Soil carbon stock and river carbon fluxes in an humid tropical environment: the Nyong river basin (South Cameroon)

Jean-Loup Boeglin (1), Jean-Luc Probst (1,2), Jules-Rémy Ndam-Ngoupayou (3), Brunot Nyeck (3), Henri Etcheber (4), J. Mortatti (5) and Jean-Jacques Braun (1,6)

(1) Laboratoire des Mécanismes de Transfert en Géologie (UMR UPS-CNRS-IRD 5563) 38, rue des 36 Ponts 31400 Toulouse (France), boeglin@lmtg.ups-tlse

(2) Ecole Nationale Supérieure d'Agronomie de Toulouse, Institut National Polytechnique, Avenue de l'Agrobiopole, BP 107, Auzeville Tolosane, 31326 Castanet Tolosan (France), jean-luc.probst@ensat.fr

(3) Département des Sciences de la Terre, University Yaoundé I (Cameroon), ndam@yahoo.fr

(4) Centre de Recherche sur les Environnements Sédimentaires et Océaniques, University Bordeaux I (France), h.etcheber@epoc.u-bordeaux1.fr

(5) CENA, University São Paulo, Campus Piracicaba, Avenida Centanario 303, Piracicaba 13400 SP (Brazil), jmortatt@cena.usp.br

(6) Indian Institute of Science, Department of Metallurgy, Bangalore 560 012 (India), braun@civil.iisc.ernet.in

Abstract:
This study is focused on the transfers of carbon under its different forms in the tropical humid environment, from analyses realized on soils and waters in nested silicated catchments of the South Cameroon forested area (Nyong river basin). The carbon stock reaches 59000 $t.km^{-2}.yr^{-1}$ in the soil cover (mean thickness = 30 m), presenting a notable enrichment in the 2 upper meters of the profiles. The dissolved organic carbon fluxes (0.3 $t.km^{-2}.yr^{-1}$), so that the atmospheric/soil CO_2 uptake by weathering are weak, in relation with a low weathering rate (3 mm/1000yr). The dissolved organic carbon appears very abundant in the coloured drainage waters (fluxes between 5 and 8 $t.km^{-2}.yr^{-1}$ after the stations), from the same magnitude than the total dissolved mineral species; it plays a leading role in the dissolution and the transport of trace elements, so that in the compensation of the anionic deficit observed in these waters. The particulate organic carbon (fluxes between 0.6-1.4 $t.km^{-2}.yr^{-1}$) represents about 20% of the total suspended solids. From the total carbon outputs determined here, the turn over of this element in the soils can be estimated to 9000 yr; however, this value considerably decreases considering that only the carbon contained in the upper part of the soil cover is easily mobilizable and reactive.

Key words : organic carbon, inorganic carbon, river water, soil cover, weathering rate, CO_2 uptake, tropical catchments, equatorial Africa

1. Introduction

The role of organic so that inorganic carbon in the environmental equilibrium is nowadays generally accepted. So, at a global scale, the interactions between the carbon cycle on the one hand and the weathering of rocks and soils or the continental water circulation on the other hand have been frequently demonstrated (Berner et al., 1983; Meybeck, 1987; Ludwig et al., 1998; Amiotte-Suchet et al., 2003). Hydrochemical studies of carbon transfers, realized on different-size catchments located in all climatic areas, are complex because this element is found under several forms (mineral or organic, dissolved or particulate). The carbon origin in the continental waters (atmospheric or soil CO_2, dissolution and erosion of rocks, soil organic matter, aquatic microorganisms...), so that its possible exchange or transformation reactions can be determined using isotopic tracing of carbon (Amiotte Suchet et al., 1999; Aucour et al., 1999; Barth and Veizer, 1999; Brunet et al., in press) and of other elements like strontium (Negrel et al., 1993; Gaillardet et al., 1999), or geochemical modelling (Probst et al., 1994; Amiotte-Suchet and Probst, 1995; Gaillardet et al., 1997, Mortatti and Probst, 2003). If data of carbon concentrations and fluxes are available for many rivers, as Niger (Martins and Probst, 1991; Boeglin and Probst, 1996), Congo (Probst et al., 1994; Seyler et al., 1995) or Amazon (Richey et al., 1990) in the case of tropical basins, the carbon contents and stocks in the soil cover of corresponding watersheds have generally not been determined.

The purpose of this work is to analyse the carbon concentrations in the different water reservoirs under its different forms in relation with the weathering rate and the carbon content in the soils of five nested catchments belonging to the Nyong basin in South Cameroon. This forested granitic watershed is considered as well-representative of the humid tropical domain. Such a study has been rarely performed on this type of environment (McDowell and Asbury, 1994, and White et al., 1998, in Puerto Rico; Stoorvogel et al., 1997a and Stoorvogel et al., 1997b, in Ivory Coast), contrary to the temperate northern-american or european environments (see for example the compilations of Velbel, 1995; White and Blum, 1995; Drever and Clow, 1995).

2. Characterization of the Nyong river basin

The Nyong basin, covering an area of 27,800 km² between 2°58' and 4°32' of North latitude, is wholly located in the Cameroonian territory. Five nested catchments have been followed up in the present study, i.e. from upstream to downstream: the experimental Mengong catchment near to Nsimi village, the Awout watershed (tributary of the So'o) at Messam, the So'o watershed (tributary of the Nyong) at Pont So'o, the upper Nyong basin at Mbalmayo and at Olama station after the Nyong and So'o confluence (fig. 1).

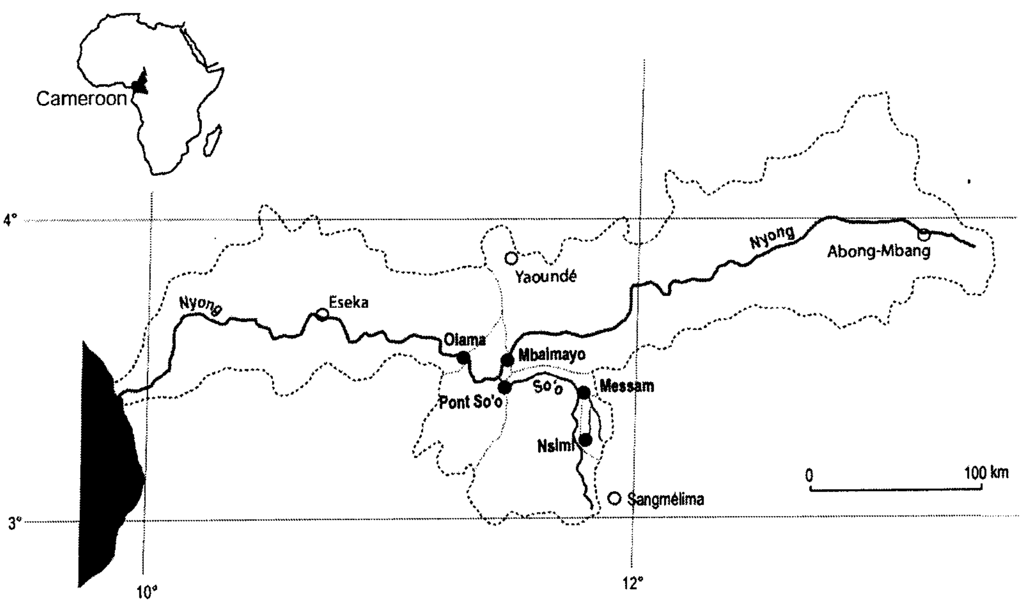

Fig. 1 - Location map of the Nyong basin (South-Cameroon); the studied stations are indicated by black circles

The study area belongs to the South-Cameroonian Plateau, vast smoothly-ondulating area, with altitudes between 650 and 850 meters. The morphology, presenting large depressed swampy zones (about 20% of the Nsimi catchment area) between eroded hills, is derived from an original half-orange landscape (Bilong et al., 1992).

The regional substratum is granite-type. After Vicat (1998), the Southern part of the study area, mainly constituted of Liberian granitoids of the Ntem group (2600-2900 Myr) corresponds to the edge of the Congo craton, whereas the Northern part, with gneisses and migmatites of the Yaoundé series metamorphized during the Panafrican orogenesis (~ 600 Myr) is the Western continuation of the Oubanguide chain.

At the scale of the Nsimi catchment, a spatial distribution of pedologic horizons have been performed from pits and holes (Nyeck et al., 1993) so that from a resistivity measurement network (Ritz et al., 1998). The lateritic profile developed on slopes and hills (thickness up to 50 m) is characterized by a deferruginisation and a nodulation within the ferricrete, which is caped by a sandy-clayey homogeneous cover yellowish to reddish in colour. In the depressed zone, hydromorphic soils (1-3 m thick), essentially constituted by grey colluvial sandy clays presenting a notable organic matter enrichment (>10%) at their upper part, overlay the truncated mottled clay horizon.

The Southern Cameroon is submitted to a four seasons Guinean climate; the two rainy seasons (March to May, September to November) are separated by a short dry season, whereas the well-marked long dry season goes from December to February. After Olivry (1986), the annual rainfall is between 1500 and 2000 mm, with a mean temperature of about 25°C presenting a 2-3°C annual amplitude, and a potential evapotranspiration of 1250 $mm.yr^{-1}$. For the water year 1998/99, rainfall (P) and runoff (R) average respectively 1822 and 387 mm for the Mengong catchment and 1667 and 283 mm for on Nyong basin at Olama; these values correspond respectively to a runoff ratio (R/P) of 21 and 17 %.

The Yaoundé-Sangmélima-Abong Mbang triangular area (fig. 1) is mainly the domain of the semi-deciduous forest, characterized by Stertuliaceae and Ulmaceae; in fact, this type of vegetation cover remains only in limited sectors surrounded with more damaged vegetation zones (Villiers in Santoir and Bopda, 1995). The swampy depressions are generally colonized by raffias. The anthropization effects on the environment are rather weak on the South-Cameroonian Plateau, in relation with low population density (5-10 $inh.km^{-2}$, except in the urban zone of Yaoundé). Human activities include forest working and overall a traditional-type agriculture using no fertilizer and producing food crops (tubers, banana, corn) or peanuts, tomatoes, cocoa bean…

3. Methodology

Soils were sampled on Nsimi catchment, in pits on hills and slopes, in holes or by drilling in the swampy depression. The organic carbon is analysed by 2 ways: (i) titration with changing of colour by an ammonium-iron (II) sulfate solution after a strong attack by a hot potassium bichromate solution (Anne's method, Rouiller et al., in Bonneau and Souchier, 1994), realized in the Hydrological Research Center in Yaoundé (Cameroon); (ii) measurement of the CO_2 amount released consecutively to the combustion of a soil aliquot, performed in the laboratories of the Centro de Energia Nuclear na Agricultura in Piracicaba (Brazil). The first method, well appropriate for carbon contents higher than 1%, appears not enough precise in the case of organic-poor horizons ($C < 0.2\%$).

Waters have been collected monthly at 6 stations (one on a spring, two on brooks, three on rivers) of the Nyong network. After measurement of the physico-chemical parameters (temperature, pH, electrical conductivity) and filtration in the field, samples were sent to the

Centre de Géochimie de la Surface in Strasbourg (France), where major cations and anions, dissolved silica, so that alkalinity and dissolved organic carbon (DOC) were analysed. The alkalinity (= "acid neutralizing capacity") was determined by sulphuric acid titration using Gran method on a Mettler memotitrator DL 40RC, with an analytical reproductibility better than 2%. The Shimadzu TOC 5000A analyser allows the measurement of DOC content by catalytic combustion; the reproductibility is about 5%, the detection limit being 0.1 $mg.L^{-1}$.

The determination of particulate organic carbon (POC) was realized on the total suspended solids (TSS) collected on glass microfiber filters during the 22-23th April 2002 flood event. The concentrations were determined by catalytic combustion on a LECO CS125 carbon analyser, at the Centre de Recherche sur les Environnements Sédimentaires et Océaniques of Bordeaux I University (France).

4. Results

4.1. Carbon in soils

Soils of the Southern-Cameroon Plateau are recognized as laterites on hills and slopes, or as hydromorphic soils in swampy depressions and valleys, all developed on a granitoid-type bedrock; so, as no occurrence of carbonate has been observed in the geological substratum and in the soil (like calcrete), the totality of the carbon present in the pedological cover is contained in the organic matter. Soil samples have been collected and analysed only in the Mengong catchment but for the different horizons. The carbon contents exhibit a very heterogeneous distribution in the different soil profiles (table I). High concentrations are only found in the first meter of the hills and slopes overlaying soils, so that of the hydromorphic soils (up to 6% in the sandy-clayey horizon) of the swampy depression. Whereas, the carbon concentrations appear very low in all the deep horizons. These results are in good accordance with the analyses performed by Humbel et al. (1977) in different ferrallitic soils of Cameroon.

An estimation of the total carbon stock in the soil cover is proposed here for the Mengong catchment, on the basis of our organic carbon analyses on the one hand, of the pedological studies (description of toposequences, determination of apparent density) realized by Nyeck et al. (1993) and of the geophysical measurements (surficial resistivity allowing an assessment of the soil profile depth along cross-sections) carried out by Ritz et al. (1998) on the other hand. For each horizon, the different parameters used in the calculation are summarized in table I. So, the organic carbon stock could be estimated to about 35,000 tons in the $17*10^6$ m^3 of the Mengong catchment soil cover. It has to be noticed that the surficial horizons of hills, slopes and especially of depression, which are by far the most enriched in organic matter, represent only 13% of the total carbon amount; the highest contribution is supplied by the saprolite (51%) in which low carbon content is widely compensated by the thickness of this formation which occupies the whole catchment.

Table I Organic carbon content and stock in the different soil horizons of the Mengong catchment

Horizon	A %	T (m)	V ($10^3.m^3$)	V %	AD	OC %	S_{OC} (tons)	S_{OC} %
Lateritic profile (with overlay on hills and slopes) from top to depth								
Upper overlay	80	0.2	96	0.6	1.30	1.5	1,870	5.3
Overlay	80	2	960	5.6	1.28	0.30	3,690	10.5
Ferricrete/nodula r	80	2	960	5.6	1.66	0.15	2,390	6.8
Mottled clays	99	5	2,970	17.4	1.29	0.15	5,750	16.3
Saprolite	99	20	11,900	69.7	1.50	0.10	17,850	50.7
Hydromorphic soils of the depression (covering truncated mottled clays) from top to depth								
Organo-mineral	15	0.5	45	0.3	1.44	4.0	2,590	7.3
Colluvial	15	1.5	135	0.8	1.62	0.5	1,090	3.1
Total catchment	-	-	17,066	100	-	-	35,230	100

A % is the percentage of the catchment area (0.60 km^2); T is the mean thickness (in m), V is the volume (in 10^6*m^3), and AD the apparent density of an horizon;, OC % is the percentage of organic carbon content; S_{OC} is the stock of organic carbon, S_{OC} % in the percentage of organic carbon stock in a given horizon compared the whole catchment; data in the last line correspond to the whole catchment.

4.2. Carbon in the surface waters

4.2.1- Dissolved Organic Carbon (DOC)

In the Mengong catchment, a distinction has to be made between the clear spring waters and the coloured outlet river waters. This colour difference has previously been pointed out by Viers et al. (1997) and by Oliva et al. (1999), and it is attributed to a notable discrepancy in DOC content (table II). For the water year 1998/99, the mean annual DOC concentration is 0.30 $mg.L^{-1}$ in the spring and 14.4 $mg.L^{-1}$ in the stream at the outlet.

Table II - Hydrological characteristics of the Nyong catchment network and average values for some physico-chemical parameters measured during the water year 1998/99 in the spring and river waters.

Station	A	Q_m	DIC C	DIC F	TDS C	TDS F	DOC C	DOC F	TSS C	TSS F	F_{CO2}
Mengong experimental catchment											
Spring	-	-	1.08	-	11.3	-	0.31	-	-	-	-
Stream	0.60	387	0.95	310	16.5	6000	14.4	5669	8.1	2870	23.4
Nyong river stations from upstream to downstream											
Messam	206	430	0.84	240	20.2	6970	23.0	9300	14.1	4110	14.6
Pont So'o	3,070	370	1.16	305	22.9	7150	15.2	6320	20.6	6970	25.1
Mbalmayo	13,555	257	1.52	260	24.7	4980	15.7	4670	13.3	3280	21.8
Olama	18,510	283	1.26	280	22.4	5590	15.4	4850	14.3	4490	23.5

S is the catchment area in km^2, Q_m is the annual mean runoff expressed in $mm.yr^{-1}$; C is the mean annual concentration in $mg.L^{-1}$; F, the annual specific flux in $kg.km^{-2}.yr^{-1}$; DIC is the dissolved inorganic carbon contained in bicarbonate, TDS is total inorganic dissolved solids, DOC is dissolved organic carbon, TSS is total suspended solids; F_{CO2} is the atmospheric/soil CO_2 specific flux consumed by weathering (in 10^3 $mol.km^{-2}.yr^{-1}$).

The mean DOC river fluxes are between 4700 and 9300 $kg.km^{-2}.yr^{-1}$ (table II); the values corresponding to the Southern part of the Nyong watershed appear to be higher than these observed for the Eastern part of the basin (Mbalmayo station). But this difference can be explained by a higher drainage intensity in the Southern part, rather than by a notable change in the vegetation and soil covers.

The organic-rich waters exhibit a very high ionic imbalance (δ) between the cationic sum (S_c) and the anionic sum (S_a), due to an important anionic deficit, as already described by Probst et al. (1992) for the Congo river waters. The mean annual deficit averages 54 to 90% according to the stations. This imbalance is mainly due to organic anions which are not taken into account in the alkalinity measurement, as shown by Fillion et al. (1998). Consequently, as seen in Figure 2, there is a very good relationship between ionic deficit δ (in $\mu eq.L^{-1}$) and DOC content (in $mg.L^{-1}$) for the Mengong river waters. The slope of the regression lines obtained for the different stations vary between 4.3 and 9.0 $\mu eq.mg^{-1}C$; the correlation coefficients R calculated for all catchments are higher than 0.86.

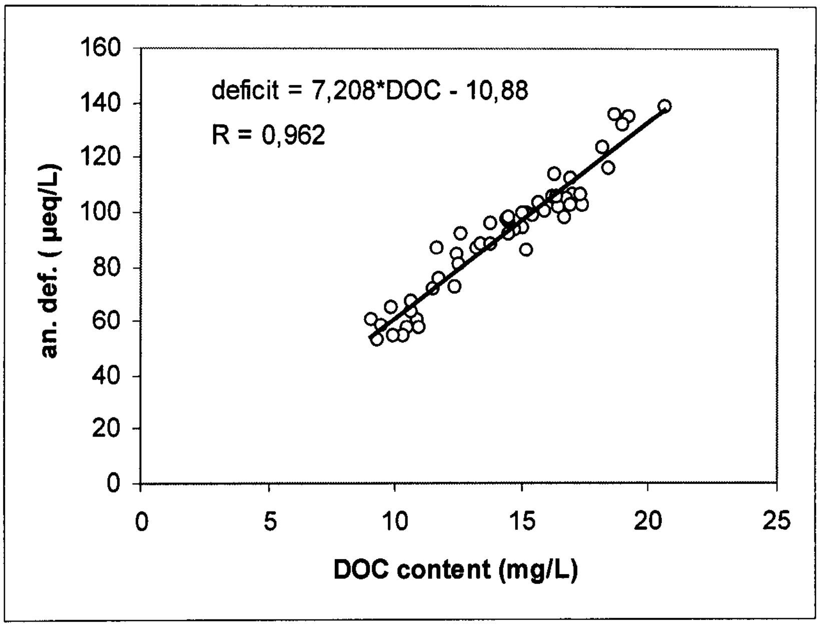

Fig. 2 - Relationships between the anionic deficit and the DOC content in the Mengong river waters during the water year 1998-99.

4.2.2- Dissolved Inorganic Carbon (DIC)

In solution, inorganic carbon is present mainly as bicarbonate species at the pH of most river waters. This ion is released consecutively to hydrolysis reactions in which soil and rock minerals are weathered under the effect of the carbonic acid (eq. 3); this acid, originating from the atmospheric CO_2 (eq. 2), is abundant in the soil solutions and is produced by the soil organic matter oxidation (eq.1):

$$CH_2O + O_2 \leftrightarrow CO_2 + H_2O \qquad (1)$$

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \qquad (2)$$

For example, the weathering reaction of orthose (or microcline) into kaolinite can be written as follows (Garrels and Mackenzie, 1971):

$$2KAlSi_3O_8 + 3H_2O + 2CO_2 \leftrightarrow Si_2Al_2O_5(OH)_4 + 2K^+ + 4SiO_2 + 2HCO_3^- \quad (3)$$

In this above reaction, it can be noticed that all bicarbonate ions released into solution originate from atmospheric/soil CO_2.

The mean annual bicarbonate concentrations are 5.5 $mg.L^{-1}$ in the spring, and between 4.8 and 7.8 $mg.L^{-1}$ in the different river waters. The corresponding concentrations of DIC at the Nyong river stations, so that all the specific fluxes are summarized in table II.

As the substratum of the Nyong drainage basin is only composed of silicate rocks, the total bicarbonate fluxes measured in the river waters sampled at the different stations can be directly related to the atmospheric/soil CO_2 as seen in reaction (3). Consequently the calculation of the CO_2 fluxes consumed by chemical weathering is directly derived from the alkalinity river fluxes. The values calculated for the different stations vary between 20 and 26 $10^3 mol.km^{-2}.yr^{-1}$ (table II).

4.2.3. Total Suspended Solids (TSS) and Particulate Organic Carbon (POC)

Studies on the drainage waters of the Nyong basin showed that the suspended matter are enriched in organic matter, the mineral fraction being mainly composed of kaolinite, quartz and goethite, so that amorphous silica present in diatom frustules or in phytoliths (Olivie-Lauquet et al., 2000). No measurement of POC concentration could be realized on the TSS during the water year 1998/99; however, POC have been measured (17 samples) during the storm flow event of 28-29th April 2002 in the Mengong river water. These measurements indicate that POC content represents on average 25.3% of the TSS content, with rather low variations compared to water discharge fluctuations. This percentage is very close to that (25.4%) obtained from the mean annual POC and TSS fluxes calculated by Ndam-Ngoupayou (1997) for the water year 1995/96 on the Mengong river. Whereas, this percentage is higher than those obtained in the same way for the Nyong at Mbalmayo (17.3%) and Olama (13.8%), showing that the suspended material are less and less enriched in organic carbon going from upstream to downstream because during the same time the TSS concentration increases due to the mechanical erosion of more inorganic materials. This pattern is comparable to those observed for most world rivers (Martins and Probst, 1991; Ludwig et al. 1996). Using these data, the POC specific fluxes can be estimated between 550 and 750 $kg.km^{-2}.yr^{-1}$ for the different stations of the Nyong river basin.

5. Discussion

5. 1- The major role of coloured waters

Two main types of water have to be distinguished in the Nyong basin : the clear waters and the coloured waters. For the last ones, the colour, which remains after filtration and cannot so be related to suspended matters, has been attributed to a high content of dissolved organic matter (Ndam-Ngoupayou, 1997); this is corroborated by our results, with mean DOC concentrations higher than 15 $mg.L^{-1}$ in all river waters, whereas they are about 0.3 $mg.L^{-1}$ in the Mengong spring waters. Moreover, this author points out that, in the Mengong catchment, clear waters are not only coming from springs, but also from hill or slope watertables and from the depression deep watertable; on the other hand, coloured waters, constituting the river waters, are also found in the surficial depression watertable. The major role of dissolved organic matter in the chemical weathering has been demonstrated by Viers et al. (1997) and by Oliva et al. (1999) in this catchment, but also by Idir et al. (1999) in the Strengbach catchment in the Vosges Mountains (France). The organic acids, abundant in the swampy depression waters, are responsible for an enhanced dissolution of soil minerals and for the transport in a complexed form of insoluble metallic elements.

5. 2- The important contribution of DOC fluxes

In term of specific fluxes in river waters, we can see in table II that the DOC values are comparable to those of inorganic TDS (in which dissolved silica flux represents 40 to 56% according to the stations), whereas these DOC fluxes are between one and two times higher than TSS fluxes. Considering that POC averages 20% of TSS, the mean annual flux of total organic carbon (DOC + POC) represents 38 to 50% of the total inorganic and organic materials (TDS+DOC+TSS) exported by the river at the different stations; these percentages correspond to (DOC + POC) specific fluxes between 5,300 and 10,100 $kg.km^{-2}.yr^{-1}$. Our results are comparable with the data given by Sigha-Nkamdjou et al. (1995) for other forested South-Cameroonian catchments (Ntem, Kadéi, Boumba, Dja, Ngoko), where the calculated fluxes are between 3300 and 5300 $kg.km.^{-2}.yr^{-1}$ for DOC, and between 600 and 1200 $kg.km.^{-2}.yr^{-1}$ for POC. For savannah Cameroonian basins (Sanaga, Mbam), Ndam-Ngoupayou (1997) obtained lower values for DOC (~1500 $kg.km.^{-2}.yr^{-1}$), undoubtedly due to lower vegetation biomass and to lower drainage intensity; on the other hand, the POC fluxes appear rather high (1000 $kg.km.^{-2}.yr^{-1}$ for the Sanaga, 4200 $kg.km.^{-2}.yr^{-1}$ for the Mbam), which have to be related to a notable TSS transfer (respectively 18 and 98 $tons.km^{-2}.yr^{-1}$). A comparison between the DOC fluxes exported on the Niger basin: 593 $kg.km.^{-2}.yr^{-1}$ at Lokodja (Martins and Probst, 1991), 455 $kg.km.^{-2}.yr^{-1}$ at Bamako (Boeglin and Probst, 1996) on the one hand, and on the Congo basin: 2.9 $tons.km^{-2}.yr^{-1}$ (Nkounkou and Probst, 1986) or 3.1 $tons.km^{-2}.yr^{-1}$ (Seyler et al., 1995) on the other hand, is a significant illustration for the influence of the vegetation type on the organic carbon solubilization. For indication, Ludwig et al. (1996) proposed a mean DOC flux of 1,043 $kg.km^{-2}.yr^{-1}$ in the dry tropical zone, and of 3,818 $kg.km^{-2}.yr^{-1}$ in the humid tropical zone.

5. 3- Low CO_2 uptake by silicate weathering

Concerning the dissolved inorganic carbon, the specific fluxes of CO_2 consumed by chemical weathering on the silicated Nyong watersheds are between 15 and $25*10^3$ $mol.km^{-2}.yr^{-1}$, which are equivalent to 660-1100 $kgCO_2.km^{-2}.yr^{-1}$. These values are very low compared with those obtained on other lateritic basins, 30 to 120 $10^3 mol.km^{-2}.yr^{-1}$ (Mortatti et al., 1992; Probst et al., 1994; Boeglin and Probst, 1998), except the one determined for the Senegal river whose watershed presents a particularly weak runoff Q ($F_{CO2} = 17*10^3 mol.km^{-2}.yr^{-1}$ for Q = 45 $mm.yr^{-1}$). Considering only the part of F_{CO2} consumed by the silicate weathering, Boeglin and Probst (1998) demonstrated that, contrary to commonly accepted opinion, the F_{CO2} corresponding to lateritic basins –where the chemical weathering is supposed to be very intense- are about 2 times lower than for the non-lateritic watersheds. In the case of the South-Cameroonian catchments, the F_{CO2} values appear 3 to 4 times lower than those previously calculated for the lateritic basins (fig. 3). In the case of the Nyong catchments, the particularly weak F_{CO2} calculated values have to be attributed to the thickness of the lateritic cover on hills and slopes which considerably slows the advance of percolating waters up to the bedrock; this hypothesis is confirmed by the very low mineral dissolved load in the clear so that in the coloured waters (Braun et al., 2002). The very low chemical weathering intensity indicated by these weak F_{CO2} values is confirmed by the calculation performed from the dissolved silica fluxes in the different upper Nyong catchments which are very low compared to the annual rainfall (see White and Blum, 1995). Supposing that 35% of the quartz of the bedrock remains in the saprolite, the weathering rate determined from the method proposed by Boeglin and Probst (1998) at Olama station averages 3.2 mm/1000yr under present conditions, which is very low compared to values generally obtained on tropical basins (6 to 15 mm/1000yr, see Nkoukou and Probst, 1987; Tardy, 1993; Mortatti and Probst, 2003); however, it has to be noticed that a rate of 2.8 mm/1000yr has been determined by Seyler et al. (1993) for the equatorial Ngoko basin in South-Eastern Cameroon.

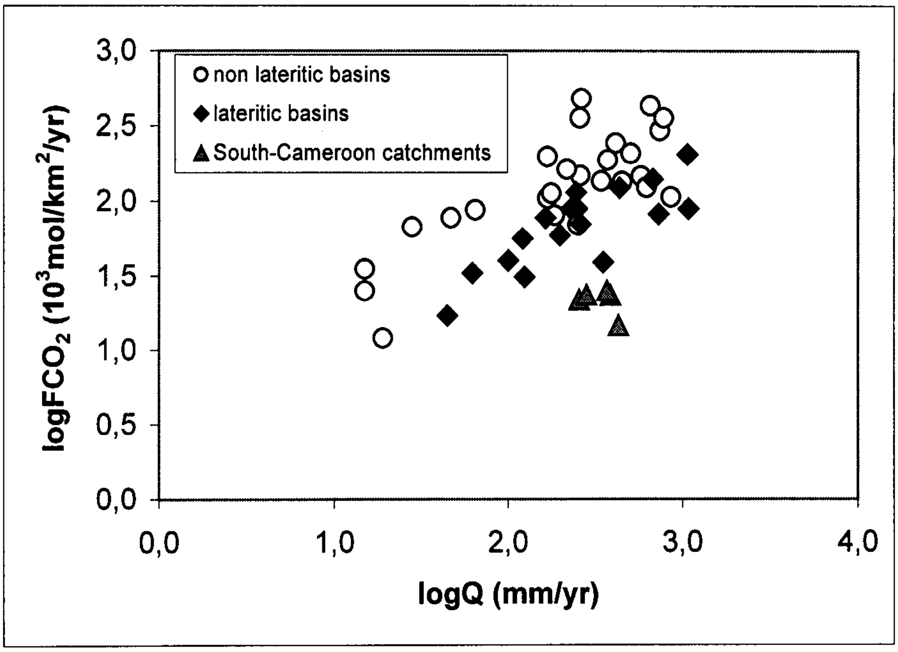

Fig. 3 - Relationship between annual CO_2 fluxes consumed by silicate weathering and mean annual runoff for rivers of different areas in the world (see Boeglin and Probst, 1998, for the list of river basins).

5. 4- Chemical properties of the DOC and transport capacity of trace elements

The mighty correlation highlighted at all the stations of the Nyong basin between the anionic deficit and the DOC content indicates indisputably that the presence of organic anions compensates for the lack of negative mineral charges, as previously admitted by Sullivan et al. (1989) or Munson and Guerini (1993).The specific charge of the organic matter (in $\mu eq.mg^{-1}$DOC), given by the slope of the regression line, is variable according to the stations: 7.2 for the Mengong, 9.0 for the Awout at Messam, 5.2 for the So'o at Pont So'o, 4.8 for the upper Nyong at Mbalmayo, and 4.3 for Nyong at Olama. The decreasing of this specific charge from upstream to downstream (with a particularly high value for the Awout stream) could be attributed to a progressive structural modification of the organic compounds in the river waters. For indication, the length of the water course from Nsimi to Olama (~100 km) is about 3 to 6 days. That means that the capacity of the dissolved organic matter to complex the cations, particularly the heavy metals, decreases from upstream to downstream, increasing the transport of heavy metals by the suspended matters.

5. 5 - Global carbon budget at the Mengong catchment scale

The quantification of the carbon transfers at the scale of the experimental Mengong catchment has been summarized in figure 4. Atmospheric inputs, essentially constituted by rainfalls, present very variable carbon contents: mean DOC is 0.61 $mg.L^{-1}$ in open field precipitations and 3.6 $mg.L^{-1}$ in throughfalls after Ndam-Ngoupayou (1997), whereas Freydier et al. (2002) determined a mean total organic carbon concentration (including fine suspended particles resulting from the combustion of biomass) of 2.5 $mg.L^{-1}$ in open field precipitations. However, these values have been obtained from a reduced number of samples which does not cover a whole annual period. Considering an annual rainfall of 1800 mm, with a mean carbon content going from 1 to 3 $mg.L^{-1}$, the corresponding input is 1.8-5.4 $tonsC.km^{-2}.yr^{-1}$.

The organic carbon stock in the soil cover of the Mengong catchment has been estimated in this study to 59,000 $t.km^{-2}$; however, only 26% of this amount of carbon are concentrated in the two upper meters of the profiles and can be drained by the surface and subsurface runoffs.

Concerning the litter fall, measurements made by Odigui Ahana (2000), in an experimental site at 100 km North of the Mengong catchment, give an annual value of 10.75 tons of total wet organic matter with a mean carbon content of 38%, which is equivalent to 4100 $tCkm^{-2}.yr^{-1}$. For the biomass, Likens et al. (1977) indicate for the forested tropical area a mean density of 450,000 $t.km^{-2}$ with an annual production of 22,000 $t.km^{-2}$.

In such a lithological environment without any carbonate rocks, the riverine inorganic carbon is only found under dissolved inorganic carbon, there is no particulate inorganic carbon. In the Mengong catchment, the DIC riverine specific flux has been estimated from the alkalinity to 310 $kgC.km^{-2}.yr^{-1}$, corresponding to the same amount of atmospheric/soil CO_2 consumed by the chemical weathering of the silicate minerals.

Concerning the organic carbon, the riverine fluxes have been estimated for the Mengong catchment to 5700 and 575 $kgC.km^{-2}.yr^{-1}$ respectively for the DOC and the POC. It has to be pointed out that, except at Messam on the Awout brook, the DOC and DIC specific fluxes are comparable from one station to another over the Nyong river basin; this indicates that the transfer dynamic of dissolved carbon does not change going from upstream to downstream part of the Nyong river basin which presents the same type of lithology and vegetation covers, independently of the sub-catchment size.

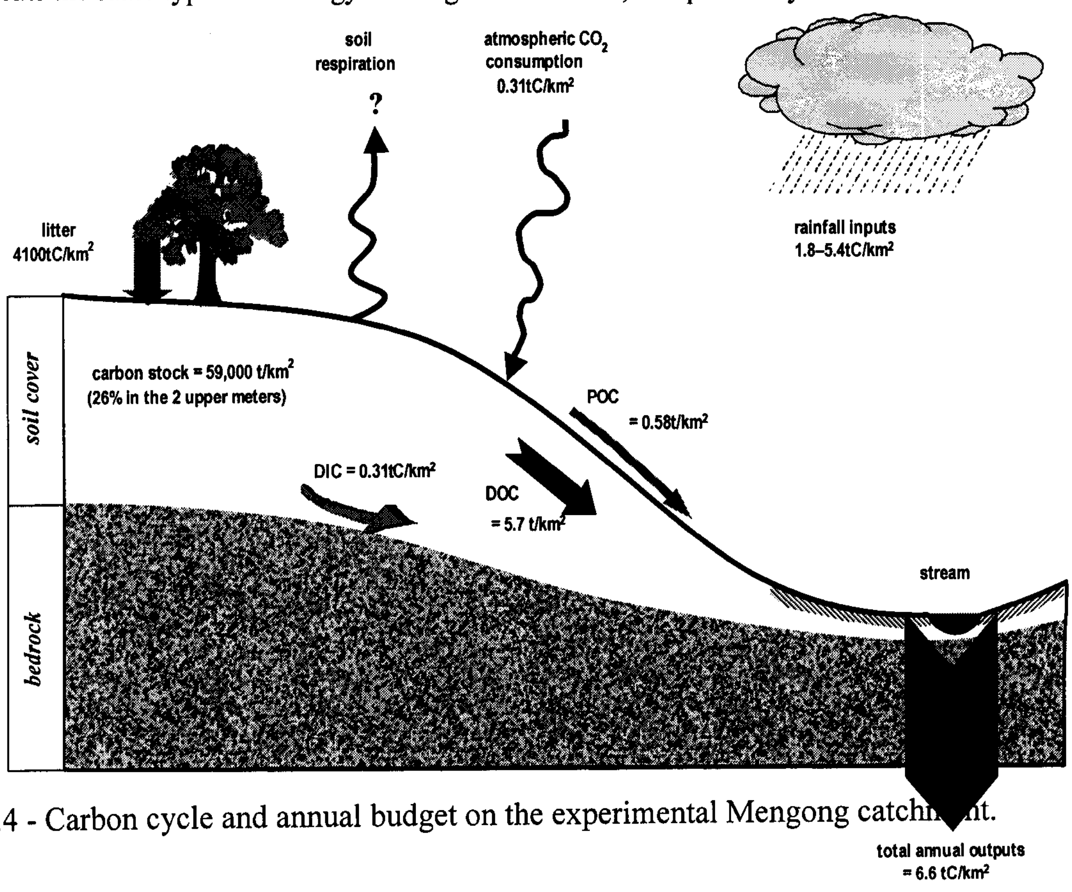

Fig.4 - Carbon cycle and annual budget on the experimental Mengong catchment.

The residence time (τ)of carbon in the Mengong catchment soils can be estimated from the total carbon stock (S_{OC}) in the soil cover (35,000 tons), and from the annual fluxes of riverine carbon {F_{DOC} (3400 $kg.yr^{-1}$) + F_{POC} (345 $kg.yr^{-1}$) + F_{DIC} (190 $kg.yr^{-1}$)}:

$$\tau = S_{OC} / (F_{DOC}+F_{POC}+F_{DIC})$$

The obtained value (9000 yr) indicates a rather slow turn over of the carbon in this catchment in the present conditions. That means also that the riverine carbon fluxes represent only 0.1‰ of the soil carbon stock. This value is of the same order of magnitude than the estimation that can be made on a global scale (0.2‰) using the data of Meybeck (1982). However, if one considers that the reactive and mobilizable carbon is essentially contained in the upper part of the profiles (stock = 9200 tons), or only in the hydromorphic depression soils (stock = 3700 tons), the residence time notably decreases respectively to 2350 yr and 950 yr, increasing also the percentage of carbon exportation respectively to 0.4‰ and 1‰.

6. Conclusion

Analyses of the different forms of inorganic and organic carbon in the soils and in the waters, performed on silicated catchments of the Southern-Cameroon forested area, provide many informations on the transfer dynamic and on the mass balance in a tropical humid environment.

(1) The upper horizons of the soil cover and the corresponding draining waters exhibit rather high concentrations in organic carbon. Considering the soil cover containing a specific carbon stock of 59,000 $tons.km^{-2}$, about 26% of this amount is concentrated in the 2 upper meters of the soil profiles (mean thickness = 30 m). In the coloured river and swamp waters, DOC fluxes are between 5000 and 9000 $kg.km^{-2}.yr^{-1}$ (which is comparable to inorganic TDS fluxes), whereas POC fluxes (representing about 20% of TSS) are between 500 and 1300 $kg.km^{-2}.yr^{-1}$. On the contrary, clear spring waters or groundwaters present very low DOC contents.

(2) In such a non-carbonated environment, the DIC fluxes are normally low. Whereas for the Nyong river basin, these fluxes (840-1520 $kgC.km^{-2}.yr^{-1}$) are lower than for other tropical silicated catchments. This can be related mainly to the low chemical weathering rate of silicate rocks that could be estimated to 3.2 mm/1000yr for the upper Nyong basin at Olama. Such a weak weathering rate can be explained by the thickness of the soil cover (until 50 m), insulating the bedrock from the interactions with the surfacial draining waters.

(3) The turn over of the carbon (organic + inorganic) in the Mengong catchment is estimated to 9000 yrs if one takes into account the whole carbon stock of the soil cover. However, considering that only the carbon contained in the hydromorphic soil horizons of the swampy zone is involved in the exchange and recycling processes, the residence time decreases to 950 yrs.

(4) The strong anionic deficit (54-90%) pointed out in all drainage waters exhibits a very good correlation with the DOC content. The specific charge of the dissolved organic matter has been estimated to 4.3-9.0 $\mu eq.mg^{-1}C$; its regular decreasing from upstream to downstream part or the Nyong river basin indicates probably a progressive structure modification of the

organic dissolved species during the transfer, so that a decreasing capacity of trace element complexation and transport.

(5) Values of carbon specific fluxes obtained at the different stations of the Nyong network appear rather close. From upstream to downstream, the DOC specific fluxes are comparable, as well as the DIC specific fluxes. On the contrary, the POC specific fluxes are variable – depending on the TSS flux – from one station to another; however, the POC/TSS ratio is slightly variable around 20%. These results can be attributed to a comparable carbon dynamic at the scale of the Nyong river basin, independently of the surface area of the different sub-catchments.

Acknowledgement

The authors would like to thank D. Million and G. Krempp from the Centre de Géochimie de la Surface in Strasbourg for chemical analyses of river waters, J.P. Bedimo-Bedimo and J. Nlozoa from the Hydrological Reseach Center of Yaoundé for hydrological measurements and field assistance. This study has been realized with the financial support of a CAMPUS/CORUS cooperation project (n° 99.0026 (04)) between the University Paul Sabatier in Toulouse and the University of Yaoundé I. This work is also a contribution to the IGCP project n°459 (UNESCO-IUGS) on"Carbon Cycle and Hydrology" and to DYLAT project of IRD.

References

Amiotte-Suchet, P., Aubert, D., Probst, J.L., Gauthier-Lafaye, F., Probst, A., Andreux, F. and Viville, D. (1999) $\delta^{13}C$ pattern of dissolved inorganic carbon in a small granitic catchment: the Strengbach case study (Vosges mountains, France). Chem. Geol, 159, 87-105.

Amiotte-Suchet, P., Probst, J.L. (1993) Modelling of atmospheric CO_2 consumption by chemical weathering of rocks: application to the Garonne, Congo and Amazon basins. Chem. Geol., 107, 205-210.

Amiotte-Suchet, P. and Probst, J.L. (1995) A global model for present-day atmospheric/soil CO_2 consumption by chemical erosion of continental rocks (GEM-CO_2). Tellus, 47B, 273-280.

Amiotte-Suchet, P., Probst, J.L., Ludwig, W. (2003) Worlwide distribution of continental rock lithology : implication for the atmospheric/soil CO_2 uptake by continental weathering and alkalinity river transport to the ocean. Global Biogeochem. Cycles, 17(2), in press.

Aucour, A.M., Sheppard, S., Guyomar, O. and Wattelet, J. (1999) Use of $\delta^{13}C$ to trace origin and cycling of inorganic carbon in the Rhône river system. Chem. Geol., 159, 87-105.

Barth, J. and Veizer, J. (1999) Carbon cycle in the St Lawrence aquatic ecosystem at Cornwall (Ontario), Canada: seasonal and spatial variations. Chem. Geol., 159, 107-128.

Berner, R.A., Lasaga, A.C., Garrels, R.M. (1983) The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxid over the past 100 million years. Am. Journ. Sci., 283(7), 641-683.

Bilong, P., Eno Belinga, S.M. and Volkoff, B. (1992) Séquence d'évolution des paysages cuirasses et des sols ferrallitiques en zones forestières tropicales d'Afrique Centrale. Place des sols à horizons d'argiles tachetées. C.R. Acad. Sci. Paris, t. 314, série II, 109-115.

Boeglin, J.L,. Probst, J.L. (1996) Transports fluviaux de matières dissoutes et particulaires sur un bassin versant en région tropicale : le bassin amont du Niger au cours de la période 1990-1993. Sci. Géol., Bull., 49(1-4), Strasbourg, 25-45.

Boeglin, J.L., Probst, J.L. (1998) Physical and chemical weathering rates and CO_2 consumption in a tropical lateritic environment: the upper Niger basin. Chem. Geol., 148, 137-155.

Bonneau, M. and Souchier, B. (1994) Pédologie 2. Constituants et propriétés des sols. Masson, 2nd ed., 665 p.

Braun, J.J., Dupré, B., Viers, J., Ndam-Ngoupayou, J.R., Bedimo-Bedimo, J.P., Sigha-Nkamdjou, L., Freydier, R., Robain, H., Nyeck, B., Bodin, J., Oliva, P., Boeglin, J.L., Stemmler, S. and Berthelin, J. (2002) Biogeohydrodynamic in the forested humid tropical environment: the case study of the Nsimi experimental watershed (South Cameroon). Bull. Soc. Géol. France, 173(4), 347-357.

Brunet, F., Gaiero, D., Probst, J.L., Depetris, P.J., Gauthier-Lafaye, F., Stille, P. (in press) $\delta^{13}C$ tracing of dissolved inorganic carbon sources in Patagonian rivers. Hydrol. Processes.

Drever, J.I. and Clow, D.W. (1995) Weathering rates of silicate minerals. In Chemical weathering rates of silicate minerals, A.F. White and S.L. Brantley Edts, Miner. Soc. of America, Reviews in Mineralogy, 31, 463-483.

Fillion, N., Probst, A. and Probst, J.L. (1998) Natural organic matter contribution to throughfall acidity in French forests. Environm. Internat., 24, 547-558.

Freydier, R., Dupré, B., Dandurand, J.L., Fortuné, J.P. and Sigha-Nkamdjou, L. (2002) Trace elements and major species in precipitations at African stations : concentrations and sources. Bull. Soc. Géol. France, 173(2), 129-146.

Garrels, R.M. and Mackenzie, F.T. (1971) Evolution of sedimentary rocks. W.W. Nortonand, New York, 397 p.

Gaillardet, J., Dupré, B., Allègre, C.J., Negrel, P. (1997) Chemical and chemical denudation in the Amazon river basin. Chem. Geol., 142(3-4), 141-173.

Gaillardet, J., Dupré, B., Louvat, P., Allègre, C.J. (1999) Global silicate weathering and CO_2 consumption rates deduced from the chemistry of large rivers. Chem. Geol., 159(1-4), 3-30.

Humbel, F.X., Muller, J.P. and Rieffel, J.M. (1977) Quantité de matières organiques associées aux sols du domaine ferrallitique au Cameroun. Cah. ORSTOM, sér. Pédol., 15(3), 259-274.

Idir, S., Probst, A., Viville, D., Probst, J.L. (1999) Contribution des surfaces saturées et des versants aux flux d'eau et d'éléments exportés en période de crue : traçage à l'aide du carbone organique dissous et de la silice. Cas du petit bassin versant du Strengbach (Vosges, France). C.R. Acad. Sci., Paris, Sc. Terre et planètes, 328, 89-96.

Likens, G.E., Bormann, F.H., Pierce, R.S., Eaton, J.S. and Johnson, N.M. (1977) Biochemistry of a forested ecosystem. Springer Verlag, Berlin.

Ludwig, W., Amiotte-Suchet, P., Munhoven, G., Probst, J.L. (1998) Atmospheric CO_2 consumption by continental erosion: present-day controls and implication for the last glacial maximum. Glob. Planet. Changes, 16-17(1-4), 107-120.

Ludwig, W., Probst, J.L. and Kempe, S. (1996) Predicting the oceanic input of organic carbon by continental erosion. Global Biochemical Cycles, 10(1), 23-41.

Martins, O. and Probst, J.L. (1991) Biogeochemistry of major African rivers: Carbon and mineral transport. In Biogeochemistry of major world rivers, E.T. Degens, S. Kempe and J.E. Richey Edts, SCOPE 42, Wiley, chap. 6, 129-155.

McDowell, W.H. and Asbury, C.E. (1994) Export of carbon, nitrogen and major ions from three tropical mountane watersheds. Limnol. Oceanogr., 39, 111-125.

Meybeck, M. (1982) Carbon, nitrogen and phosphorus transport by world rivers. Am. J. Sci., 282, 401-450.

Meybeck, M. (1987) Global geochemical weathering of surficial rocks estimated from river dissolved loads. Am. Journ. Sci., 287(5), 401-428.

Mortatti, J., Probst, J.L., Ferreira, J.R. (1992) Hydrological and geochemical characteristics of the Jamari and Jiparana river basins (Rondonia, Brazil). Geojournal, 26(3), 287-296.
Mortatti, J. and Probst, J.L. (2003) Silicate rock weathering and atmospheric/soil CO_2 uptake in the Amazon basin estimated from the river water geochemistry: seasonal and spatial variations. Chem. Geol., 197, 177-196.
Munson, R.K. and Gherini, S.A. (1993) Influence of organic acids on the pH and Acid Neutralizing Capacity of Arirondack lakes. Water Resour. Res., 29, 891-899.
Ndam-Ngoupayou, J.R. (1997) Bilans hydrogéochimiques sous forêt tropicale humide en Afrique : du bassin expérimental de Nsimi-Zoétélé aux réseaux hydrographiques du Nyong et de la Sanaga (Sud-Cameroun). Thèse Doct. Univ. Paris VI, 214 p., 2 annexes.
Negrel, P., Allègre, C.J., Dupré, B., Lewin, E. (1993) Erosion sources determined by inversion of major and trace element ratios and strontium isotopic ratios in the river waters : the Congo basin case. Earth Planet. Sci. Letters, 120, 59-76.
Nkounkou, R.R. and Probst (1987) Hydrology and geochemistry of the Congo river system. Mitt. Geol-Paläont. Inst. Univ. Hamburg, SCOPE/UNEP, 64, 483-508.
Nyeck, B., Bilong, P., Eno Belinga, S.M., Volkoff, B. (1993) Séquence d'évolution des sols sur granite dans le Sud du Cameroun. Cas des sols de Zoétélé. Ann. Fac. Sci. Univ. Yaoundé, IHS, 1, 254-277.
Odigui Ahana, D.H. (2000) Contribution à l'étude de la dynamique du carbone, de l'azote et des éléments minéraux dans un écosystème forestier : cas de la forêt secondaire de Nlobisson par Nkoabang (SE Cameroun). DEA Départ. Sc. De la Terre, Univ. Yaoundé I, 93 p., 4 annexes.
Oliva, P., Viers, J., Dupré, B., Fortuné, J.P., Martin, F., Braun, J.J. and Robain, H. (1999) The effect of organic matter on chemical weathering : study of a small tropical watershed, Nsimi Zoetele, Cameroon. Geoch. Cosmochim. Acta, 63, 4013-4035.
Olivie-Lauquet, G., Allard, T., Bertaux, J., Muller, J.P. (2000) Crystal chemistry of suspended matter in a tropical hydrosystem, Nyong basin (Cameroon, Africa). Chem. Geol., 170, 113-131.
Olivry, J.C. (1986) Fleuves et rivières du Cameroun. Monogr. Hydro. ORSTOM, 9, 733 p., 2 cartes.
Probst, J.L., Mortatti, J., Tardy, Y. (1994) Carbon river fluxes and global weathering CO_2 consumption in the Congo and Amazon river basins. Applied Geochem., 9, 1-13.
Probst, J.L., Nkounkou, R.R., Krempp, G., Bricquet, J.P., Thiebaux, J.P. and Olivry, J.C. (1992) Dissolved major element exported by the Congo and the Ubangui rivers during the period 1987-1989. J. Hydrol., 135, 237-257.
Richey, J.E., Hodges, J.I., Devol, A.H., Quay, P.D., Victoria, R.L., Martinelli, L.A., Forsberg, B.R. (1990) Biogeochemistry of carbon in the Amazon river. Limnol. Oceanogr., 35(2), 352-371.
Ritz, M., Robain, H., Pervago, E., Albouy, Y., Camerlynck, C., Descloitres, M. and Mariko, A. (1998) Improvement to resistivity pseudosection modelling by removal of near surface inhomogeneity effects: application to a soil system of Southern Cameroon. Geophys. Research, 47, 85-101.
Santoir, C. and Bopda, A. (1995) Atlas regional Sud-Cameroun. Ed. ORSTOM, Paris, 53 p., 21 pl.
Seyler, P., Etcheber, H., Orange, D., Laraque, A., Sigha-Nkamdjou, L. and Olivry, J.C. (1995) Concentrations, fluctuations saisonnières et flux de carbone dans le bassin du Congo. In Grands bassins fluviaux périatlantiques : Niger, Amazone, Congo. Edts J.C. Olivry and J. Boulègue, Orstom Editions, Collect. Colloques et Séminaires, 217-228.

Seyler, P., Olivry, J.C., Sigha-Nkamdjou, L. (1993) Hydrochemistry of the Ngoko river, Cameroon : chemical balances in a rain forest equatorial basin. In Hydrology of warm humid regions, Proceed. Symp. Yokohama, AIHS publ., 216, 87-105.
Sigha-Nkamdjou, L., Carré, P. and Seyler, P. (1995) Bilans hydrologique et géochimique d'un écosystème forestier équatorial de l'Afrique Centrale : la Ngoko à Mouloundou. In Grands bassins fluviaux périatlantiques : Congo, Niger, Amazone. Edts J.C. Olivry and J. Boulègue, ORSTOM Ed., Collect. Colloques Séminaires, 199-216.
Stoorvogel, J.J., Jansen, B.H. and Van Bremen, N. (1997a) The nutrient budget of a watershed and its forest ecosystem in the Taï National Park in Côte d'Ivoire. Biogeochem., 37, 159-172.
Stoorvogel, J.J., Van Bremen, N. and Jansen, B.H. (1997b) The material input by harmattan dust to a forest ecosystem in Côte d'Ivoire. Biogeochem., 37, 145-157.
Sullivan, T.J., Driscoll, C.T., Gherini, Munson, R.K., Cook, R.B., Charles, D.F., Yatsko, C.P. (1989) Influence of aqueous aluminium and organic acids on measurements of Acid Neutralizing Capacity in surface waters. Nature, 338, 408-410.
Tardy, Y. (1993) Petrologie des latérites et des sols tropicaux. Masson, Paris, 459 p.
Velbel, M.A. (1995) Interaction of ecosystem processes and weathering processes. In Solute Modeling in catchment systems, S.T. Trudgill Edt, 193-209.
Vicat, J.P. (1998) Esquisse géologique du Cameroun. Collect. Géocam 1/1998, J.P. Vicat, P. Bilong
Viers, J., Dupré, B., Polvé, M., Schott, J., Dandurand, J.P. and Braun, J.J. (1997) Chemical weathering in the drainage basin of a tropical watershed (Nsimi-Zoetele site, Cameroon): comparison between organic-poor and organic-rich waters. Chem. Geol., 140, 181-206.
White, A.F. and Blum, A.E. (1995) Effects of climate on chemical weathering in watersheds. Geoch. Cosmochim. Acta, 59, 1729-1747.
White, A.F., Blum, A.E., Schultz, M.S., Vivit, D.V., Stonestrom, D.A., Larsen, M., Murphy, S.F. and Eberl, D. (1998) Chemical weathering in a tropical watershed, Luquillo Mountains, Puerto Rico. I. Long-term versus short-term weathering fluxes. Geoch. Cosmochim. Acta, 62, 209-226.