326	1442	533	212	76.6	36.4	14.4	4.0	1.33	330

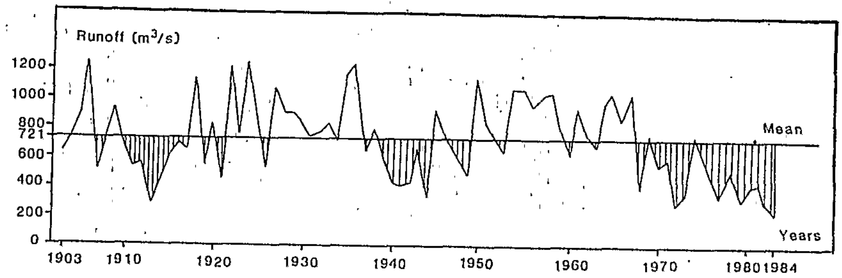

Fig. 2. Fluctuations of the annual module of the Senegal River at Bakel gauging station since 1903.

discharge (721 $m^3 s^{-1}$). The water budget of the Senegal Basin, calculated during the study period by Gac and Kane (1986), shows that the runoff coefficient is only 7.3%.

SEPARATING THE STREAM FLOW COMPONENTS FROM THE ANNUAL HYDROGRAPH

Hydrograph separation is one of our more serious problems in hydrology, and the flow components of this hydrograph are not well-defined. Many papers have been devoted to hydrograph separation methods: Barnes (1939), Schoeller (1962), Castany (1963), Roche (1963), Cottez (1967), Pinder and Jones (1969), Rambert (1971), Linsley et al. (1975), Reminieras (1976), Pilgrim et al. (1978, 1979), Gac (1980), Merot et al. (1981), Blavoux and Mudry (1983), and Probst (1983). However, few data are available on annual hydrograph separation methods, notably: Schoeller (1962), Kudelin (1946, 1965), Rezai-Valyce (1970), Dinçer and Payne (1971), Rambert (1971), Gac (1980), and Bottomley et al. (1985).

In order to separate the annual hydrograph components of the Senegal River at Bakel gauging station, we can analyse the time response of the river discharge during the recession period (Fig. 3). The plot of logarithmic values of discharge versus time allows determination of three segments of approximately straight lines. The slopes of these straight lines are different and characterize the recession of the different hydrological reservoirs. The recession curves can be expressed by an exponential decrease:

$$Q_t = Q_0 \, e^{-kt} \quad (1)$$

where Q_t and Q_0 are respectively discharge at time, t and $t = 0$, k is the recession constant which depends on the characteristics of the reservoirs, t is the time.

It is important to note that Maillet (1906), was one of the first to supply an exponential equation in order to express the spring discharge recession. This exponential equation has been later used by several authors (Barnes, 1939; Roche, 1963; Chow, 1964; Probst, 1983), in order to express the different component discharges. The recession constants of the Senegal River are given in

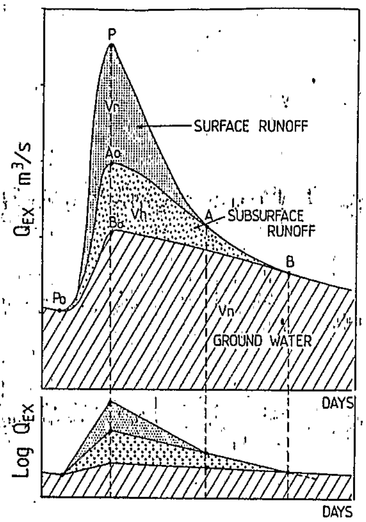

Fig. 3. Separation method of the different flow components of the annual hydrograph.

Table 2 for each reservoir. According to these values, we can write the following equations for the different reservoirs:

$$Q_r = Q_0\, e^{-0.098t} \text{ for the surface runoff} \quad (2)$$

$$Q_h = Q_0\, e^{-0.039t} \text{ for the subsurface runoff} \quad (3)$$

$$Q_n = Q_0\, e^{-0.027t} \text{ for the groundwater flow} \quad (4)$$

For example, an application of this hydrograph separation is given in Fig. 4 for the water year 1980–1981. The contribution of the different components, calculated using the hydrograph separation is given in Table 3 for the period 1979–1984.

TABLE 2

Recession constants for each flow component, with time in days (r, h, and n are respectively surface runoff, subsurface runoff and groundwater flow)

Years	K_r	K_h	K_n
1979/80	0.098	0.038	0.027
1980/81	0.092	0.040	0.026
1981/82	0.103	0.040	0.028
1982/83	0.106	0.033	0.025
1983/84	0.093	0.042	0.027
Average	0.098	0.039	0.027

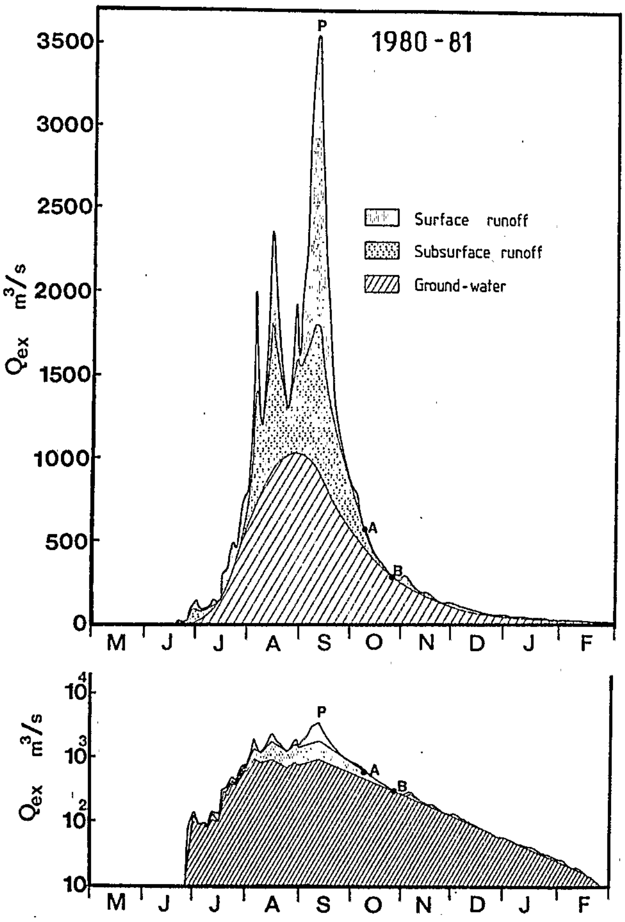

Fig. 4. Application of the separation of the different flow components to the annual hydrograph 1980–1981.

TABLE 3

Annual volumes discharged by each flow component, calculated from hydrograph separation (in $10^9 m^3$)

Years	Total flow	Surface runoff	Subsurface flow	Groundwater flow
1979/80	9.48	0.95	1.14	7.39
1980/81	12.68	2.41	3.42	6.85
1981/82	13.38	1.47	2.54	9.37
1982/83	9.55	1.53	2.48	5.54
1983/84	6.55	0.90	0.97	5.06
Average	10.40	1.45	2.11	6.84

TABLE 4

Average monthly suspended sediment concentrations in the Senegal River at Bakel gauging station (mg l^{-1})

Years	M	J	J	A	S	O	N	D	J	F	M	A	Average
1979/80	40.0	55.0	144.8	205.3	210.2	70.9	18.7	13.2	16.6	26.9	18.7	30.3	156.6
1980/81	34.3	161.4	333.1	301.9	174.4	62.5	30.8	60.1	46.6	18.4	32.5	19.9	207.8
1981/82	5.6	65.3	420.6	199.5	163.2	55.5	27.9	20.3	12.2	16.3	6.6	13.3	175.0
1982/83	13.7	20.8	266.8	194.1	143.9	86.5	21.0	18.2	46.5	48.0	29.8	9.3	148.9
1983/84	9.3	721.6	505.1	258.1	162.2	114.2	57.3	46.7	41.1	47.9	27.5	25.7	239.0
Average	29.0	363.0	351.0	232.0	171.0	76.0	28.1	26.0	31.4	31.0	22.5	19.9	185.0

According to these values, the mean relative contribution of the surface, subsurface and groundwater flows are respectively 14, 20 and 66% of the total river discharge. We can then note also that, during the study period the surface runoff represents only 1% of the total rainfall input. This result is perfectly compatible with the surface runoff measurements carried out by Roose and Lelong (1976) and Roose (1977) in these African tropical regions.

SUSPENDED SEDIMENT EXPORT AND MECHANICAL EROSION

Few data are available on the suspended sediment transport by the Senegal River. Some measurements have been carried out since 1908 (Seguy, 1955). Mandin (1957) has observed that the suspended sediment concentration is more important before the peak discharge. Michel (1968, 1969, 1973), Sall (1982) and Michel and Sall (1984) were the first to study the bed-stream erosion of the Senegal River. Estimates by Michel (1968) for the annual suspended sediment transport, range between 1 and 2.8 million tons according to the water year. Michel (1968) has also noted that during the rainy season, the grass growth decreases first the runoff discharge and then the mechanical erosion.

Calculated values of mean monthly suspended sediment concentrations are reported in Table 4. The mean monthly concentration ranges from 5.6 mg l^{-1} in May to 720 mg l^{-1} in June, while the annual average for the study period is about 185 mg l^{-1}. As seen in Fig. 5, the suspended sediment concentration

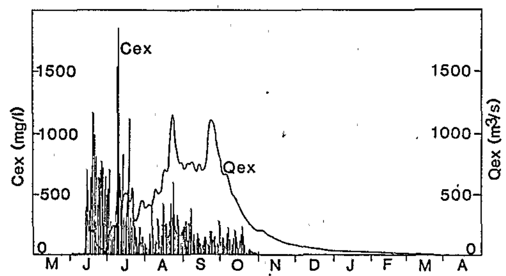

Fig. 5. Comparison of variations of daily suspended sediment concentrations with daily discharges for the water year 1983–1984.

begins to increase in May with the first arrival of surface runoff and reaches its maximum during June, July and August, before the peak discharge. The highest concentration was observed during the driest year (1983–1984).

It should be noted also that the lag between maximum concentration and peak discharge has already been observed for several African rivers: Carmouze (1976), Gac (1980), Kane (1985), Meybeck (1985) and Nkounkou and Probst (1987).

As seen in Fig. 6, the relationships between mean monthly concentrations and discharges are cyclical. According to Carmouze (1976), Kattan (1984), Gac and Carn (1986) and Gac and Kane (1986), the following three periods could be distinguished in this relationship:

(1) The first period is characterized by a strong increase of the suspended sediment concentration with discharge. This phase can be attributed to the first arrival of suspended sediment produced by rain splash erosion and transported by the first surface runoff. This period corresponds also to the reworking of sediments which were accumulated in the river bed during the last flows.

(2) The second period is characterized by a decrease of suspended sediment concentration with a strong discharge increase. This period corresponds to dilution of the sediment concentration and can be attributed to the end of both slope and channel erosion. This period corresponds to the river transport of the eroded sediment.

(3) The third period is characterized by a decrease of sediment concentration with discharge. This phase corresponds to sediment deposition over the alluvial plains and river bed.

The yearly suspended sediment loads are calculated using the following method:

$$T = \sum_{i=1}^{i=365} C_i Q_i \times 86.4 \times 10^{-3} \quad (5)$$

where T = total suspended load in tons; C_i = mean daily suspended sediment concentration in mg l^{-1}; and C_i = mean daily discharge in m^3 s^{-1}.

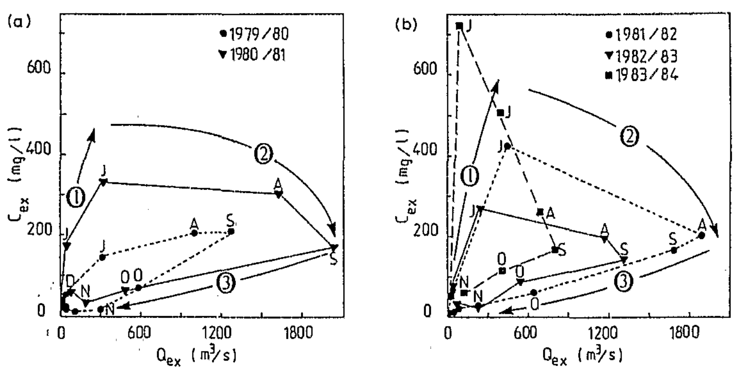

Fig. 6. Relationships between suspended sediment concentrations and discharges for each water year (monthly averages). Where *1* is erosion; *2* transport and *3* is sedimentation.

The results of the suspended sediment exportations are reported in Table 5 for the study period.

The annual suspended sediment load of the Senegal River at Bakel gauging station ranges from 1.4 to 2.6 million tons and averages 1.9 million tons, i.e. a specific transport of 8.75 tons $km^{-2} yr^{-1}$. If we consider that the precipitation and discharge during the study period were below the normal conditions, one might have expected higher sediment concentrations and higher total loads under normal conditions.

ESTIMATION OF THE SUSPENDED SEDIMENT CONCENTRATION IN SURFACE RUNOFF AND THE RELATIVE CONTRIBUTION OF CHANNEL EROSION

Estimation of suspended sediment concentration in surface runoff

In most of the studies on river-suspended loads, the river-suspended sediment concentration is correlated with the total river discharge, but we know that the river-suspended sediments are mainly produced by mechanical erosion processes on slopes, and that the suspended sediment concentration may then be correlated with the surface runoff. In order to better understand the suspended sediment dynamics in a drainage basin, some authors have tried to establish this correlation: Guy (1964), Mansue and Anderson (1974), Piest et al. (1975), Walling and Webb (1982) and Rieger and Olive (1984).

Then, it could be interesting to calculate as did Callede (1974), the suspended sediment concentration in surface water using measurements in river water. In the Chari–Logone basin, Gac (1980) used the value (1 g l^{-1}) proposed by Callede (1974) for surface runoff concentration in order to calculate the relative contribution of the surface runoff. Finally, Probst (1983, 1986), Kattan (1984), Etchanchu and Probst (1986) and Probst and Bazerbachi (1986) have calculated the suspended sediment concentration in surface runoff using hydrological models.

Considering that the river-suspended sediments are carried from the slopes into the river by the surface runoff water, it may be possible to calculate the concentration in surface runoff. Hence, we have to suppose that the sediment concentrations are negligible in both subsurface and groundwater flows:

TABLE 5

Monthly and yearly suspended sediment loads (in tons) in the Senegal River at Bakel gauging station (T_s is specific transport in tons $km^{-2} yr^{-1}$)

Years	M	J	J	A	S	O	N	D	J	F	M	A	Total	T_s
1979/80	180.0	6030.3	119452	544927	717594	108812	14202	3465	1921	1126	210	135	1484824	6.8
1980/81	51.4	9036.3	282819	1309947	904090	79682	15248	13402	4880	686	392	66	2634563	12.1
1981/82	5.2	5890.2	496802	1009370	710664	94988	16054	4589	1402	655	90	49	2340000	10.7
1982/83	20.9	18.3	178649	605657	493091	125108	11812	3203	4262	1661	313	32	1422400	6.5
1983/84	4.7	145325	527345	481937	343397	129851	19976	6697	2632	963	177	80	1656000	7.6
Average	52.4	33260	321013	790368	633767	107688	15458	6271	3019	1018	236	72	1907557	8.7

$$C_{ex} V_{ex} = C_r V_r \quad (6)$$

$$C_r = (C_{ex} V_{ex})/V_r \quad (7)$$

Where C and V are, respectively, the concentrations and the water volumes, and the indices ex and r represent, respectively, the total river flow, and the surface runoff.

In this study, mean suspended sediment concentrations in surface runoff have been calculated for each water year using the annual global method proposed by Etchanchu and Probst (1986). The annual average concentration is calculated by dividing the total annual suspended load by the annual surface runoff volume (eqn. 7).

As seen in Table 6, the mean suspended sediment concentration in surface runoff is about 1.3 g l^{-1}, without taking into account the channel erosion contribution. These preliminary results could be compared with those obtained by Callede (1974) who estimated a value of 1 g l^{-1} in the Sarki Basin (Republic of Central Africa). It may also be compared with those obtained by Etchanchu and Probst (1986) who estimated, after correction for channel erosion, a value of 1.02 g l^{-1} in an agricultural basin of southwestern France, whereas, Probst (1983) and Probst and Bazerbachi (1986) calculated a concentration of 0.5 g l^{-1} in the upstream part of the Garonne Basin, without taking into account large storm events and without correction for channel erosion.

Estimation of the relative contribution of channel erosion

Stream channel erosion has been defined as the sediment detachment of the bed and the stream channel banks, caused by flowing water (White, 1982). Few investigations have been devoted to this subject (Leopold et al., 1964; Duysings, 1978; Dickinson and Scott, 1979; Hooke, 1980; Buckhouse et al., 1981; and Guy, 1981). The determination of the channel erosion from total river-suspended load is a very difficult task. In fact, channel erosion depends on several factors such as river-bed slope, flow velocity, bank vegetation, and sediment particle size. All of these factors complicate the determination of stream bank erosion (Robinson, 1977).

TABLE 6

Volumes (V, 10^9 m^3) of total and surface runoff flows and suspended concentrations (C, mg l^{-1}) in the total and surface runoff flows (ex and r are respectively total and surface runoff)

Years	C_{ex}	V_{ex}	V_r	C_r
1979/80	156.6	9.480	0.948	1560
1980/81	207.8	12.677	2.409	1090
1981/82	175.0	13.380	1.472	1590
1982/83	148.9	9.553	1.528	930
1983/84	239.0	6.927	0.900	1650
Average	185.0	10.403	1.456	1320

In this study, the relative contribution of channel erosion has been estimated using two simple methods:

(1) The first is based on the plot of the monthly suspended load versus the mean monthly discharge during five water years. As seen in Fig. 7, two periods can easily be distinguished in this relationship, according to the river discharge. During the high-flow period, the increase of monthly suspended load is more rapid when the mean monthly discharge increases, than during the low-flow period. The equations of these two relationships are as follows:

$$\text{high flow: } T_s = 38.115 Q_{ex}^{1.3237}, \quad \text{with } r = 0.971 \tag{8}$$

$$\text{low flow: } T_s = 43.824 Q_{ex}^{1.1022}, \quad \text{with } r = 0.973 \tag{9}$$

T_s is the monthly suspended load in tons and Q_{ex} is the mean monthly discharge in $m^3 s^{-1}$.

During low-water periods, the river discharge is mainly supplied by the groundwater flows and we can consider that the river-suspended loads mainly originated from reworking of bed sediment and bank erosion. Whereas, during high flow, the river discharge is supplied both by groundwater and surface runoff. Then the river-suspended sediment loads are produced both by slope and channel erosion.

The annual contribution of channel erosion may be estimated by extrapolation of eqn. (9) to the high-flow period. The results of these first estimates are

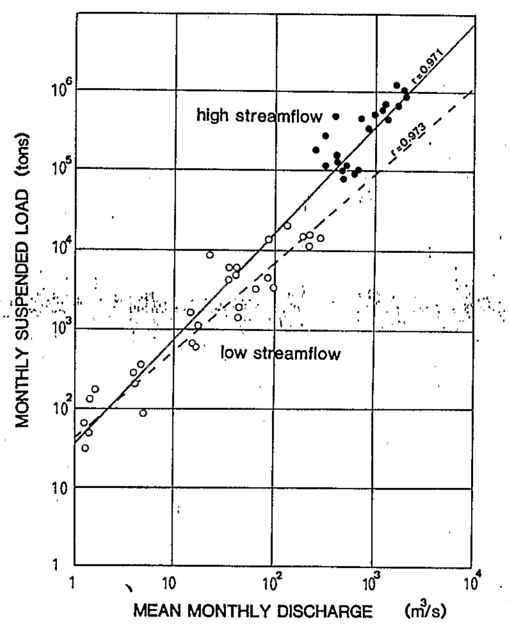

Fig. 7. Relationships between total monthly suspended loads and mean monthly discharges for five water years.

given in Table 7 and Fig. 8 for each water year. The channel erosion represents only 13–22% of the total river-suspended loads.

(2) The second method is based on the plot (Fig. 8) of the mechanical erosion (E_r) versus the annual surface runoff volume (V_r). For five water years, the equation of this relationship is linear:

$$E_r = 3.17V_r + 4.14 \quad (10)$$

When the volume of the surface runoff is equal to zero, we can consider that there is no slope erosion. Then the intercept of eqn. (10) may be viewed as representing the sediment loads produced by channel erosion. For the five water years, the mean annual contribution of channel erosion (4.14 tons $km^{-2} yr^{-1}$) represents about 47% of the mean annual river-suspended sediment load (8.75 tons $km^{-2} yr^{-1}$).

The results obtained by the two methods are very different and the channel erosion contribution estimated by the second method seems to be over-evaluated. We have reported in Table 8 some estimates of the channel erosion

TABLE 7

Relative contribution of the channel erosion to the total sediment load in the Senegal River (in %), and corrected values of the suspended sediment concentrations in the surface runoff

Years	Total suspended load tons	Channel erosion		Concentration in surface runoff ($mg\,l^{-1}$)
		tons	%	
1979/80	1484824	311725	21	1228
1980/81	2634563	430946	16	915
1981/82	2340000	455444	20	1284
1982/83	1422400	314258	22	725
1983/84	1656000	219193	13	1593
Average	1907557	346313	19	1100

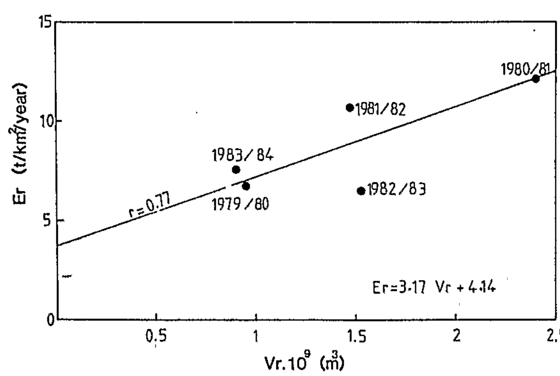

Fig. 8. Relationship between the mean mechanical erosion rate (specific transport) and the surface runoff volume for five water years.

TABLE 8

Relative contributions of the channel erosion to the total sediment load for some rivers (%)

Major land resource area	Channel erosion	Source
Southern Coastal Plain, U.S.A	0–30	(1)
Highland Rim and Pennyroyal, U.S.A	0–1	(1)
Cumberland Mountains, U.S.A	0	(1)
Southern Piedmont, U.S.A	0–34	(1)
Southern Mississippi Valley Loess, U.S.A	16–23	(1)
Alabama–Mississippi Blackland Prairie, U.S.A	0–23	(1)
Sand Mountain Area, U.S.A	0	(1)
Southern Appalachian Ridges and Valleys, U.S.A	0–1	(1)
Bleu Ridge, U.S.A	1–14	(1)
U.S.A, rivers	24	(2)
Forest streams, Luxembourg	53	(3)
Girou River, southwest France	30	(4)
Senegal River	13–22	(5)

Source: (1) Roehl (1962), quoted by Gregory and Walling (1973); (2) Robinson (1977); (3) Duysings (1985); (4) Etchanchu and Probst (1986); and (5) this study (first method).

contribution given by different authors. As seen in this table, the result obtained for the Senegal River by the first method is comparable to those estimated by Roehl (1962) and Robinson (1977) for some U.S.A. rivers, and by Etchanchu and Probst (1986) for the Girou River in southwestern France. Whereas, for two U.S.A. drainage basins (Brandywine Creek in Pennsylvania and Rio Puerco in New Mexico), Leopold et al. (1964) have shown that 50% of the suspended sediment is removed from the basins by low and moderate flows, which mainly correspond to the channel erosion processes. These percentages are comparable to those estimated by Duysings (1985) for some forest streams in Luxembourg.

As discussed above, the first calculations of suspended sediment concentration in surface runoff were made without taking into account the channel erosion. In fact, if we recalculate the concentration of suspended sediment in the surface runoff taking into account this contribution estimated using the first approach (Table 7), our estimate is reduced and tends to an average of $1.1\,\mathrm{g\,l^{-1}}$. This result is perfectly comparable with those obtained by Callede (1974) and Gac (1980) in Africa, and Etchanchu and Probst (1986) in Europe. All of these estimates show that the suspended sediment concentration in surface runoff tends to a value of $1\,\mathrm{g\,l^{-1}}$.

CONCLUSION

The studied period is included in the last drought event and the deficit of the mean annual runoff reaches 54% of the mean long-term module. The amount of suspended sediment exported by the Senegal River averages 8.7 tons $\mathrm{km^{-2}\,yr^{-1}}$. The consistent below-normal precipitation would tend toward lower sediment concentrations and total loads than one might have expected under normal or average conditions of slope erosion. The seasonal variations show that the river-suspended sediment concentration reaches its maximum before the peak river discharge. This lag may be characterized by a cyclical relationship between discharge and concentration. Three periods which correspond to three predominant processes, can be distinguished in this cycle: erosion, transport and sedimentation.

Surface runoff, estimated using a hydrograph separation method, represents on average only 1% of the annual amount of precipitation and 14% of the annual river flow. This estimate is comparable to surface runoff measurements in these African tropical regions. Whereas the annual river particulate loads are closely related to the annual volume of the surface runoff and the contribution of slope erosion processes represents 50–80% of the total river-suspended sediment transport, according to the method of estimation. The second contribution is carried by channel erosion, which represents at least 20% of the total river transport. This percentage is perfectly compatible with those obtained for some American and European rivers.

After correction for the sediment load produced by channel erosion, the mean yearly suspended sediment concentration in the surface runoff has been estimated to 1.1 $g\,l^{-1}$. This result tends to the value calculated for other African and European river basins: 1 $g\,l^{-1}$.

Finally, the first contribution to the river-suspended sediment transport is carried by slope erosion and surface runoff. The initial concentration (1 $g\,l^{-1}$) in surface runoff is diluted in the Senegal River water by subsurface and groundwater discharges. Then the river-suspended sediment load is increased by the channel erosion contribution and more particularly by reworking of stream bed sediment during the first flows. This second contribution seems to be more important during the rising limb of the annual hydrograph and produces the maximum concentration in river water before the peak discharge.

REFERENCES

Barnes, B.S., 1939. The structure of discharge recession curves. Trans. Am. Geophys. Union, 20(4): 721–725.

Billon, B., 1968. Mise au point des mesures de débits solides en suspension (République du Tchad). Cah. ORSTOM, Sér. Hydrol., V(2): 3–13.

Billon, B., Guiscafre, J., Herbaud, J. and Oberlin, G., 1969. Le bassin du fleuve Chari. ORSTOM, Paris, 450 pp.

Blavoux, B. and Mudry, J., 1983. Séparation des composantes de l'écoulement d'un exutoire karstique à l'aide des méthodes physico-chimiques. Hydrogéol. Géol. Ing., 4: 269–278.

Bottomley, D.C. and Johnston, L.M., 1985. Neutralization of acid runoff by groundwater discharge to streams in Canadian Precambrian Shield watersheds. J. Hydrol., 75: 1–26.

Buckhouse, J.C., Skovlin, J.M. and Knight, R.W., 1981. Streambank erosion and ungulate grazing relationships. J. Range Manage., 34: 339–340.

Callede, J., 1974. Bassin versant représentatif de Sarki (R.C.A.). Rapp. ORSTOM, 120 pp.

Carmouze, J.P., 1976. La régulation hydrogéochimique du lac Tchad. Contribution à l'analyse biodynamique d'un système endoréique en milieu continental. Trav. Doc. ORSTOM, 58: 418 pp.

Carre, P., 1972. Quelques aspects du régime des apports fluviatiles des matériaux solides en suspension vers le lac Tchad. Cah. ORSTOM, Sér. Hydrol., IX(1): 19–46.
Castany, G., 1963. Traité pratique des Eaux Souterraines. Dunod, Paris, 686 pp.
Chouret, A., 1973. Etude des transports solides en suspension au Tchad (campagne 1971–1972). Rapp. ORSTOM, N'Djamena, 11 pp.
Chow, Ven Te., 1964. Handbook of Applied Hydrology: A Compendium of Water Resources Technology. McGraw-Hill, New York, N.Y., 1400 pp.
Clerfayt, A., 1956. Composition des eaux de rivières au Congo. Influence des facteurs géologiques et climatiques. Centr. Belge Etud. Doc. Eaux, (31): 26–31.
Cottez, S., 1967. Applications hydrogéologiques de l'analyse des hydrogrammes des cours d'eau. Rapp. Bur. Rech. Géol. Min., No. DS.67.A.42.
Dickinson, W.T. and Scott, A.M., 1979. Analysis of streambank erosion variables. Can. Agric. Eng., 21: 19–25.
Dinçer, T. and Payne, B.R., 1972. An environmental isotope study of the south-western Karst region of Turkey. J. Hydrol., 14: 233–258.
Duysings, J.J.H.M., 1978. Contribution of bank erosion to sediment transport in a Luxembourg catchment. Unpubl. M.Sc. Thesis, Lab. Phys. Geogr. Soil Sci., Univ. Amsterdam, 50 pp.
Duysings, J.J.H.M., 1985. Streambank contribution to the sediment budget of a forest stream. Unpubl. Ph.D. Thesis, Lab. Phys. Geogr. Soil Sci., Univ. Amsterdam, 190 pp.
Etchanchu, D. and Probst, J.L., 1986. Erosion et transport de matière en suspension dans un bassin versant en région agricole. Méthode de mesure du ruissellement superficiel, de sa charge et des deux composantes du transport solide dans un cours d'eau. C.R. Acad. Sci. Paris, t. 302, II(17): 1063–1067.
Gac, J.Y., 1980. Géochimie du bassin du lac Tchad. Bilan de l'altération, de l'érosion et de la sédimentation. Trav. Doc. ORSTOM, 123: 251 pp.
Gac, J.Y. and Pinta, M., 1973. Bilan de l'érosion et de l'altération en climat tropical humide. Cah. ORSTOM, Sér. Géol., 5(1): 83–96.
Gac, J.Y. and Carn, M., 1986. Bilan quantitatif de l'érosion mécanique sur le haut bassin du fleuve Sénégal. In: 11ème Réun. Sci. Terre, Clermont-Ferrand, 1986. Soc. Géol. Fr., Paris, Ext. Abstr., p. 73.
Gac, J.Y. and Kane, A., 1986. Le fleuve Sénégal: I. Bilan hydrologique et flux continentaux de matières particulaires à l'embouchure. Sci. Géol. Bull., 39(1): 99–130.
Gregory, K.J. and Walling, D.E., 1973. Drainage Basin Form and Process. A Geomorphological Approach. Edward Arnold, London, 458 pp.
Grove, A.T., 1972. The dissolved and solid load carried by some West African rivers: Senegal, Niger Benue and Chari. J. Hydrol., 16: 277–300.
Guy, H.P., 1964. An analysis of some storm-period variables affecting stream sediment transport. U.S. Geol. Surv. Prof. Pap., 462 E: 46 pp.
Guy, P.R., 1981. Riverbank erosion in the Mid-Zambezi Valley, downstream of Lake Kariba. Biol. Conserv., 19: 199–212.
Hart, R.C., 1982. The Orange River: Preliminary results. In: E.T. Degens (Editor), Transport of Carbon and Minerals in Major World Rivers. Part 1. Mitt. Geol. Palaeontol. Inst., Univ. Hamburg, SCOPE/UNEP Sonderb. 52: p. 435.
Hart, R.C., 1983. The Orange River: Supplementary results. In: E. Degens, S. Kempe and H. Soliman (Editors), Transport of Carbon and Minerals in Major World Rivers. Part 2. Mitt. Geol. Palaeontol. Inst., Univ. Hamburg, SCOPE/UNEP Sonderb., 55: 451–457.
Hooke, J.M., 1980. Magnitude and distribution of river bank erosion. Earth Surf. Process., 5: 143–157.
Kane, A., 1985. Le bassin du Sénégal à l'embouchure. Flux continentaux dissous et particulaires. Invasion marine dans la vallée du fleuve. Thesis Univ. Nancy II, 205 pp.
Kattan, Z., 1984. Hydrologie de surface et érosion mécanique sur les bassins amont du Chari-Logone et du Sénégal. Rapp. Diplome Etud. Approfondies (D.E.A.), Univ. Strasbourg, 53 pp.
Kempe, S., 1983. Impact of the High Dam on water chemistry of the Nile. In: E.T. Degens, S. Kempe

and H. Soliman (Editors), Transport of Carbon and Minerals in Major World Rivers. Part 2. Mitt. Geol. Palaeontol. Inst., Univ. Hamburg, SCOPE/UNEP Sonderb. 55: 401–423.
Kudelin, B.I., 1946. Sur la méthode d'estimation de l'alimentation souterraine des rivières. C.R.Acad. Sci. U.R.S.S., 52: 61–64.
Kudelin, B.I., 1965. Ecoulement souterrain sur le territoire de l'URSS et problème des ressources en eau. Vestn. Akad. Nauk. SSSR, 9: 40–46.
Lenoir, F., 1972. Exportation chimique d'un bassin intertropical (le Bandama, Côte d'Ivoire). Influence des conditions hydrologiques. Thesis ORSTOM, Nice, 335 pp.
Leopold, L.B., Wolman, M.G. and Miller, J.P., 1964. Fluvial Processes in Geomorphology. Freeman, San Francisco, Calif., 522 pp.
Linsley (Jr.), R.K., Kohler, M.A. and Paulhus, J.L.H., 1975. Hydrology for Engineers. McGraw-Hill, New York, N.Y., (2nd ed.), 482 pp.
Lisitsin, A.P., 1972. Sedimentation in the world ocean. Soc. Econ. Paleontol. Mineral. Spec. Publ. 17, Tulsa, Okla., 218 pp.
Lô, H., 1984. Le bassin de la Gambie; contribution à l'hydrologie et à la dynamique fluviale en milieu tropical humide africain. Thesis Univ. Nancy II, 396 pp.
Maillet, E., 1906. Le vidage des systèmes de réservoirs. Ann. Ponts Chaussées, Mém. Doc., 21(8): 38 pp.
Mandin, R., 1957. Rapport sur les mesures de débits solides à Dagana-Bakel Fadougou. Bull. Mission Aménage. Fleuve Sénégal (M.A.S.), 44: 60 pp.
Mansue, L.J. and Anderson, P.W., 1974. Effects of land use and retention practices on sediment yields in the Stony Brook Basin, New Jersey, U.S. Geol. Surv., Water-Supply Pap., 1978-L: 33 pp.
Martins, O., 1982. Geochemistry of the Niger river. In: E.T. Degens (Editor), Transport of Carbon and Minerals in Major World Rivers. Part I. Mitt. Geol. Palaeontol. Inst., Univ. Hamburg, SCOPE/UNEP Sonderb. 52: 397–418.
Martins, O., 1983. Transport of carbon in the Niger river. In: E.T. Degens, S. Kempe and H. Soliman (Editors), Transport of Carbon and Minerals in Major World Rivers. Part 2. Mitt. Geol. Palaeontol. Inst. Univ. Hamburg, SCOPE/UNEP Sonderb. 55: 435–449.
Mathieu, P., 1971. Erosion et transport solide sur un bassin versant forestier tropical, (bassin de l'Amitioro, Côte d'Ivoire). Cah. ORSTOM, Sér. Géol., III(2): 31–59.
Mérot, Ph., Bourguet, M. and Leuch, M., 1981. Analyse d'une crue à l'aide du traçage naturel par l'oxygène 18 mesuré dans les pluies, le sol, le ruisseau. CATENA, 8: 69–81.
Meybeck, M., 1985. Variabilité dans le temps de la composition chimique des rivières et de leurs transports en solution et en suspension. Rev. Fr. Sci. Eau, 4: 93–121.
Michel, P., 1968. Le façonnement actuel de la vallée du Sénégal et de ses bordures de Bakel à R. Toll. Comité. Trav. Sci. Hist., Paris, Bull. Sect. Géogr., 80: 447–484.
Michel, P., 1969. Les grandes étapes de la morphogénèse dans les bassins des fleuves Sénégal et de Gambie pendant le quaternaire. Bull. Inst. Fr. Afr. Noire, 31, Sér. A(2): 293–324.
Michel, P., 1973. Les bassins des fleuves Sénégal et Gambie. Etude géomorphologique. Mém. ORSTOM, 63, 845 pp.
Michel, P. and Sall, M., 1984. Dynamique des paysages et aménagement de la vallée alluviale du Sénégal. Mém. ORSTOM, 106, pp. 89–109.
Monnet, C., 1972. Contribution à l'étude de la dynamique et de la nature des suspensions d'un fleuve intertropical, le Bandama. Côte d'Ivoire. Evolution des éléments chimiques des eaux de son estuaire. Thesis ORSTOM, Nice, 427 pp.
Nkounkou, R.R. and Probst, J.L., 1987. Hydrology and geochemistry of the Congo river system. In: E.T. Degens, S. Kempe and G. Wei-bin (Editors), Transport of Carbon and Minerals in Major World Rivers. Part 4. Mitt. Geol. Palaeontol. Inst. Univ. Hamburg, SCOPE/UNEP Sonderb. (in press).
Nouvelot, J.F., 1969. Mesure et étude des transports solides en suspension au Cameroun. Cah. ORSTOM, Sér. Hydrol., VI(4): 43–85.
Nouvelot, J.F., 1972. Le régime des transports solides en suspension dans divers cours d'eau au Cameroun de 1969 à 1971. Cah. ORSTOM, Sér. Hydrol., IX(1): 44–74.

Olivry, J.C., 1977. Transports solides au Cameroun. I.A.H.S. Publ., 122, Paris Symp., pp. 134–141.

Olivry, J.C., 1982. Le point en 1982 sur l'évolution de la sécheresse en Sénégambie et aux iles du Cap-vert. Cah. ORSTOM, Sér. Hydrol., XX(1): 47–70.

Pias, J., 1962. Les sols du moyen et du bas Logone, du bas Chari, des régions riveraines du lac Tchad et du Bahr El Ghazal. Mém. ORSTOM, 2: 438 pp.

Pias, J., 1968. Les formations sédimentaires tertiaires et quaternaires de la cuvette tchadienne et les sols qui en dérivent. Mém. ORSTOM, 43: 408 pp.

Piest, R.F., Bradford, J.M. and Spomer, R.G., 1975. Mechanisms of erosion and sediment movement from gullies. In: Present and prospective technology for predicting sediment yields and sources. U.S. Dep. Agric., Agric. Res. Serv. Publ., ARS-S-40: 162–176.

Pilgrim, D.H., Huff, D.D. and Steele, T.D., 1978. A field evaluation of subsurface and surface runoff. II. Runoff processes. J. Hydrol., 38: 319–341.

Pilgrim, D.H., Huff, D.D. and Steele, T.D., 1979. Use of specific conductance and contact time relations for separating flow components in storm runoff. Water Resour. Res., 15(2): 329–339.

Pinder, G.F. and Jones, J.F., 1969. Determination of the ground-water component of peak discharge from chemistry of total runoff. Water Resour. Res., 5(2): 438–445.

Probst, J.L., 1983. Hydrologie du bassin de la Garonne — Modèles de mélanges — Bilan de l'érosion — Exportation des phosphates et des nitrates. Thesis Univ. Paul Sabatier, Toulouse, 148 pp.

Probst, J.L., 1986. Dissolved and suspended matter transported by the Girou river (France): Mechanical and chemical erosion rates in a calcareous molasse basin. Hydrol. Sci. J., 31(1): 61–79.

Probst, J.L. and Bazerbachi, A., 1986. Transports en solution et en suspension par la Garonne Supérieure. Sci. Géol., Bull., 39(1): 79–98.

Rambert, B., 1971. Application de l'analyse des hydrogrammes des cours d'eau à l'évaluation de l'écoulement souterrain. Rapp. Bur. Rech. Géol. Min., 71 SGN 389 HYD: 34 pp.

Reminieras, G., 1976. L'hydrologie de l'Ingénieur. Eyrolles, Paris, 456 pp.

Rezai-Valyce, Gh., 1970. Recherches sur les facteurs de l'écoulement dans les bassins de Picardie et de Haute-Normandie. Thesis, Univ. Sci. Paris VI, 144 pp.

Rieger, W.A. and Olive. L.J., 1984. The behaviour of suspended sediment concentration during storm events. In: Drainage Basin Erosion and Sedimentation. Proc. Conf. Erosion, Transportation and Sedimentation in Australian Drainage Basins, Univ. Newcastle, N.S.W., pp. 121–126.

Robinson, A.R., 1977. Relationship between soil erosion and sediment delivery. I.A.H.S., Publ. 122, Paris Symp., pp. 159–167.

Roche, M.,. 1963. Hydrologie de Surface. Gauthier-Villars (ORSTOM), Paris, 430 pp.

Rochette, C., 1974. Le bassin du fleuve Sénégal. Monogr. Hydrol., 1, ORSTOM, 391 pp.

Roehl, J.W., 1962. Sediment source areas, delivery ratios and influencing morphological factors. I.A.H.S. Publ., 59: 202–213.

Roose, E., 1977. Erosion et ruissellement en Afrique de l'Ouest. Trav. Doc. ORSTOM, 78: 108 pp.

Roose, E. and Lelong, F., 1976. Les facteurs de l'érosion hydrique en Afrique tropicale. Etudes sur petites parcelles expérimentales de sol. Rev. Géogr. Phys. Géol. Dyn., 18(4): 365–374.

Sall, M., 1982. Dynamique et morphogénèse actuelle au Sénégal occidental. Thesis, Univ. Louis Pasteur, Strasbourg, 604 pp.

Schoeller, H., 1962. Les Eaux Souterraines. Masson, Paris, 642 pp.

Seguy, J., 1955. Rapport sur les mesures de débits solides du fleuve Sénégal à Dagana (campagne 1955). Bull. Mission Aménage. Fleuve Sénégal (M.A.S.), 42: 28 pp.

Soliman, H.A., 1982. The Nile river: Study of carbon transport. In: E.T. Degens (Editor), Transport of Carbon and Minerals in Major World Rivers. Part. 1. Mitt. Geol. Palaeontol. Inst. Univ. Hamburg, SCOPE/UNEP Sonderb. 52: p. 433

Soliman, H.A., 1983. Nile research at the Asyut University. In: E.T. Degens, S. Kempe and H. Soliman (Editors), Transport of Carbon and Minerals in Major World Rivers. Part. 2. Mitt. Geol. Palaeontol. Inst. Univ. Hamburg, SCOPE/UNEP Sonderb. 55: 385–399.

Sow, A., 1984. Pluie et écoulement fluvial dans le bassin du fleuve Sénégal. Thesis Univ. Nancy, 435 pp.

Walling, D.E., 1983. The sediment delivery problem. J. Hydrol., 65: 209–237.

Walling, D.E., 1984. The sediment yields of African rivers. I.A.H.S. Publ. 144, Harare Symp., pp. 265–283.

Walling, D.E. and Webb, B.W., 1982. Sediment availability and the prediction of storm-period sediment yields. I.A.H.S. Publ. 137, Proc. Exeter Symp., pp. 327–337.

White, W.R., 1982. Studies and reports in hydrology. Sedimentation problems in river basin. UNESCO Publ. 35: 152 pp.