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FACTORS OF THE CHEMICAL COMPOSITION OF SEEPAGE AND GROUNDWATERS IN THE INTERTROPICAL ZONE (WEST AFRICA)

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ABSTRACT

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In connection with a large research programme about the *actual dynamics* of ferrallitic and ferruginous soils of West Africa, 5000 samples of rainfall, throughfall, runoff, drainage and phreatic waters have been analysed during 4—11 years of field observations. Samples of eight stations, representative of different bioclimatic conditions (sub-Equatorial to pre-Sahelian), have been tested.

The analysed parameters are: pH, resistivity, major cations and anions, total organic carbon and nitrogen, phosphorus, silica, aluminium and iron. The results show:

(1) The slight influence of the bioclimatic differentiation on the mean chemical composition of the waters: all analysed waters are lightly mineralized (strong resistivity, total chemical charge generally lower than 100 mg/l), with an increasing mineralization from rainfall water to seepage water, at 2 m depth, but decreasing at the water table level (except for Si and Na).

(2) The marked variability of the amounts of dissolved chemical species compared to the seasons and the flow volumes.

(3) The complexity of phenomena controlling the chemical composition of waters. In the soil layers, this composition would depend principally on biological and biochemical processes, in relation to the activity of organisms but at the level of phreatic waters the chemical composition would rather be controlled by physicochemical conditions (solution—mineral equilibria).

INTRODUCTION

The chemical composition of groundwaters depends on many causes: rainwaters have a notable chemical charge, especially in marine salts (M. Schoeller, 1962) and in elements which originate from atmospheric dusts (silts, clays, pollen and bacteria) or from urban and industrial activity (Crozat, 1978; Dessèvre Delepoule, 1978).

Rain waters leach the greencover, carry away available constituents and are loaded with biophile elements, such as C, Mg, Ca and K (Duchaufour,

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1977). The importance of this input (throughfall) is related to the rainfall volume, the nature and density of greencover (Mathieu, 1972).

In the soil layer many interactions occur: percolating waters rapidly acquire a chemical composition similar to that of the groundwater; this fact has been confirmed in temperate regions for acid and calcareous soils (M. Schoeller, 1958; H. Schoeller, 1966). But the chemical charge of soil waters varies during the seasons and with the hydraulic potential: strongly bonded water in the microporous and matrix interstices is much more charged with products from mineral hydrolyses than free waters, which are renewed by rainfall waters and leach only a part of the chemical charge of the micropores (Vedy and Bruckert, 1979).

Modern works emphasize the water—rock mineral interactions to explain the chemical composition of underground water: Jacks (1973) shows that the major part of the ionic charge is originated from the rock-mineral dissolution; Tardy (1969) indicates that the mineralization of groundwater is related to the weathering type; Bourrié (1978) defines the respective proportion of major anions and cations in spring waters of the Vosges and the Massif Central, France, coming from atmospheric input and weathering reactions. In conclusion, the composition of groundwaters is often interpreted essentially in terms of solution—mineral equilibria.

In connection with a large research programme about the actual dynamics of ferrallitic and ferruginous tropical soils of West Africa, runoff, seepage waters and phreatic groundwaters have been continuously sampled during several years, analysed and compared with rainfall waters and throughfall waters (Roose, 1980b). The chemical charge transported by soil and phreatic waters is in ionic and solid or colloidal form: this latter is very important and considerably influences the top soil profile differentiation. But in the present paper, the problem of the ionic charge of water will be treated only in view of precising the role of the soil layer towards the groundwater chemical composition.

METHODS

The experimental device in the field

Eight stations representative of natural soil—vegetation ecosystems of West Africa have been equipped with experimental devices — rain gauges, lysimeters, runoff and oblique drainage plots (Fig. 1) — allowing to sample rainfall, rain water, throughfall, runoff, vertical and oblique drainage waters at each device. Phreatic waters have also been sampled in springs, near by the plots. The experimental device has been precisely described in recent works (Roose, 1978, 1980a).

The eight stations (Fig. 2) are distributed from the southern, forested Ivory Coast, near Abidjan, to the pre-Sahelian area near Ougadougou (Upper

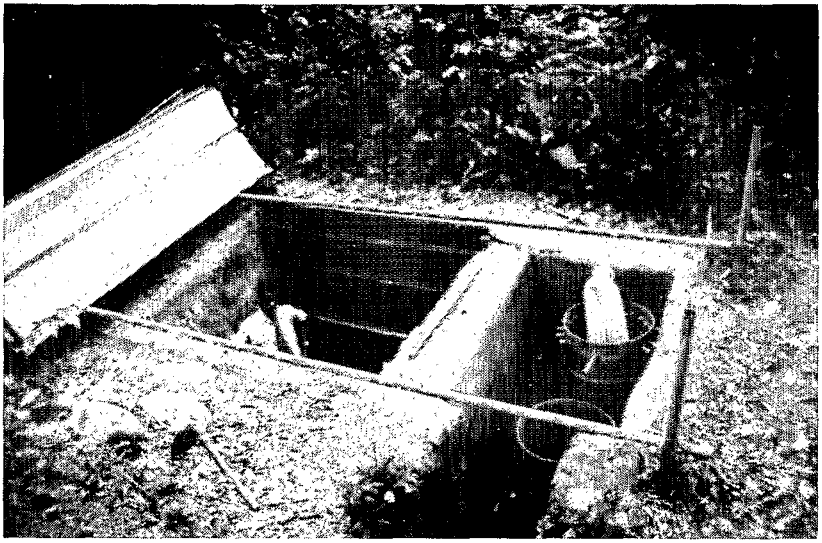

Fig. 1. Experimental device at Divo, Ivory Coast.
On a face of the trench, the gutters to sample the oblique drainage water can be seen.

Volta). These stations make it possible to characterize different soil—vegetation ecosystems, representative of a wide bioclimatic sequence, which extends from the zone of desaturated ferrallitic soils in the south, to the zone of tropical ferruginous soils in the north. Climate, vegetation, bedrock and geomorphology characteristics are given in Table I.

During 4—11 successive years, the following samples were taken at each station and at each rainfall: (1) rainfall water and throughfall; (2) runoff water; (3) soil drainage waters at several depths (0.30—2 m), collected in lysimeters (vertical drainage) and in oblique drainage plots (oblique drainage); and (4) phreatic groundwaters, sampled in springs.

On the whole, more than 5000 samples of different types of waters have been collected and stored prior to be analysed in plastic bottles, which were previously washed with the water to be analysed, filled up to the top, maintained in darkness and as soon as possible (one day to six weeks) transported to the analytical laboratory of Adiopodoume (Ivory Coast).

Laboratory analysis

The physicochemical parameters studied are: pH, temperature, resistivity, Ca, Mg, K, Na, SO_4, Cl, organic carbon, total nitrogen, NO_3, NH_4, total phosphorus, Fe, Al and SiO_2.

The methods of analysis are those which are practiced in the O.R.S.T.O.M. Laboratory of Adiopodoume (Nalovic, 1968; Gouzy, 1973). The raw water is decanted, then filtered (folded fast filter paper Pratt Dumas® No. *4*).

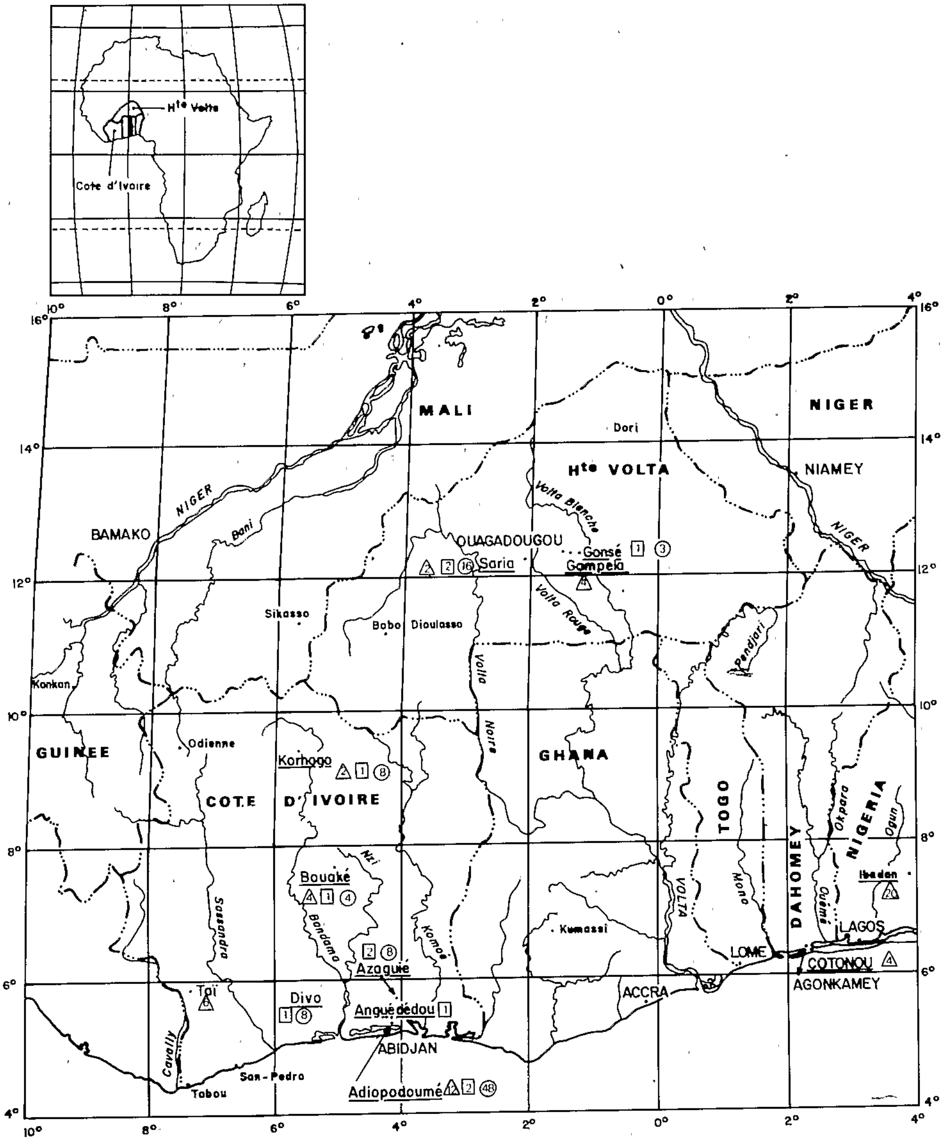

Fig. 2. Localities of stations in West Africa (taken from Roose, 1978).
Gonse: O.R.S.T.O.M.—C.T.F.T.; Gampela: C.T.F.T.—O.R.S.T.O.M.; Saria: O.R.S.T.O.M.—I.R.A.T.; Korhogo: O.R.S.T.O.M.; Bouake: I.R.A.T.—O.R.S.T.O.M.; Divo: O.R.S.T.O.M.—I.F.C.C.; Azaguie: O.R.S.T.O.M.—I.R.F.A.; Anguededou: O.R.S.T.O.M.—I.R.C.A.; Adiopodoume: O.R.S.T.O.M.; Agonkamey: O.R.S.T.O.M.; Ibadan: I.I.T.A.
△ = erosion site; □ = ERLO site; ○ = DV site.

TABLE I

Ecological characteristics of the experimented stations

	Adiopodoume	Anguedegou	Azaguie	Divo	Bouake	Korhogo	Saria	Gonse
Climate	← Sub-Equatorial (two rainfall seasons) →					transitional tropical	pure tropical	
rainfall (mm)	2,150	2,100	1,750	1,550	1,200	1,350	830	860
PET* (mm)	1,250	1,300	1,314	1,280	1,300	1,660	1,885	1,905
rainfall erosivity index (Wischmeier, 1962)	1,260	1,000	885	825	512	676	450	430
temperature (°C)	26.2	26.2	26.2	26.0	26.1	27.0	28.0	28.1
Greencover	← wet dense forest →				wooded savannah		bush savannah	
		evergreen		semi-deciduous	Guinean	Soudanian	Soudano-Sahelian	
Landforms	strongly incised plateau		narrow hills	wide hills	wide hills	residual relief and long piedmont slopes	residual relief and very long piedmont slopes	
grade of slope (%)	<65	<39	14	10	4	3	0.7	0.5
length slope (m)	20—500	100—500	180	300	700	750—1,000	2,000	3,000
Soils	strongly desaturated ferrallitic			medium desaturated ferrallitic			tropical ferruginous	
Bedrock	argillaceous sands upper Tertiary		chloritic schists	granites	granites (pegmatite lodes)	granites (quartz lodes)	granites	
			← Precambrian →					

* PET = potential evapotranspiration.

Organic carbon is determined by the oxygen which is consumed during oxidizing of organic matter with $KMnO_4$. Total nitrogen is titrated by the Kjeldhal method. The other used are the classical methods.

RESULTS

For several thousand samples the representation of eighteen parameters needs treatment and simplification of the data.

A preliminary analysis of the results of the individual samples shows their relative homogeneity: all titrated waters, including seepage (drainage) and phreatic waters, have low solute concentrations, generally between 0.2 and 4 meq./l and high resistivities, between $5 \cdot 10^3$ and 10^5 Ω cm.

Statistical treatment of the results has been executed for the results of two stations (Adiopodoume and Korhogo): element—element bivariate relations, distribution of the parameter values depending upon the seasons and the volume of flow (runoff, seepage, etc.).

Fig. 3 indicates the distribution of the resistivity values of the oblique drainage waters of Adiopodoume according to the seasons; the abscissa give the cumulated heights of rainfall since the beginning of the year: the first drainage waters, at the beginning of the main rainfall season, appear to have lower resistivities — therefore to be more mineralized — than the other waters; the chemical charge of the water is minimal at the middle of the rainfall season. This process of seasonal dilution occurs more or less marked at all sampling stations. We can see in Fig. 3 that low values of resistivity may exist during the whole rainfall season. However, the main factor is in fact not the seasonal influence but the volume of flow: small volumes and consequently low dilutions occur also at the middle of the rainfall season, when low-intensity rainfalls are occurring. On the other hand, the volumes of flow are always small and the resistivities show always minima at the end and particularly at the beginning of the rainfall season.

Fig. 4 gives the distribution of Ca^{2+} concentrations in oblique drainages waters of Adiopodoume; it shows clearly the influence of the volume of flow on concentrations: for high volumes of flows, characterizing for the middle of the rainfall season, the lowest concentration values always appear. This influence also exists, more or less, for the other major anions and cations; but it is unappreciable or nonexistent for the less mobile elements, such as SiO_2 and the sesquioxydes of Al and Fe (Fig. 5).

Generally, at each station, concentration values decrease when the volumes of flow are increasing. Consequently, and in view of determining the flux of dissolved products in waters, mean concentration values, balanced by flow volume (MPV: "moyenne pondérée par les volumes"), have been calculated:

$$\mathrm{MPV} = \Sigma Vc/\Sigma V$$

where V is the flow volume (l); and c is the concentration (mg/l).

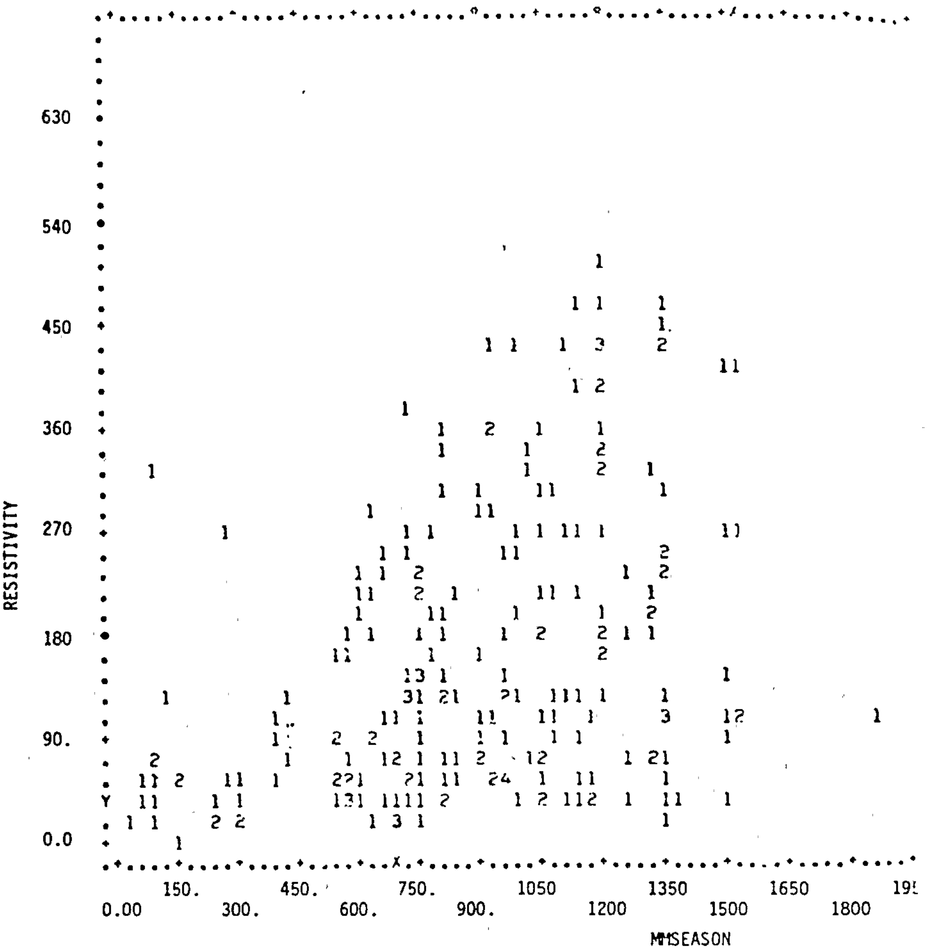

Fig. 3. Seasonal variations of resistivity in oblique drainage waters at the Adiopodoume station.
The resistivity values, in Ω cm, are plotted as a function of the cumulated heights (mm) of rainfall (*MMSEASON*).

The MPV-values obtained for 18 parameters in the eight stations are presented in Table II. The alkalinity values, which probably correspond with near-neutral pH-values of the HCO_3^- species in these waters, have been calculated with reference to ionic balance; this constituent is prevailing, so the approximation is good.

The MPV-values of the major ions expressed in mg/l are low, similar to those which have been obtained in springs and phreatic waters of the crystalline area, with a humid, temperate, or tropical, climate (Tardy, 1969; Bourrié, 1978).

In general, concentration values increase from rainfall and throughfall waters to runoff and drainage waters, down to 2 m depth, but they decrease

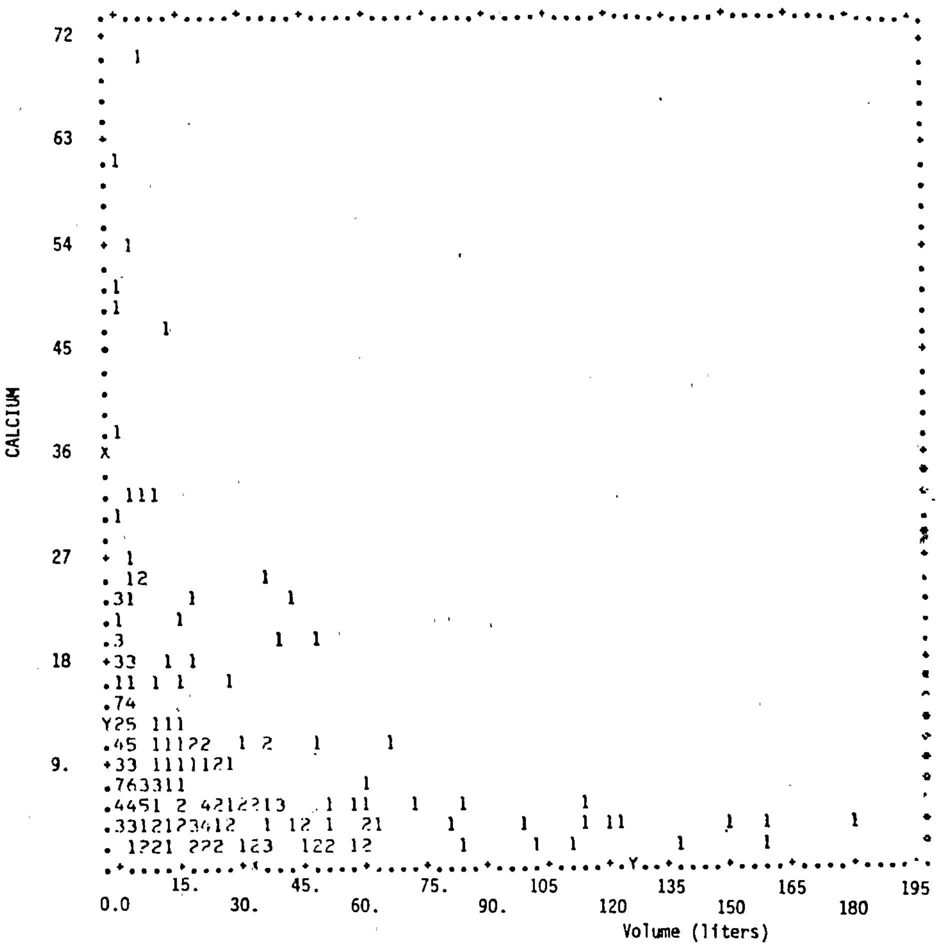

Fig. 4. Variation of calcium concentration (mg/l) in oblique drainage waters at the Adiopodoume station, as fraction of the volume of flow (liters).

at the level of the phreatic waters, except for SiO_2 and Na; these constituents seem to be less absorbed by plant roots than the others.

The fact that maximum concentration values generally correspond to drainage waters is clearly shown in Fig. 6, giving the MPV-values in reference to the logarithm of the drainage volume (expressed in height of water). The plots of each station can be identified with abbreviations of localities. The drainage volume has been calculated from data of monthly rainfall, runoff and potential evapotranspiration, with reference to an available variable reservoir of water in the soil estimated at the stations: maximum, 200 mm at Adiopodoume, minimum, 60 mm at Saria (Table III). In Fig. 6 Adiopodoume and Anguedegou are plotted together, and Saria and Gonse in a similar manner.

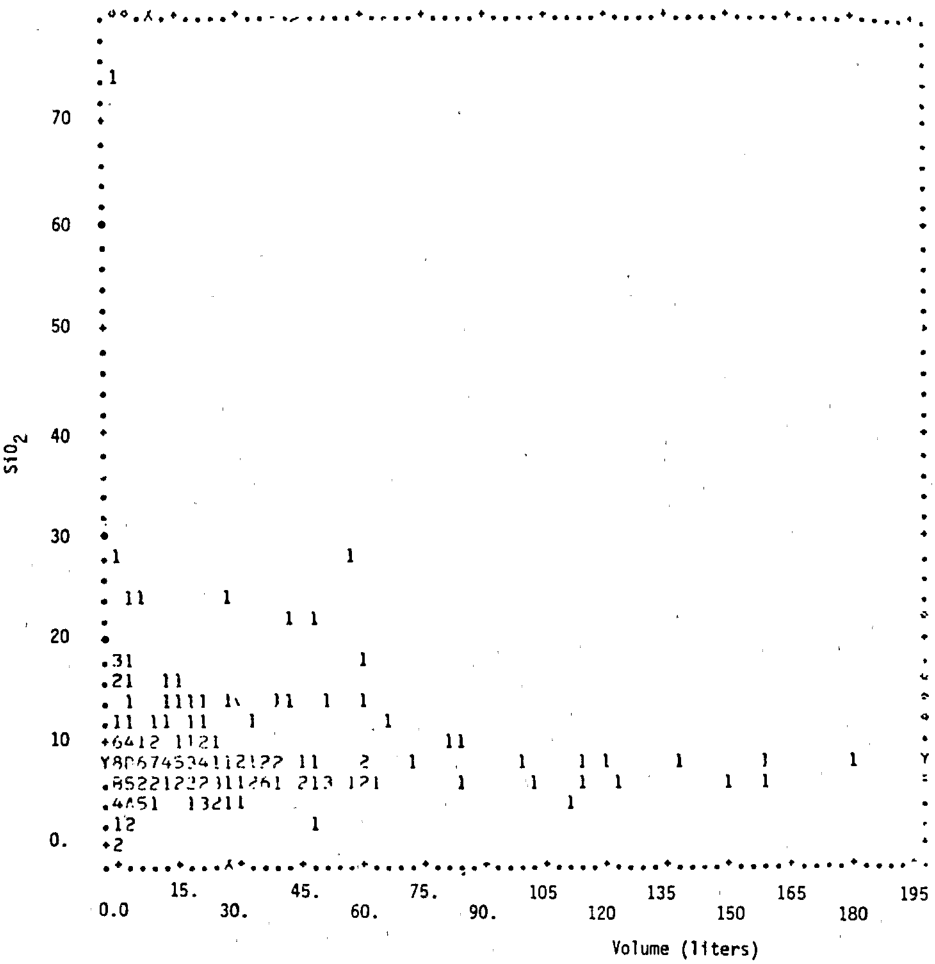

Fig. 5. Variation of silica concentration (mg/l) in oblique drainage waters at the Adiopodoume station, as a function of the volume of flow (liters).

DISCUSSION

The first point of discussion is the influence of the bedrock nature on the chemical composition of waters. We can see in Table II and in Fig. 6 that waters in the chloritic schist or argillaceous sand areas do not differ from those in the granitic area. This is not surprizing, in spite of the well-known control of rock mineral on the groundwater composition (M. Schoeller, 1962; Tardy, 1969); in fact, in the whole bioclimatic sequence considered, the lateritization processes have destructed all the primary minerals, except quartz, and the weathering minerals are always the same: kaolinite, iron oxide and oxy-hydroxide, the stabilities of which in the surface are very great.

The second point of discussion concerns the influence of flow volume. It

TABLE II

Chemical characteristics of the different waters sampled at the eight experimental stations, West Africa — mean pH-values, electrical resistivities and concentrations of dissolved chemical species (MPV): major cations and anions, organic elements, nutrients and sesquioxides

Station	Vegetation*	Rainfall	Throughfall	Runoff	Drainage		Spring
					upper level	lower level	
pH:							
Adiopodoume (R2)	f.	6.7	6.7	6.7	6.3	6.8	5.3
Anguededou	h.	—	—	6.6	6.6	6.5	—
Azaguie	f.	—	—	6.6	6.7	6.8	—
Divo	f.	—	—	6.7	6.7	7.0	—
Bouake	s.f.	—	—	6.8	6.7	6.7	—
Korhogo	s.	6.0	6.2	6.9	6.7	7.0	6.1
Saria (P7)	s.	—	—	6.4	6.5	—	6.9
Gonse	s.	—	—	6.4	7.0	6.6	—
Resistivity (Ω cm):							
Adiopodoume (R2)	f.	48,800	25,000	28,700	27,200	17,900	38,100
Anguededou	h.	—	—	32,300	21,800	19,600	—
Azaguie	f.	—	—	34,000	23,000	22,500	—
Divo	f.	—	—	18,100	9,500	6,200	—
Bouake	s.f.	—	—	27,700	32,600	25,600	—
Korhogo	s.	68,900	54,000	46,900	32,000	23,200	44,600
Saria (P7)	s.	91,700	76,000—20,000 (a)	76,540	24,700	—	21,800
Gonse	s.	—	—	31,800	27,700	25,900	—
SO_4:							
Adiopodoume (R2)	f.	1.2	2.5	3.1	5.1	6.2	1.4
Anguededou	h.	—	—	8.8	12.6	17.6	—
Azaguie	f.	—	—	3.5	5.0	3.6	—

Divo	f.	—	—	5.7	10.7	3.2	—
Bouake	s.f.	—	—	0.8	1.8	1.2	—
Korhogo	s.	1.0	1.7	2.1	4.0	5.2	2.3
Saria (P7)	s.	1.6	1.7—1.9 (a)	2.1	3.4	—	1.6
Gonse	s.	—	—	1.3	3	6	—
Cl:							
Adiopodoume (R2)	f.	2.1	4.9	2.8	4.4	6.6	3.9
Anguededou	h.	—	—	3.5	5.2	8.4	—
Azaguie	f.	—	—	1.2	2.8	3.7	—
Divo	f.	0.88 (b)	1.8—3.4 (b)	3.2	10.4	6.4	—
Bouake	s.f.	—	—	1.1	1.6	0.8	—
Korhogo	s.	0.3	0.8	1.3	2.5	2.5	0.3
Saria (P7)	s.	0.3	0.6—2.2 (a)	0.8	2.3	—	1.9
Gonse	s.	—	—	0.7	0.4	0.8	—
HCO_3 (estimated):							
Adiopodoume (R2)	f.	4.3	18.0	28.2	14.0	49.4	5.5
Anguededou	h.	—	—	14.7	18.3	11.2	—
Azaguie	f.	—	—	12.5	12.6	11.4	—
Divo	f.	—	—	18.0	45.0	98.6	—
Bouake	s.f.	—	—	—	—	—	—
Korhogo	s.	4.8	6.2	9.2	9.6	20.2	8.6
Saria (P7)	s.	4.3	6.2—18 (a)	5.4	42.4	—	24.8 (27.9)(c)
Gonse	s.	—	—	14.8	15.1	26.0	—
Ca:							
Adiopodoume (R2)	f.	1.8	3.8	5.6	3.7	6.9	2.4
Anguededou	h.	—	—	3.7	6.0	6.5	—
Azaguie	f.	—	—	3.6	4.3	4.1	—
Divo	f.	2.4 (b)	2.4—3.4 (b)	7.0	8.2	12.0	—
Bouake	s.f.	—	—	4.5	2.0	2.2	
Korhogo	s.	1.9	2.4	2.1	2.6	4.1	1.7
Saria (P7)	s.	2.14	2.6—4.9 (a)	2.3	7.7	—	3.4
Gonse	s.	—	—	4.9	4.8	7.3	—

TABLE II (*continued*)

Station	Vegetation*	Rainfall	Throughfall	Runoff	Drainage		Spring
					upper level	lower level	
Mg:							
Adiopodoume (R2)	f.	0.4	2.2	2.7	1.8	5.1	0.5
Anguededou	h.	—	—	2.3	3.3	3.8	—
Azaguie	f.	—	—	0.9	1.6	1.4	—
Divo	f.	0.44 (b)	0.8—1.2 (b)	1.9	5.0	10.0	—
Bouake	s.f.	—	—	1.2	0.4	0.3	—
Korhogo	s.	0.1	0.4	0.6	0.9	1.8	0.4
Saria (P7)	s.	0.31	0.39—1.2 (a)	0.5	2.4	—	0.6
Gonse	s.	—	—	0.7	0.8	1.6	—
K:							
Adiopodoume (R2)	f.	0.3	3.9	4.8	2.6	13.1	0.1
Anguededou	h.	—	—	4.6	5.3	6.7	—
Azaguie	f.	—	—	1.4	1.3	0.9	—
Divo	f.	0.31 (b)	2.5—3.5 (b)	5.1	19.6	19.2	—
Bouake	s.f.	—	—	4.1	0.3	0.3	—
Korhogo	s.	0.3	1.3	1.3	1.8	7.1	1.0
Saria (P7)	s.	0.39	1.24—7.1 (a)	1.14	2.9	—	1.3
Gonse	s.	—	—	1.8	1.7	3.3	—
Na:							
Adiopodoume (R2)	f.	0.82	1.75	1.91	2.64	3.12	2.43
Anguededou	h.	—	—	1.2	1.85	2.00	—
Azaguie	f.	—	—	1.0	1.8	2.4	—
Divo	f.	1.0 (b)	0.7—1.2 (b)	0.67	3.74	4.9	—
Bouake	s.f.	—	—	0.66	0.8	1.0	—
Korhogo	s.	0.15	0.20	0.35	0.44	0.90	1.80
Saria (P7)	s.	0.12	0.14—0.3 (a)	0.38	4.7	—	6.0
Gonse	s.	—	—	0.2	0.6	1.0	—

Organic C:							
Adiopodoume (R2)	f.	1.3	7.4	11.2	8.7	8.1	1.0
Anguededou	h.	—	—	11.5	11.3	11.4	—
Azaguie	f.	—	—	9	15	9.7	—
Divo	f.	—	—	12.9	14.6	6.7	—
Bouake	s.f.	—	—	8.5	2.3	1.4	—
Korhogo	s.	1.07	3.8	5.2	3.4	3.0	1.2
Saria (P7)	s.	1.3	3.9—9.7 (a)	2.5	1.1	—	0.7
Gonse	s.	—	—	3.2	3.0	4.5	—
Total N:							
Adiopodoume (R2)	f.	1.4	2.5	4.5	3.3	3.4	1.6
Anguededou	h.	—	—	3.6	4.3	5.9	—
Azaguie	f.	—	—	5.4	2.3	2.2	—
Divo	f.	1.73 (b)	2.2—2.4 (b)	4.4	6.1	5.9	—
Bouake	s.f.	—	—	4.5	1.9	1.9	—
Korhogo	s.	0.9	1.1	2.0	1.2	2.1	0.8
Saria (P7)	s.	0.63	0.61—0.88 (a)	1.1	1.9	—	1.3
Gonse	s.	—	—	2.8	2.4	2.3	—
N-NO$_3$:							
Adiopodoume (R2)	f.	0.26	0.74	1.17	0.77	1.61	0.17
Anguededou	h.	—	—	0.51	1.13	1.70	—
Azaguie	f.	—	—	0.4	0.9	0.9	—
Divo	f.	0.15 (b)	0.13—0.21 (b)	2.4	3.5	3.7	—
Bouake	s.f.	—	—	0.46	0.74	0.93	—
Korhogo	s.	0.48	0.21	0.20	0.25	1.0	0.03
Saria (P7)	s.	—	—	—	—	—	0.5
Gonse	s.	—	—	—	—	—	—
N-NH$_4$:							
Adiopodoume (R2)	f.	0.24	0.27	0.73	0.30	0.42	0.16
Anguededou	h.	—	—	0.58	0.52	0.60	—
Azaguie	f.	—	—	0.6	0.3	0.2	—

TABLE II (*continued*)

Station	Vegetation*	Rainfall	Throughfall	Runoff	Drainage		Spring
					upper level	lower level	
Divo	f.	0.27 (b)	0.22—0.3 (b)	0.7	0.7	0.2	—
Bouake	s.f.	—	—	0.25	0.14	0.13	—
Korhogo	s.	0.26	0.10	0.13	0.14	0.28	0.09
Saria (P7)	s.	—	—	—	—	—	—
Gonse	s.	—	—	—	—	—	—
PO_4:							
Adiopodoume (R2)	f.	0.32	0.87	2.23	0.67	0.77	1.25
Anguededou	h.	—	—	0.84	1.10	0.98	—
Azaguie	f.	—	—	1.13	0.8	1.0	—
Divo	f.	0.99 (b)	1.2—2.5 (b)	1.27	0.97	0.34	—
Bouake	s.f.	—	—	1.02	0.38	0.26	—
Korhogo	s.	0.30	0.38	0.74	0.57	0.90	0.92
Saria (P7)	s.	0.77	1.1—0.4 (a)	0.91	0.13	—	0.15
Gonse	s.	—	—	1	0.8	0.7	—
Fe_2O_3:							
Adiopodoume (R2)	f.	0.04	0.12	0.75	0.26	0.30	0.06
Anguededou	h.	—	—	0.40	0.50	0.70	—
Azaguie	f.	—	—	0.4	0.35	0.27	—
Divo	f.	0.05 (b)	0.08—0.17 (b)	0.34	0.55	0.26	—
Bouake	s.f.	—	—	0.59	0.07	0.05	—
Korhogo	s.	0.13	0.12	0.30	0.20	0.18	0.14
Saria (P7)	s.	0.03	0.10—0.18 (a)	0.15	0.07	—	0.15
Gonse	s.	—	—	0.10	0.17	0.10	—

Al_2O_3:							
Adiopodoume (R2)	f.	0.08	0.11	0.28	0.28	0.35	0.07
Anguededou	h.	—	—	0.30	0.40	0.30	—
Azaguie	f.	—	—	0.23	0.24	0.27	—
Divo	f.	0.06 (b)	0.05—0.08 (b)	0.20	0.41	0.22	—
Bouake	s.f.	—	—	0.51	0.09	0.04	—
Korhogo	s.	0.07	0.07	0.38	0.68	0.63	0.16
Saria (P7)	s.	0.04	0.07	0.05	0.11	—	0.01
Gonse	s.	—	—	0.08	0.30	0.06	—
SiO_2:							
Adiopodoume (R2)	f.	0.7	1.3	3.5	7.2	8.3	8.4
Anguededou	h.	—	—	2.2	3.8	5.2	—
Azaguie	f.	—	—	4.0	5.4	5.6	—
Divo	f.	0.30 (b)	1.2—0.4 (b)	3.6	11.5	15.5	—
Bouake	s.f.	—	—	5.1	2.4	2.8	—
Korhogo	s.	0.7	1.4	3.1	6.8	6.3	19.2
Saria (P7)	s.	0.68	0.78—0.9 (a)	1.06	16.3	—	35.6
Gonse	s.	—	—	3.9	4.4	6.5	—

(a) = under gramineous plants or trees, respectively.
(b) = sampling at Lamto: savannah or forest, respectively (Villecourt and Roose, 1978).
(c) = mean value of 24 samples.
* f. = forest; h. = hevea; s. = savannah; s.f. = wooded savannah.

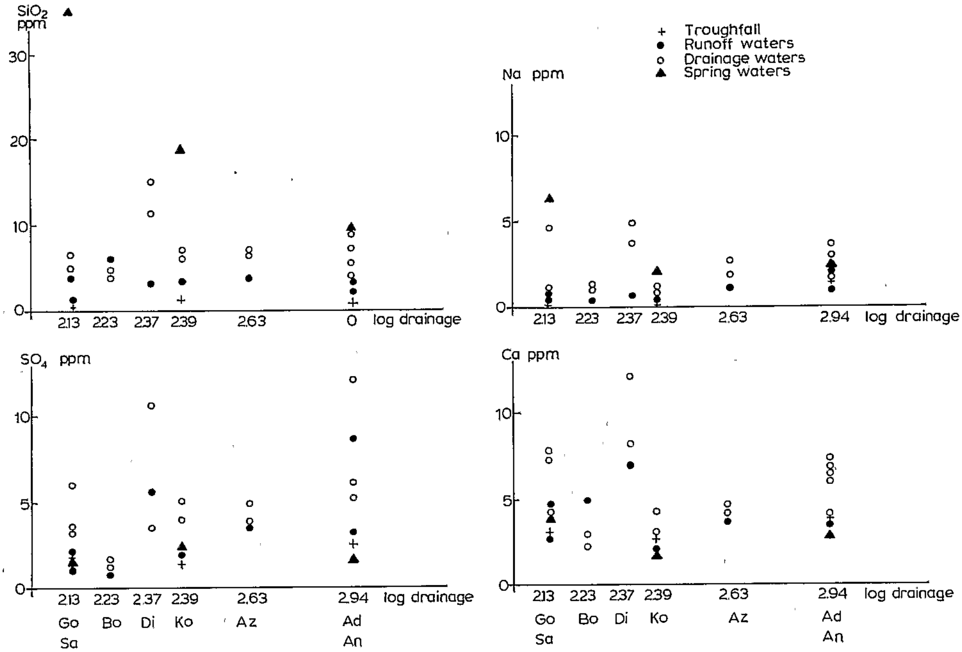

Fig. 6. Mean concentrations of total dissolved solids in different types of waters, in relation with soil drainage intensity.
The plotted points give the MPV concentration values as a function of the logarithm of the drainage height in the soil (see Table II).

is known that, generally, the dissolved concentrations of surface and phreatic waters decrease for increasing specific flow (Meybeck, 1976; Bourrié, 1978). The empirical relation, established by Meybeck for water of the main rivers of the world is:

$$M = aQ_S^{-0.6}$$

where a is a constant; M is the total dissolved concentration in mg/l; and Q_S is the specific discharge flow in $m^3\ s^{-1}\ km^{-2}$.

A striking feature, in Fig. 6, is the similarity of the concentration values in the different types of water for increasing drainage volumes, except for SiO_2 and Na of spring waters, which vary from 8 ppm in southern Ivory Coast to 35 ppm in the pre-Sahelian area.

This similarity is interesting. No doubt, dissolved amounts are perceptibly higher in rain and throughfall waters of the sub-Equatorial area than in those of the tropical and pre-Sahelian areas (see Table II). However, the soil solutions are submitted to a much stronger evapotranspiration in the latter than in the former area.

The theoretical concentration soil solutions of dissolved species coming from throughfall waters, after evapotranspiration, may be calculated using the concentration factor c. This factor is:

TABLE III

Hydrologic balance of the different stations, West Africa

	Adiopodoume—Anguedegou	Azaguie	Divo	Bouake	Korhogo	Saria	Gonse
Annual rainfall (mm)	2,131	1,767	1,453	1,202	1,353	826	860
Real evapotranspiration (mm)	1,230	1,305	1,204	1,028	1,064	649	813
Runoff (mm)	22	35	15	4	41	41	22
Deep drainage (mm)	879	427	235	170	248	136	25
Total flow (mm)	901	462	250	174	289	177	47
Concentration factor: (rainfall)/(drainage) ratio	2.42	4.14	6.18	7.08	5.46	6.07	34.4

$c = R/D$

where R is the mean annual rainfall height (mm); and D is the mean annual drainage height (mm).

This ratio (Table II) ranges from 5.46 and 6.07 in Korhogo and Saria, respectively, to 2.42 in Adiopodoume.

With the help of the concentration factor a balance of the chemical soil—water interactions may be established (Table IV): the negative values in column *3* indicate the amount of dissolved constituents which seem to be retained in the soil, positive values indicate the amount of dissolved constituents, which seem to be added to the initial concentration of throughfall water, when it percolates through the soil layer. In column 4 the percentages of each element in the soil, subtracted or added, have been calculated.

The balance shows that the majority of dissolved elements is retained in the soil, probably because their biochemical precipitation or their consumption by roots or micro-organisms. This retention concerns primarily the nutrients (C, N, PO_4); the absorption exceeds generally 50% of the theoretical concentration of the soil water [(theoretical concentration) = (throughfall concentration) × c, see Table IV, column (*1*)]. The major anions and cations are almost always retained, but in a smaller proportion. The sesquioxides show an irregular behaviour: they seem to be sometimes absorbed, sometimes added. This irregularity is perhaps due to the presence of a part of these elements in colloidal form, the proportions of which may fluctuate in relation to the conditions of sampling and conservation of the waters.

Consequently, only a fraction of the chemical charge which comes into the soil, where it is concentrated by evapotranspiration, is carried down with drainage waters into the deep layers of soil and into phreatic waters. The retention of dissolved solids exists also in the deep layers of the soil (between 2 m depth and the water table), since the concentration of solution in spring waters is lower than in drainage waters, except for Si and Na, as above mentioned.

In these very dilute solutions, chemical precipitation of salt is very unlikely. The chemical composition of water seems to be rather controlled by biochemical and biological processes: most of chemical elements released by decay of plant detritus and humification are recaptured by roots and micro-organisms in the aerated layers of the soils. The biological turnover is more active in the more dense forests than in bush savannah; so the flux of products is 5- to 10-fold more intensive in the sub-Equatorial than in the pre-Sahelian areas, in relation to the much more important volume of drainage waters. But in terms of dissolved concentrations. the differences are not necessarily significant for soil waters which drain through the biologically active part of the soil.

For the sesquioxides, the problem could be different. Throughfall and runoff waters, with near-neutral pH, are undersaturated in SiO_2, with respect to quartz (concentration below 10^{-4} mol/l, i.e. 6 mg/l; see Tardy, 1969), but soil drainage and spring waters are saturated or oversaturated (see Table II).

TABLE IV

Balance of the chemical interactions in the soil

	(*1*) (dissolved amounts in throughfall waters) × *c* (mg/l)	(*2*) dissolved amounts in drainage water (mg/l)	(*3*) balance = (*2*) − (*1*) (mg/l)	(*4*) per cent leached (−) or absorbed (+) in soil (*3*)/(*1*) × 100
Adiopodoume:				
Ca	3.80 × 2.42	5.30	−3.90	−42
Mg	2.20 × 2.42	3.45	−1.87	−35
K	3.90 × 2.42	7.85	−1.60	−17
Na	1.75 × 2.42	2.88	−1.36	−32
SO_4	2.50 × 2.42	5.55	−0.50	−8
Cl	4.90 × 2.42	5.50	−6.36	−54
HCO_3	18.0 × 2.42	31.7	−11.86	−27
NO_3	0.74 × 2.42	1.41	−0.38	−21
C	7.40 × 2.42	8.4	−9.51	−53
N	2.50 × 2.42	3.35	−2.70	−45
NH_4	0.27 × 2.42	0.36	−0.29	−45
PO_4	0.87 × 2.42	0.72	−1.39	−66
Fe_2O_3	0.12 × 2.42	0.28	−0.01	−3
Al_2O_3	0.11 × 2.42	0.31	+0.04	+15
SiO_2	1.30 × 2.42	7.75	+4.6	+146
Korhogo:				
Ca	2.40 × 5.46	3.35	−9.75	−74
Mg	0.40 × 5.46	1.35	−0.83	−38
K	1.30 × 5.46	4.45	−2.65	−37
Na	0.20 × 5.46	0.67	−0.42	−39
SO_4	1.70 × 5.46	4.60	−4.68	−50
Cl	0.80 × 5.46	2.50	−1.87	−43
HCO_3	6.20 × 5.46	14.9	−18.95	−56
NO_3	0.21 × 5.46	0.62	−0.53	−46
C	3.80 × 5.46	3.20	−17.55	−85
N	1.10 × 5.46	1.55	−4.46	−74
NH_4	0.10 × 5.46	0.21	−0.34	−62
PO_4	0.38 × 5.46	0.73	−1.34	−65
Fe_2O_3	0.12 × 5.46	0.19	−0.47	−70
Al_2O_3	0.07 × 5.46	0.66	+0.28	+74
SiO_2	1.40 × 5.46	6.55	−1.09	−14
Saria:				
Ca	2.60 × 6.07	7.70	−8.08	−51
Mg	0.39 × 6.07	2.40	+0.03	+1
K	1.24 × 6.07	2.90	−4.63	−61
Na	0.14 × 6.07	4.70	+3.85	+453
SO_4	1.70 × 6.07	3.40	−6.92	−67
Cl	0.60 × 6.07	2.30	−1.34	−37
HCO_3	6.20 × 6.07	42.40	+4.77	+13

TABLE IV (*continued*)

	(*1*) (dissolved amounts in throughfall waters) × *c* (mg/l)	(*2*) dissolved amounts in drainage water (mg/l)	(*3*) balance = (*2*) − (*1*) (mg/l)	(*4*) per cent leached (−) or absorbed (+) in soil (*3*)/(*1*) ×100
NO_3	—	—	—	—
C	3.90 × 6.07	1.10	−22.6	−95
N	0.61 × 6.07	1.90	−1.80	−49
PO_4	0.40 × 6.07	0.13	−2.30	−95
Fe_2O_3	0.10 × 6.07	0.07	−0.54	−89
Al_2O_3	0.07 × 6.07	0.11	−0.31	−74
SiO_2	0.78 × 6.07	16.30	+15.88	+3,780

Little dissolution of quartz and a fortiori of the siliceous constituents (micas, phytolites, etc.) is possible, in the top layer of the soil. On the other hand, kaolinite which is the exclusive clay mineral in all the soils of the bioclimatic sequence, must be stable, since at pH 6—7 and for dissolved silica near 10^{-4} mol/l, the solutions are saturated with respect to this mineral, when dissolved Al exceeds 10^{-9} mol/l, i.e. 10^{-3} mg/l (Gardner, 1970). The addition of Al in the chemical charge of drainage waters might result from the colloidal mobility of this element.

Finally, the mean dissolved concentrations in the waters are rather uniform from south to north, in spite of very marked differences in bioclimatic conditions, perhaps because the decreasing biological activity from the Equatorial to pre-Sahelian area would be balanced by the increasing importance of the evapotranspiration and of the concentration ratio. This bioclimatic regulation would be an important factor, together with the impact of human activity, which would explain the large variability of the mineralization values in surface waters vs. the specific flow (Meybeck, 1976).

CONCLUSION

The chemical analysis of runoff, throughfall, seepage waters (drainage) and spring waters from eight localities of West Africa, which are bioclimatically well differentiated, shows that the mineralization is increasing from rainfall and throughfall waters to runoff and to drainage waters, but decreases in spring waters, except for Si and Na.

The instantaneous and seasonal variations of mineralization, in relation to rainfall intensities and dryness occurrences, are very marked. To estimate the chemical flux through the soil layers and the biogeochemical balances, it is necessary to calculate the mean dissolved concentration balanced by flow volume (MPV: "moyenne pondérée par volume"), which assumes the accurate hydrologic budget of the soil to be known.

The mean values obtained for the West Africa stations are at the same concentration levels, whatever the stations may be, in spite of the marked bioclimatic differences and of the increasing importance from south to north of the concentration ratio (related to evapotranspiration). This similarity would result from the regulation due to biological activity: decreasing of dissolved concentrations in rainfall and throughfall waters and reducing of the plant residue decay in soil from the Equatorial to pre-Sahelian areas would be balanced by the increasing importance of the concentration ratio.

REFERENCES

Bourrié, G., 1978. Acquisition de la composition chimique des eaux en climat tempéré. Application aux granites des Vosges et de la Margeride. Univ. Strasbourg, Strasbourg, Strasbourg, Mém. Sci. Géol. 52, 174 pp.

Crozat, G., 1978. L'aérosol atmosphérique en milieu naturel. Étude des différentes sources de potassium en Afrique de l'Ouest (Côte d'Ivoire). D. Sci. Thesis, University of Toulouse, Toulouse, 70 pp.

Dessèvre Delepoule, A., 1978. Les eaux de la région Rouennaise. Contamination et interrelations des pluies, nappes et rivières d'après leurs caractéristiques chimiques et isotopiques. D. Spéc. Sci. Thesis, University of Rouen, Rouen, 159 pp.

Duchaufour, P., 1977. Pédologie, I. Pédogenèse et classification. Masson, Paris, 477 pp.

Gardner, L.L., 1970. A chemical model of the origin of gibbsite from kaolinite. Am. Mineral., 55: 1380—1389.

Gouzy, M., 1973. Méthodes d'analyses utilisées dans le Laboratoire d'Analyses du Centre ORSTOM d'Adiopodoumé. Rapp., O.R.S.T.O.M., Abidjan, 432 pp (mimeographed).

Jacks, G. 1973. Chemistry of some ground water in silicate rocks. R. Inst. Technol., Stockholm, 73 pp.

Mathieu, P., 1972. Apports chimiques par les précipitations atmosphériques en savane et sous forêt. Influence du milieu forestier sur la migration des ions et des transports solides (Bassin d'Amitioro, Côte d'Ivoire). D. Sci. Thesis, University of Nice, Nice, 441 pp.

Meybeck, M., 1976. Total mineral dissolved transport by world major rivers. Hydrol. Sci. Bull., 21(2): 265—284.

Nalovic, L., 1968. Les méthodes d'analyse des sols et des eaux utilisées dans le Laboratoire du Centre ORSTOM d'Adiopodoumé. Rapp. O.R.S.T.O.M., Abidjan, 123 pp. (mimeographed).

Roose, E.J., 1978. Pédogenèse actuelle d'un sol ferrugineaux issu de granite pour une savane arborée du plateau Mossi (Haute-Volta) — Gonsé — Campagnes 1968 à 1974. Rapp. O.R.S.T.O.M., Paris, 121 pp. (mimeographed).

Roose, E.J., 1980a. Dynamique actuelle d'un sol ferrallitique très désaturé sous cultures et sous forêt dense humide subéquatoraiale du Sud de la Côte d'Ivoire. Rapp. O.R.S.T.O.M., Paris, 204 pp. (mimeographed).

Roose, E.J., 1980b. Dynamique actuelle de sols tropicaux d'Afrique de l'Ouest. Étude expérimentale des transferts solides et en solution. Impact de l'utilisation des sols. D. Sci. Thesis, University of Orléans, Orléans, 587 pp.

Schoeller, H., 1966. Comparaison de la composition chimique des solutions de sol à rendzine avec celle des nappes phréatiques sous-jacentes. C.R. Acad. Sci., Paris, 262: 337—338.

Schoeller, M., 1958. Variation de la composition chimique des solutions du sol avec la nature pédologique et comparaison de la composition chimique de ces solutions avec celle des nappes phréatiques sous-jacentes. C.R. Acad. Sci., Paris, 246: 2507—2508.

Schoeller, M., 1962. Les eaux souterraines. Masson, Paris, 462 pp.

Tardy, Y., 1969. Géochimie des altérations. Étude des arènes et des eaux de quelques massifs cristallins d'Europe et d'Afrique. Mém. Serv. Carte Géol. Alsace—Lorraine, Strasbourg, 31, 199 pp.

Vedy, J.C. and Bruckert, S., 1979. Les solutions du sol. Composition et signification pédogénétique. In: M. Bonneau and B. Souchier (Editors), Pédologie, Tome 2: constituants et propriétés du sol. Masson, Paris, pp. 161—186.

Villecourt, P. et Roose, E.J., 1978. Charge en azote et en éléments minéraux majeurs des eaux de pluie, de pluviolessivage et de drainage dans la savane de Lamto (Côte d'Ivoire). Rev. Ecol. Biol. Sol, 15(1): 1—20.

Wischmeier, W.H., 1962. Rainfall erosion potential — Geographic and location differences of distribution. Agric. Eng., No. 43, pp. 212—215.

10