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Impact of hydrological and land use processes on the quality of water in the Gucha catchment, southwestern Kenya

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Abstract The paper examines the hydrological and land use processes that are affecting the quality of water in the Gucha catchment situated within the lake basin region in southwestern Kenya. The significance of hydrological processes on the quality of water resources in the catchment is examined. Major land use categories such as cultivation, settlement, and transport infrastructure are examined paying special attention to their role on water resources quality degradation within the catchment. The implications of these processes and activities on water resources management and development are critically evaluated and suggestions made on various strategies that could be applied to counteract or minimize the adverse effects of these processes. Information generated in this study is vital in water resources development planning and management within the catchment and could be of great significance in other catchments in the Lake Victoria drainage area that experiences similar climatic, hydrological, land use and catchment characteristics as the Gucha catchment.

GUCHA CATCHMENT

The Gucha catchment is located on the southwestern corner of the Lake Victoria drainage area in western Kenya. The total area of the catchment is 2196 km². Gucha River is the tributary of the greater Gucha-Migori River whose total drainage area is 5180 km² (Ojany & Ogendo, 1986). Considering the Gucha-Migori River system as a whole, the Gucha catchment constitutes approximately 42% of the total basin area of the Gucha-Migori River system. The catchment covers large parts of Kisii and Nyamira districts with only a small portion occurring in the South Nyanza district.

The Gucha River has been harnessed for water supply development for Kisii and Nyamira towns. There are several small scale self-help and private water supply projects within the basin. In the catchment population growth rate is one of the highest in the country, being 0.63% per annum. In 1985 the total population in the basin was 1.02 million with one of the highest population densities in Kenya (>400 persons/km²). The main resources in the basin are fertile agricultural lands and water resources (surface water and groundwater). Continued high rates of population expansion within the basin pose a great danger to the water resources. The examination of the impacts of this increased population pressure on water resources is vital and will play an important role in devising future water resources planning and management strategies in the catchment.

Geology and topography

The geology of the Gucha catchment consists mainly of old Bukoban system rocks which are of Palaeozoic age. Those within the catchment are represented by the Kisii series. A narrow belt of Precambrian and Kavirondian systems of rock occur in the lower western parts of the catchment. The Bukoban system consists of a broad north-south belt of acidic volcanics with a narrow belt of quartzite and escarpments. On the far western and southeastern parts of the catchment is found a quartzitic belt which is sandwiched by a broad belt of basalt. Kisii soapstones within the central parts of the catchment are derived from the basalt by hydrothermal activity. Post-Kavirondian conglomerates, grits and sandstones are predominant in some parts of the catchment such as Wanjare-South Mugirango. Most of the western parts lie within the rhyolite and tuff belt. Western parts that border the South Nyanza district are predominantly covered by porphyritic and non-porphyritic felsite and andesite.

The Gucha River rises from an elevation of 1500 m at its confluence with Gucha-Migori to 1800 m in the Kisii uplands which in some parts rise up to an altitude of 3000 m. The main watershed of the Gucha River occurs within the Kisii uplands which are above the sub-Miocene erosion surface (Pulfrey, 1960).

Drainage and hydrology

The main drainage feature within the Gucha catchment is the Gucha River which has several tributaries such as Omogongo, Echichiro and Enyangweta. The gradient of the river is 0.015 from the highest point (1800 m) to the lowest point (1500 m). The total annual discharge of the river has been estimated to be 838×10^6 m^3. The annual total sediment transport rate within the main Gucha River ranges from 0.37×10^6 to 0.43×10^6 t year^{-1}. However, the annual sediment transport rate are variable and dependent on the geology and climate (Ongwenyi, 1983). The stream discharge ranges from 7.5 to 45.7 m^3 s^{-1}. The annual flow of the Gucha River at Macalder mines in South Nyanza district has been computed to be in the range of 236×10^6 m^3 year^{-1} and 1440×10^6 m^3 year^{-1} with the suspended sediment concentration in the order of 45 mg l^{-1}. The total dissolved solids (TDS) for the river has been computed to be of the order of 36 mg l^{-1}. However the 1984 survey of one of the tributaries of Gucha River, the Nyakobisara, at RGS 1KA5 shows suspended sediment concentration to be 91 mg l^{-1}.

In general, surface water resources of the catchment can be said to be fresh and non-saline with occasional high colour and turbidity. Surface waters are mainly of fair values of organic pollution (Omari, 1986).

The groundwater resources of the Gucha catchment are vast and of good quality. Within the catchment, sections which are covered by the Kavirondian volcanics yield 870 m^3 of water per hour. Those which are covered with volcanic tuff, agglomerates and post-intrusive granites yield 7835 m^3 of water per hour (Ongwenyi, 1983). Groundwater aquifers within the catchment lie at a depth of between 13 and 60 m below the land surface. Although groundwater resources are of good quality, their development is limited because of the availability of vast surface water resources in form of streams and rivers. However the use of groundwater in form of natural springs is important. It is these springs which draw water from underground reservoirs that form baseflow during dry seasons.

CLIMATE

The climate of the Gucha catchment is influenced by its position and altitude within the lake basin. The catchment stands in the upper eastern flanks of lake victoria basin thereby having an advantage of the rain produced by the convergence of the easterlies (south and north easterlies) and Congo air stream that flows from the Congo-Zaire basin in Central Africa. Rainfall is evenly distributed throughout the year. The upper parts of the catchment receive greater rainfall amounts than the lower parts bordering South Nyanza and Narok districts. The Kisii uplands have mean annual rainfall total of 2000 mm while the eastern section of the catchment receives 1200 mm of rainfall per annum. Two rainfall maxima are recognisable. These are short and long rain seasons. The long rain season is experienced during the months of April-May and the short rain during the months of September-November. Due to high elevation (1500 to 3000 m), temperature and rates of evapotranspiration in the catchment are generally low. The average minimum and maximum night temperature is 13.5°C and 30°C. The rates of evaporation varies with changes in elevation. At 2100 m the rate of evaporation is 1600 mm while at 1500 m the rate of evaporation is 2000 mm. The relative humidity is normally in the range of 50% to 60%.

VEGETATION AND SOILS

No primary vegetation is to be found in most parts of the Gucha catchment with exception of the valley floors. This is due to the fact that primary vegetation has been cleared by the inhabitants of the catchment to give room to cultivation and settlement. Most of the current vegetation found in the catchment is of secondary character. In the recent years, even the primary vegetation that occurred within the valley bottoms has been cleared as a result of swamp reclamation. The vegetation cover of the catchment presently being secondary in character consists of agricultural crops such as tea, coffee, maize, bananas, millet, beans, and pyrethrum. There are also tree species such as eucalyptus, cypress, black wattles,and pines (*Pinus paculata* and *Pinus radiata*). Grasses consist of *Pennisetum clandistenum*. There are 260 ha of exotic forests of which 103 ha have been gazetted by the government.

Soils within the catchment are underlain by volcanic rocks with little metamorphics. There are generally moderately deep to very deep reddish brown to red latosols (mostly Ferralsols and Nitosols). On valley bottoms, black marsh soils are found. In general soils are of fairly high infiltration capacities except those which occurs on bottom lands. They have in general high moisture retention capacities.

LAND USE AND DEMOGRAPHIC PROFILE

The three main land use categories can be summarized as: (a) agricultural and rural settlement, (b) urban settlement, and (c) other social, industrial and transportation establishments.

The agricultural land use covers most of the district. In 1985 it was estimated that 90% of the catchment is under cultivation. Farming units are generally small being in the range of 1.4 to 2.2 ha in size. At an elevation of 1600 m cultivation of wheat, maize, pyrethrum, beans and millet is important, while at an altitude of 1550 m to 1600 m, tea growing and dairy farming are important. Areas lying below 1550 m are important for the cultivation of bananas, cassava, finger millet, and sugar cane. In the 1984 livestock census, it was estimated that there were approximately 0.57 million cattle and 0.17 million shoats (goats and sheep). Because of the scarcity of grazing lands, most of the farmers have adopted a zero grazing system.

Urban settlement in the catchment consists of the Kisii municipality which covers an area of 35 km^2, Keroka, Ogembo and Nyamira townships. These settlements have been found to be one of the main water resources polluters. Municipal and industrial effluent from Kisii town ends up in the Nyakobisara River which is a tributary of the Gucha River. The other categories of land use consists of social, industrial, transport, and commercial establishments. The industrial establishments consists of mainly coffee and tea factories. Transport and commercial land uses are exemplified by the tarmac roads such as Kisii-Migori-Kericho road and several all-weather, feeder and access roads including footpaths.

The Gucha catchment has a total population of 1.02 million according to the 1985 population census projection. It is estimated that, by the year 2000, there will be approximately 1.84 million people in the catchment. The annual population growth rate is currently at 3.63%, which is one of the highest in the country. Population densities have also been increasing over the years. It is estimated that by the year 2000 population density will be greater than 500 persons/km^2. In the past, there has been population translocation to other districts in the Rift Valley Province but this may not be possible in the near future because of the current hostile political climate in the country whereby the inhabitants of the less densely populated Rift Valley districts are having difficulty living peacefully with the newcomers from other parts of the country. The future population situation in the Gucha catchment is bleak unless vigorous and comprehensive population growth control programmes are initiated and accepted by the Gucha inhabitants themselves.

WATER QUALITY CHARACTERISTICS

The quality of water essentially determines the extent to which water can be used for various purposes. The examination of the physical, chemical and biological characteristics of any water resource is an important undertaking as this enables the determination of the chemical, physical and biological constituents in water and the determination of the extent to which a particular water resource can be utilized for variety of purposes. In the Gucha catchment, attempt was made to determine the chemical and physical characteristics of water using standard analytical procedures.

Laboratory analyses carried out on water samples involved gravimetric, spectrophotometric and volumetric analyses.

The results of laboratory analyses of the samples shows water to be of good quality and could be used for various purposes such as drinking, agriculture and livestock utilities. The electrical conductivity which is an indicator of the total dissolved solids in water is 63.4 μS. This small figure indicates low quantity of the dissolved solids in water. The pH of water is 7.1 which is within the WHO (World Health Organization) recommended standard for drinking water. The pH of the Gucha River water is also within the accepted range for irrigation. This implies that water is suitable for agricultural purposes such as irrigation. The carbonate hardness values were low been 22.5 mg l^{-1} which indicates that the water is soft and suitable for washing – including laundry. The levels of the total dissolved solids was also low, being 33.8 mg l^{-1}. Elements and compounds such as chloride, sulphate, silicon dioxide, fluoride, potassium, sodium, magnesium, lead, copper and zinc were found in low concentrations which do not impart serious consequences on the quality of water and were below the recommended standards for drinking water as well as irrigation. The levels of saline ammonia as nitrogen were higher than the recommended levels for ions in drinking water. The levels of saline ammonia as nitrogen was 0.5 mg l^{-1} while the acceptable level is 0.05 mg l^{-1}. The presence of saline ammonia as nitrogen in high concentration is an indication of organic pollution. However, the levels of nitrites and nitrates were low, below the recommended levels for drinking water. This indicated that organic pollution is a relatively recent phenomena. The only metal which has a concentration higher than the recommended level is iron. The level of iron is 1.4 mg l^{-1}. This is attributed to the geology of the catchment which consists of iron-bearing volcanic rocks.

The main water quality factors limiting the use of water in the Gucha catchment are currently high colour and turbidity which are above the recommended WHO standards. Organic pollution exemplified by the presence of saline ammonia as nitrogen in water is limiting the extent to which water of River Gucha could be used for various purposes.

Although soil erosion is not a serious problem in the Gucha catchment, bank and channel erosion are partly responsible for the sediments transported by the river. In addition cultivation in areas adjacent the river also contributes to the observed sediment transport rates. Other factors in sediment production are untarmacked and feeder access roads (Omari, 1986). The average suspended sediment concentration is 325.5 ppm while the total sediment transport rate is 0.4×10^6 t year^{-1} (Ongwenyi, 1979).

Without the application of synthetic fertilizers to the modern agricultural systems, it is difficult to achieve the targeted agricultural outputs. The applications of fertilizers and pesticides have been found to be responsible for the agro-chemical pollution which is becoming important in the catchment. Agro-chemical pollution is widespread in parts of the catchment that are intensively cultivated. In urban areas chemical, physical and biological agents of pollution are significant. Urban based pollution may be categorized as industrial or municipal-based. Industrial-based pollution emanates from the disposal of untreated effluent from the tea and coffee factories. Municipal-based wastes emanate from the Kisii municipality and several townships such as Keroka and Ogembo. Lack of sewage treatment and disposal systems in these townships is partly responsible for the organic pollution in the Gucha River. As most of the human waste disposal systems in the catchment consist of pit latrines, groundwater quality will definitely be seriously affected in the near future. This may introduce pathogenic bacteria not only to the groundwater systems but also the surface water resources.

The examination of the suitability of the Gucha River water for various purposes was attempted by reference to the set international and national standards. While in some cases water is not suitable for a given purpose, in other situations it is usable. In urban centres such as Kisii and Keroka, baking and canning industries are vital development enterprises. However the high turbidity and colour of the Gucha River water is constraining the baking and canning establishments. Canning and baking establishments require water with less than 10 JTU. Colour in water is unsuitable in baking, canning and laundry processes. Hardness values of the Gucha River water does not constrain any industry. Iron and magnesium values are higher than the recommended standards. These may cause serious staining problems in fabrics during laundering processes. They may also introduce undesirable colours in baked and canned products. High levels of iron and magnesium also introduce deposits in cooling systems.

Groundwater systems have been harnessed in both rural and urban areas within the Gucha catchment. Constructed wells and boreholes are vital for industrial and domestic water supply. In general groundwater quality is good and yields are relatively high. The major threat to groundwater quality lies in the design of human and livestock waste disposal systems in the catchment.

In summary, the major factors that continue to be a threat on the water quality of the Gucha River and its tributaries are: industrial effluents, agricultural wastes, municipal wastes and domestic wastes.

While soil erosion is not a serious problem in the catchment, continued increase in population will force people to start cultivating in areas of steep slopes and river banks thus increase the possibility of high of rates soil erosion in the future. High rates of urban population expansion within the catchment at an estimated rate of 15% per annum is considerably high by Kenyan standards. This will have a major threat on water quality as most of the growing urban centres do not have sewage disposal systems. Even the disposal of solid wastes is disorganized, unplanned, and is an eminent threat on water resources quality in the catchment.

CONCLUSIONS AND RECOMMENDATIONS

In this paper, it has been shown that although the waters of Gucha catchment are currently of relatively good quality, it is expected that, with the high population growth rates, serious adverse changes will occur to water resources in the catchment. This is compounded by the fact that, this catchment already has one of the highest population densities in the country. The rates of urbanization in the catchment are also relatively high and will continue to exert a strong pressure on the existing water resources in the catchment in terms of water quality. There is need for coordinated efforts by both government and nongovernmental organizations to ensure that the quality of water resources is maintained and protected against pollution by unsuitable land use activities. Four main factors were found to be a major threat on the quality of water in the catchment. These are industrial effluent mainly from tea, coffee, and canning factories; agricultural wastes and residues (mainly fertilizers and pesticides); municipal wastes (mainly from hotels, hospitals and residential areas in the urban centres); and finally domestic wastes (which originate from the residential units in the urban centres). Poor urban and physical planning is aggravating this problem and hence amalgamation of physical planning concepts with environmental virtues in the catchment and elsewhere is called for. There should be regulated use of agricultural chemicals such as fertilizers and pesticides within the catchment. This calls for proper training of farmers and extension officers in training centres where demonstrations on the proper use of farm chemicals can be undertaken. The creation of an independent water quality monitoring unit within the Ministry of Water Development has the objective of detecting at an early stage cases of water pollution. But because of limitations imposed by lack of funds, personnel and other logistical support, the unit has not been able to carry out effective water quality monitoring in the country. There is a need to strengthen this unit and support research aimed at investigating the effects of land use changes on the quality of water resources in the country. While relocation of the industrial establishments in the catchment is expensive, there is need to modify the out-dated industrial processes which are indeed creating a lot of problems to the environment and in particular to the water resources in the catchment. The construction of sewage disposal systems in the main urban centres such as Kisii and Keroka is necessary for treatment of domestic and municipal wastes. Industrial entrepreneurs should be encouraged to establish industrial effluent treatment units within their establishments. Because it is expensive to create such industrial effluent treatment units, the government should subsidize the cost of creating such units through non-taxation of the imported effluent treatment equipment and provision of non-taxable land for the construction of the waste-water treatment units. In Kenya there are several scattered laws which address themselves to the maintenance of environmental quality. There is need for their amalgamation in order to come up with one strong environment protection law which will be easier to implement and therefore go a long away in helping control the problem of water pollution in the country.

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Hydrogeochemistry of the Ngoko River, Cameroon: chemical balances in a rainforest equatorial basin

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Abstract The Ngoko River constitutes the upper part of the Sangha River, a tributary of the Zaïre-Congo River. It is a strictly undisturbed watershed (67 000 km^2) located within the equatorial evergreen forest of southeastern Cameroon. Daily and weekly measurements of streamflow and solid transport respectively were made at the basin outlet during two hydrological cycles (1989-1991). Rainfall samples were also collected at nine sites within the catchment. Rainwater and streamwater were both analysed for the following ions (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^-, HCO_3^-, SO_4^{2-}, NO_3^-, SiO_2). The hydrological regime is essentially pluvial, with maximum discharge in November and low flow in March. The annual water balance shows that evapotranspiration accounted for 78% of the total precipitation over the period of study, and that the streamflow was around 355 mm year^{-1}. The mean suspended load was about 26 mg l^{-1} and the calculated annual sediment discharge was 584 10^3 t year^{-1} (i.e. 8.6 t km^{-2} year^{-1}). Chemical analyses shown annual cycles for most parameters, with maximum values at the end of the long dry season (March) and minimum values at the end of the long wet season (November). With regard to the solute transport, some chemical species (conductivity, HCO_3^-, Ca^{2+}, Mg^{2+}) decreased with increasing discharge, whereas K^+, SO_4^{2-}, NO_3^- and Cl^- displayed no consistent relationship with discharge and were relatively uniform throughout the year. Over the period of study, the rainfall chemical input (t km^{-2} year^{-1}) to the catchment from was calculated to be 0.26 Ca^{2+}, 0.29 Mg^{2+}, 0.37 Na^+, 0.19 K^+, 0.49 Cl^-, 1,24 SO_4^{2-}, 0.43 SiO_2. During the same period the output from the catchment to the streamflow was calculated to be 1.27 Ca^{2+}, 0.62 Mg^{2+}, 0.43 Na^+, 0.47 K^+, 0.45 Cl^-, 0,61 SO_4^{2-}, 4.74 SiO_2 and 0.26 NO_3^-. Implication of the hydrochemical balance for weathering, erosion and denudation rates in a medium-size basin in the humid tropical zone is discussed.

INTRODUCTION

Most studies devoted to water chemistry of equatorial basins have considered large River systems, such as the Amazon (Gibbs, 1967, 1972, 1977; Schmidt, 1972; Meade *et al.*, 1979; Stallard & Edmond, 1981, 1983; Furch, 1984) and the Congo-Zaïre

(Symoens, 1968; Meybeck, 1978; Sholkovitz *et al.*, 1978, Molinier, 1979; Deronde & Symoens, 1980; Moukolo *et al.*, 1990; Kinga Mouzeo, 1983; Nkounkou & Probst, 1987; Probst *et al.*, 1992). The large River basins encompass too many lithological, climatic and vegetation units to permit a fine examination of the respective contribution of each unit.

The French Research Institute for Development (ORSTOM) initiated a research programme focussed on a medium scale essentially undisturbed equatorial basin, almost entirely covered by evergreen forest (Fig. 1). The aim of this programme is to understand the actual biogeochemical mechanisms in this type of pristine forested basin.

In this paper, we report the results of a two-year study on particulate and dissolved fluxes transported by the Ngoko River (Cameroon). Atmospheric inputs were measured in order to calculate chemical and erosion rates.

STUDY AREA

The Ngoko River constitutes the upper part of the Sangha River, itself a tributary of the Zaïre-Congo River. With the Dja and Boumba Rivers, its two main tributaries, the Ngoko River drains an homogeneous forested basin which covers 67 000 km^2, i.e. 2% of the Zaïre basin area. Watershed elevations range from 350 m (at the outlet) to 800 m, with an average elevation of 650 m. It extends from 11°E to 16°E (longitude) and from 1°30′N to 5°N (latitude).

The southern Cameroonian climate is dominated by the monsoon from the southwest which bring moisture. This moisture is distributed in two rainy seasons, one from mid-March to mid-June, as the Intertropical Front begins its northward excursion, and the other from mid-August to mid-November as the monsoon returns to the south (Suchel, 1972). During the dry season, large quantities of dust are transported southward, from the Saharan desert to the Gulf of Guinea, by the Harmattan trade wind (Morales, 1979). The mean annual temperature is 25°C, and the effective insolation is between 1500 and 1750 hours per year.

The humid evergreen forest covering 95% of the Ngoko basin, consists mainly of Caesalpiniaceae (*Gilbertiodendron dewevrei* is the dominant taxon) with a little portion of semi-deciduous forest, composed of Sterculiaceae and Ulmaceae (Fig. 2).

The Ngoko basement (Fig. 3) is mainly composed of crystalline and metamorphic rocks, from 2500 to 1800 10^6 years old. According to their age, one finds the Ntem unit, the intermediate, Mbalam and Dja series. On the top, the Upper Dja series consists of calcareous and dolomitic rocks.

Typical soils of the Ngoko basin have been characterized by Segalen (1967). Ferrallitic and yellow soils predominate on ridge tops. Gleyed and pseudogleyed hydromorphic soils occur on the lower slopes with imperfect drainage. More complete information about morphology, lithology and vegetation of the southern Cameroon is reported in Letouzey (1968) and Olivry (1986).

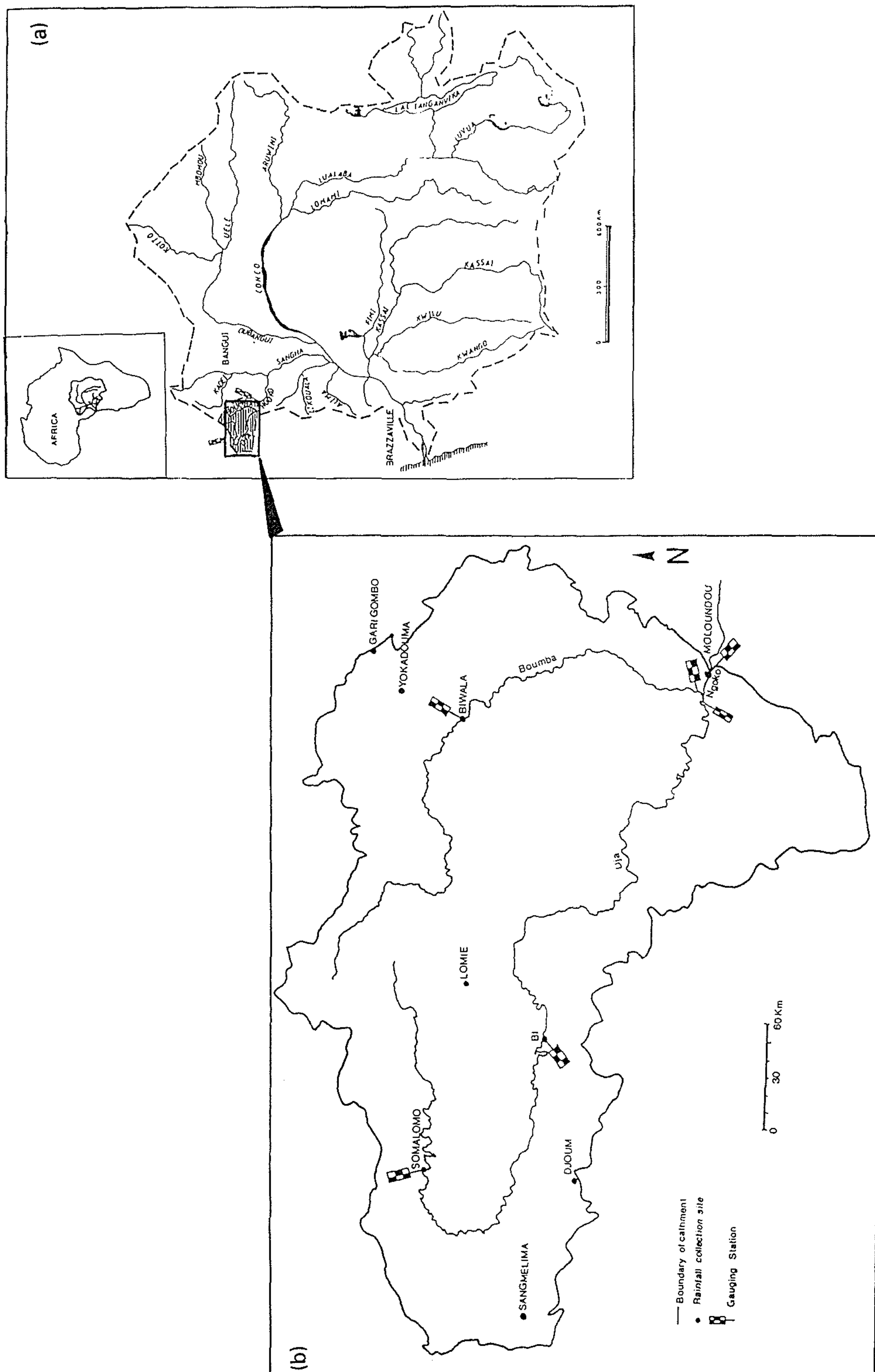

Fig. 1 (a) General location map of the Ngoko basin, as part of the Zaïre-Congo basin. (b) Map of the Ngoko basin showing the rainfall collection sites and gauging stations.

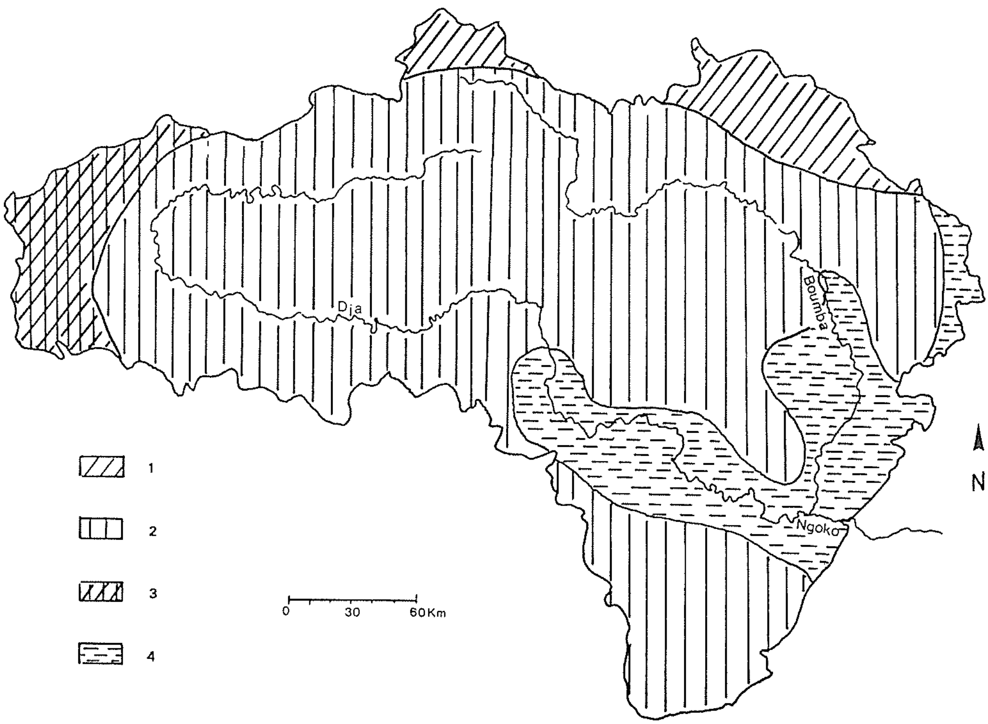

Fig. 2 Vegetation map of the Ngoko basin.
1: Rainforest drier type; 2: rainforest wetter type; 3: mosaïc of 1 and 2; 4: swamp forest.

METHODS: SAMPLING SITES AND ANALYSES

The bulk fallout (total precipitation) was obtained from nine standard meteorological Plexiglass raingauges located in open sites or in clearings, generally near national meteorological stations. These collectors are continually exposed to the precipitation and designed to minimize evaporation. Samples were collected daily and individual samples mixed over one month periods and filtered through 0.45 μm Millipore filters prior to chemical analysis.

River discharge (total runoff) is recorded continuously on a limnigraph at the main gauging station of Moloundou, located at the basin outlet. Secondary stations on the tributaries (Moloundou-Bac, Biwala on the Boumba River and Moloundou-Sotref, Bi, Somalomo on the Dja River) are instrumented with staff gauges (Fig. 1). Water sampling for chemical analysis was performed once a month or more frequently during annual flood. This frequency is sufficient for the precise determination of the chemical fluxes, since the chemical variability is much smaller than variations in discharge.

Conductivity, pH and alkalinity were measured in the field. Conductivity was measured with a temperature-corrected conductimeter, and alkalinity was determined by potentiometric titration with 0.02N hydrochloric acid. The titration curve was then analysed by the method of Gran (Stumm & Morgan, 1981). Samples were filtered through 0.45 μm filters the day of their collection, and stored in polyethylene bottles in the dark until analysis. Chemical analyses were performed in the ORSTOM

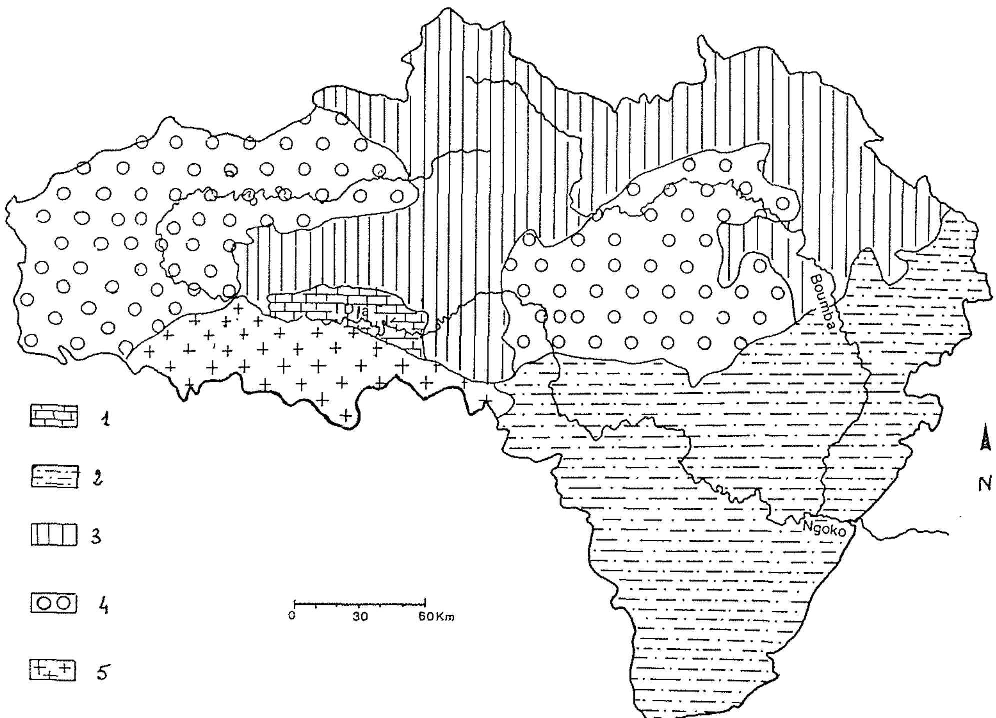

Fig. 3 Geological map of the Ngoko basin.
1: Upper Dja series (calcareous and dolomitic rocks); 2: lower Dja series (sandstone, quartzite); 3: intermediate series (schists with chlorites); 4: gneiss, mica schist; 5: Ntem series (granite, amphibolite).

Laboratory in France. Chloride, sulphate, nitrate were determined by ion chromatography; calcium, magnesium, sodium and potassium by atomic absorption, with a detection limit of 0.1 mg l^{-1} for both elements.

Dissolved silica was measured by plasma spectrophotometry, with a detection limit of 50 μg l^{-1}. Accuracy of the chemical data was checked by ion balance calculations. According to Schoeller (1962) data sets with imbalances greater than 10% must be discarded. The mean deviation from cation-anion balances for all River and rain samples is 2.5% (N = 132 SD = 11%). Waters with imbalances greater than 10% (mostly rainwaters with concentrations close to the detection limit) usually show anion deficiency.

In order to estimate precisely the solid discharge, the sampling procedure was the following: Once a month, three samples of 2 litres each were collected on five vertical profiles across the River section, together with stream velocities. Suspended matter concentration was then determined by weighing the fraction retained by the 0.45 μm pore size filters. Solid discharge was computed using the formula:

$$Q_s = \int_0^l \int_0^d C_i V_i \, \mathrm{d}l \, \mathrm{d}d$$

where C_i is the concentration of suspended matter, V_i, stream velocity, l, length of the cross section, and d, river depth.

RESULTS AND DISCUSSION

Stream hydrology

The main hydrological features of the Ngoko River and its two major tributaries are summarized in Table 1. The stream regimes of these three Rivers were characterized by high discharge from August to November during the long rainy season, followed by a decline until the low flow reached in March. The short rainy season caused the secondary peak discharge, occurring in May or June. This kind of stream regime, mainly pluvial, is typical of many equatorial Rivers (Devroey, 1951; Rodier, 1964; Olivry, 1977; Molinier, 1979; Molinier & Mbemda, 1979; Molinier *et al.*, 1981; Frecaut & Pagney, 1982; Moukolo *et al.*, 1990). Representative hydrographs of the Ngoko are shown in Fig. 4 and the discharge characteristics are reported in Table 2. The Dja basin represents 62% of the total area of the Ngoko basin, and contributes to the Ngoko streamflow in the same proportion. Mean water discharges for 1989-90 and 1990-91 water-years are respectively 286 and 294 $m^3\ s^{-1}$ for the Boumba, 451 and 487 $m^3\ s^{-1}$ for the Dja, and 734 and 780 $m^3\ s^{-1}$ for the Ngoko. Up to 23 $10^9\ m^3\ year^{-1}$ are discharged from the Ngoko to the Congo basin.

Table 1 Physical characteristics of the Boumba, Dja and Ngoko basins. *Q*: Annual discharge ($m^3\ s^{-1}$), q: Specific discharge ($l\ s^{-1}\ km^{-2}$).

River	Gauge station	Area	Water Year		Water Year	
		(km^2)	1989/90	1989/90	1990/91	1990/91
			Q ($m^3\ s^{-1}$)	q ($l.s^{-1}\ km^{-2}$)	Q ($m^3\ s^{-1}$)	q (l s-1 km^{-2})
BOUMBA	BIWALA	10310	110	10.7	114	11.1
	MOLOUNDOU-BAC	27260	286	10.5	294	10.8
DJA	SOMALOMO	5473	81.7	14.9	70.7	12.9
	BI	19516	290	14.2	257	13.2
	MOLOUNDOU-SOTREF	39715	451	11.4	488	12.3
NGOKO	MOLOUNDOU	67075	734	10.9	780	11.6

Water budgets: precipitation and evapotranspiration

The quantity of rainwater collected varied widely from site to site. We calculated the annual rainfall (from April to March as the hydrological year) by using the Thiessen method applied to the raingauge station network (Fig. 5).

Equatorial forest is responsible for an intensive evapotranspiration. The annual runoff deficit, calculated from a simple water budget, is between 1115 and 1322 mm $year^{-1}$ (Table 3). These values are comparable to those calculated by Olivry (1986) on the Dja basin or by Rodier (1964) on the Zaïre-Congo. Finally, the runoff coefficient is about 22% on the Ngoko basin.

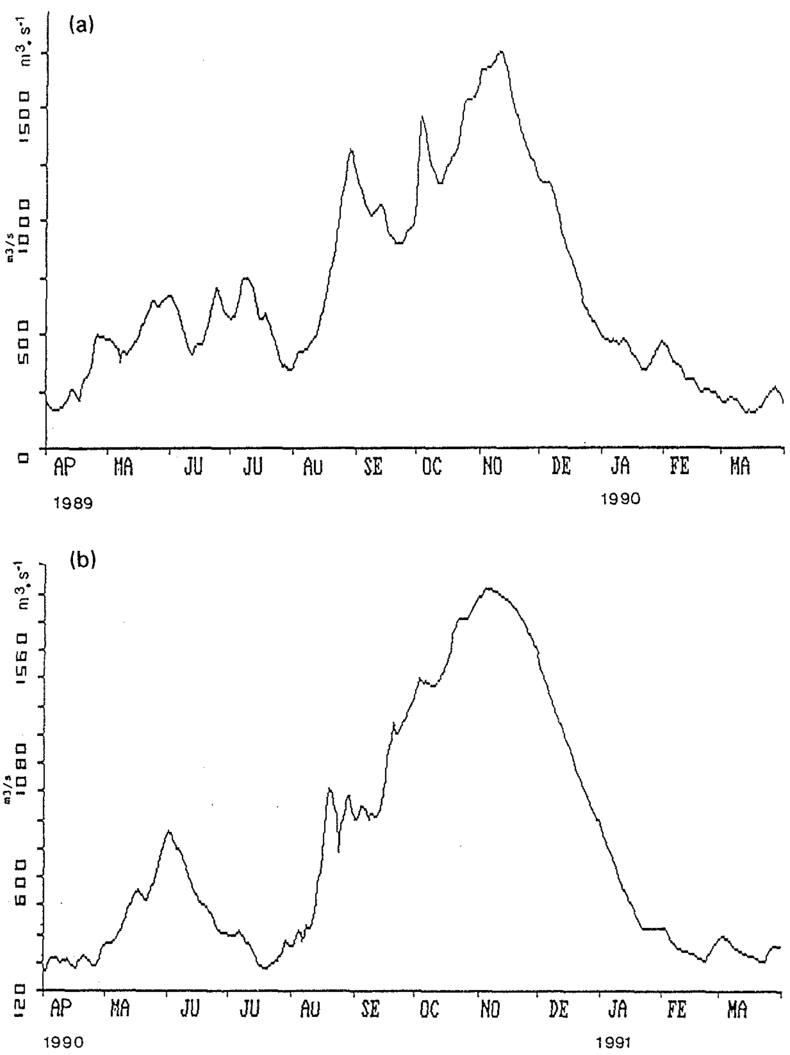

Fig. 4 Mean daily discharge of the Ngoko River at the outlet (Moloundou): (a) water year 1989-90; (b) water year 1990-91.

Particulate transport

In the Boumba, Dja and Ngoko Rivers, the suspended sediment load ranged from 7 to 110 mg l^{-1} (i.e. a factor 15 of variation). The average concentration calculated for

Table 2 Main characteristics of Ngoko River discharge ($m^3\ s^{-1}$) at Moloundou gauge station. (MinDD: minimum daily discharge; MaxDD: maximum daily discharge; CLWD: characteristic low water discharge; CFD: characteristic flood discharge).

Water Year	Annual	MinDD	CLWD	CFD	MaxDD
1989/90	734	156	172	1680	1750
1990/91	780	203	227	1800	1830

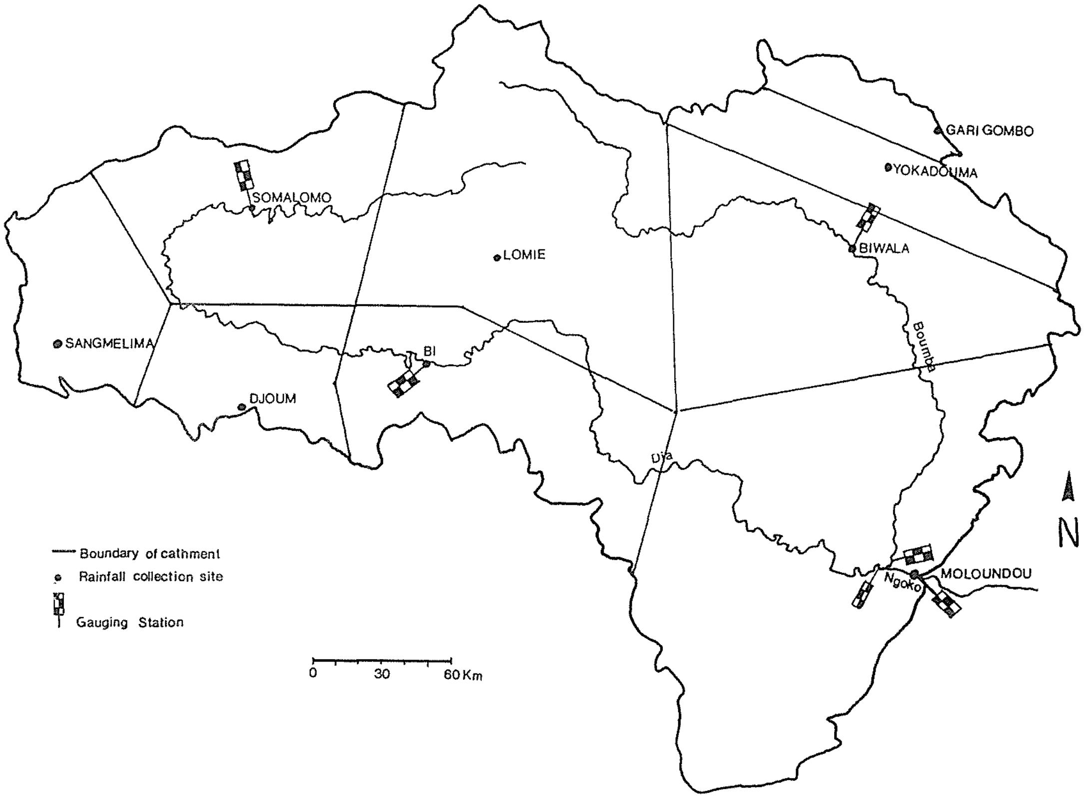

Fig. 5 Raingauge station network and Thiessen polygons.

123 samples from the Ngoko River at Moloundou is 26 mg l^{-1}. This value is lower than in the Sanaga River (mean 58 mg l^{-1}, Olivry, 1978) and in other Cameroonian (Nouvelot, 1969, 1972) or African Rivers which drains dry tropical regions, such as the Chari-Logone (Gac, 1980), the Senegal (Kattan *et al.*, 1987), the Gambia (Lo, 1984), the River Jong in Sierra Leone (Wright, 1982). On the other hand, our data for the Ngoko are close to values obtained by Moukolo *et al.* (1990) on the Zaïre-Congo.

The mean annual load of suspended sediment exported by the Ngoko is 584 10^3 t, i.e. a specific transport of 8.6 t km^{-2} $year^{-1}$. The suspended sediment load is maximum at the beginning of the long rainy season (August), then decreases with increasing discharge until the end of the rainy season (mid-November). Concentrations reach then a low step that is maintained until the end of the long dry season (from

Table 3 Annual precipitation, runoff, and estimates of runoff deficit and runoff coefficient for the Ngoko basin (water years 1989-90 and 1990-91).

Water Year	Precipitation	Discharge	Runoff Deficit	Runoff Coeficient
Apr. 1-Mar31	P (mm)	Q (mm)	RD (mm)	RC (%)
1989/90	1460	345	1115	23,6
1990/91	1689	367	1322	21,7

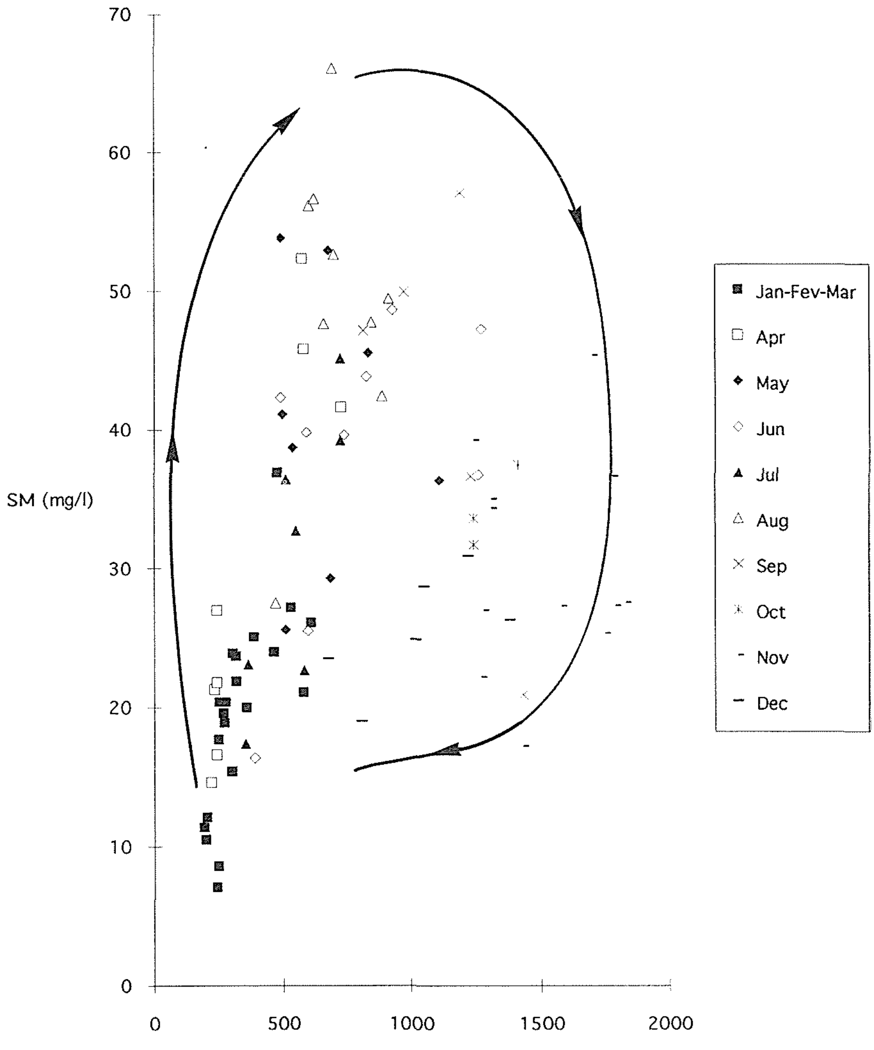

Fig. 6 Relationship between suspended sediment concentration and River discharge in the Ngoko at Moloundou.
= : Seasonal trend of suspended load.

January to March). The relationship between discharge and suspended matter load is illustrated versus time in Fig. 6. As in most Rivers, the solid discharge increases with increasing water discharge (Fig. 7), so that 25% of the suspended sediment is exported in 60 days.

Dissolved transport

Composition of streamwaters The physical parameters and the composition of waters of Rivers Boumba, Dja and Ngoko (more than 400 analyses) are summarized in Table 4.

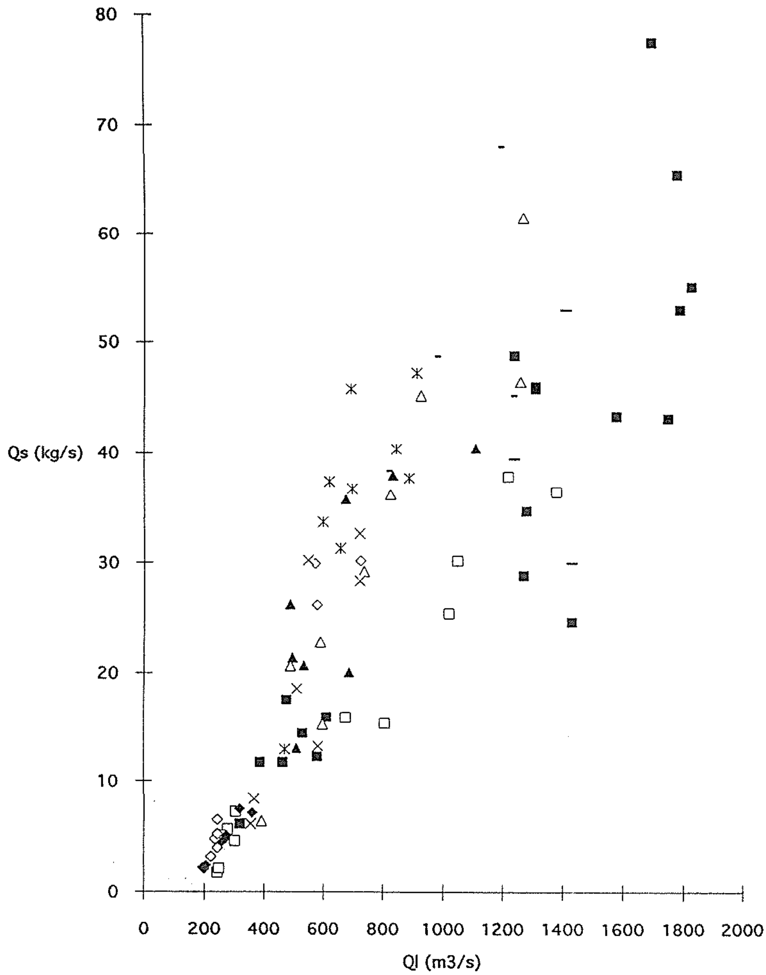

Fig. 7 Relationship between solid discharge and water discharge in the Ngoko at Moloundou.

Temperature fluctuations of streamwater are directly correlated to the variation in climate. Maximum water temperatures around 30°C occur during the dry season in January, while minimum temperatures around 23°C occur during the long wet season in November.

Table 4 Streamwater chemistry at the streamgauging stations. Data are averaged over the 1989-90 and 1990-91 water years. *n*: number of samples; SD: standard deviation.

RIVER	STATION	n	T	pH	CND	Ca	Mg	Na	K	HCO3	Cl	SO4	NO3	SiO2	TDS
			°C		$\mu S\ cm^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	$mg\ l^{-1}$	mg l-1
DJA	SOMALOMO	6	26,2	6,39	33,68	1,37	0,61	0,79	0,48	6,87	1,14	0,60	0,34	10,98	22,86
DJA	BI	4	26,0	6,50	14,93	1,35	0,67	0,74	1,08	7,05	0,55	0,50	0,16	8,23	20,32
DJA	MOLOUNDOU-	12	26,8	6,89	50,04	2,70	1,26	1,00	0,72	14,29	1,19	1,13	0,74	12,40	34,71
	SOTREF	SD	1,5	0,35	30,50	0,78	0,40	0,54	0,51	4,93	0,53	0,19	0,38	8,80	12,98
BOUMBA	BIWALA	9	26,0	6,88	47,47	2,83	1,39	1,46	0,98	15,71	1,59	0,69	1,98	14,09	38,55
		SD	1,3	0,57	25,20	0,95	0,26	0,61	0,45	4,23	0,59	0,29	3,13	11,00	17,49
BOUMBA	MOLOUNDOU-	13	26,0	7,08	70,28	5,43	2,54	1,29	1,03	30,33	1,31	0,97	0,63	13,37	55,38
	BAC	SD	1,4	0,46	35,82	2,22	1,24	0,65	0,48	9,89	0,47	0,27	0,50	8,98	17,89
NGOKO	MOLOUNDOU	18	26,5	6,87	61,86	3,57	1,74	1,21	1,33	18,85	1,26	1,71	0,73	13,34	40,40
		SD	1,5	0,40	34,13	1,32	0,67	0,58	0,94	7,20	0,50	1,83	0,60	9,29	14,07

Streams are characterized by slightly acid to slightly basic waters, with pH values ranging from 5.7 to 7.8. A trend toward higher values in the dry season and lower values in the wet season is seen in the Ngoko. A similar trend was observed in the tropical River Jong (Wright, 1982), and is probably due to the larger contribution of more acidic groundwaters to the streamflow during the dry season than during the rainy season.

Conductivity averages 70 $\mu S\ cm^{-1}$, 48 $\mu S\ cm^{-1}$ and 62 $\mu S\ cm^{-1}$ in the Rivers Boumba, Dja and Ngoko respectively. Ca and Mg concentrations are also higher in the Boumba waters, reflecting lithologic differences between the watersheds such as the occurrence of calco-alkaline gneiss in the Boumba basin. Cation abundances (meq l^{-1}) are in the order $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$, and anion abundances: $HCO_3^{-} > Cl^{-} \geq SO_4^{2-} > NO_3^{-}$. Bicarbonate represents 80% of the sum of anions. Dissolved silica concentrations are very close in the Rivers Boumba, Dja and Ngoko. As in most Rivers, electrical conductivity in the Rivers studied is directly related to the total dissolved solids concentration (TDS), defined here as the sum of cations plus anions plus dissolved silica (Fig. 8).

Variation in chemical concentration with discharge As in many Rivers, conductivity and concentration of most of the chemicals decreases with increasing discharge. This pattern has been observed by many authors (Livingstone, 1963; Kennedy & Malcolm, 1977; Buckley, 1977; Miller & Drever, 1977; Foster, 1978; Feller & Kimmins, 1979). The generally accepted model is that groundwater is more concentrated than surficial waters and that decrease in chemical concentration with increasing stream discharge reflect contribution of surface flow to high discharge.

In the Boumba, Dja and Ngoko Rivers, different types of elemental behaviour may be distinguished: for TDS, calcium, magnesium and bicarbonate, the relationship with discharge is curvilinear, with a rather good regression coefficient, suggesting a simple dilution process of rich groundwater by less concentrated surface water (Fig. 9). Sodium, potassium, chloride and sulphate show only poor correlation with discharge,

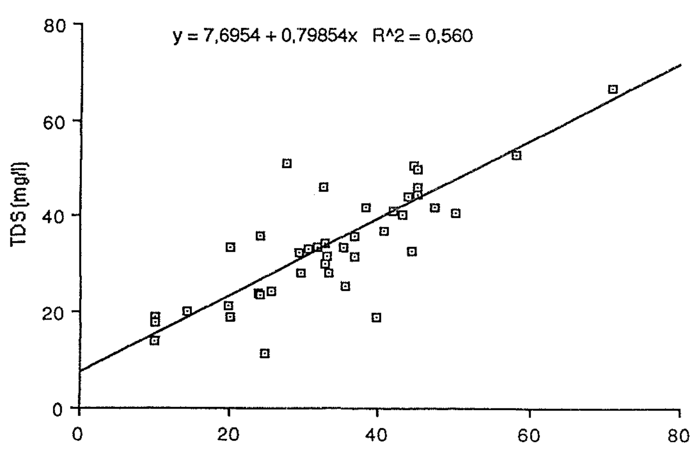

Fig. 8 Relationship between total dissolved solid concentration (cations + anions + dissolved silica) and conductivity for stream samples.

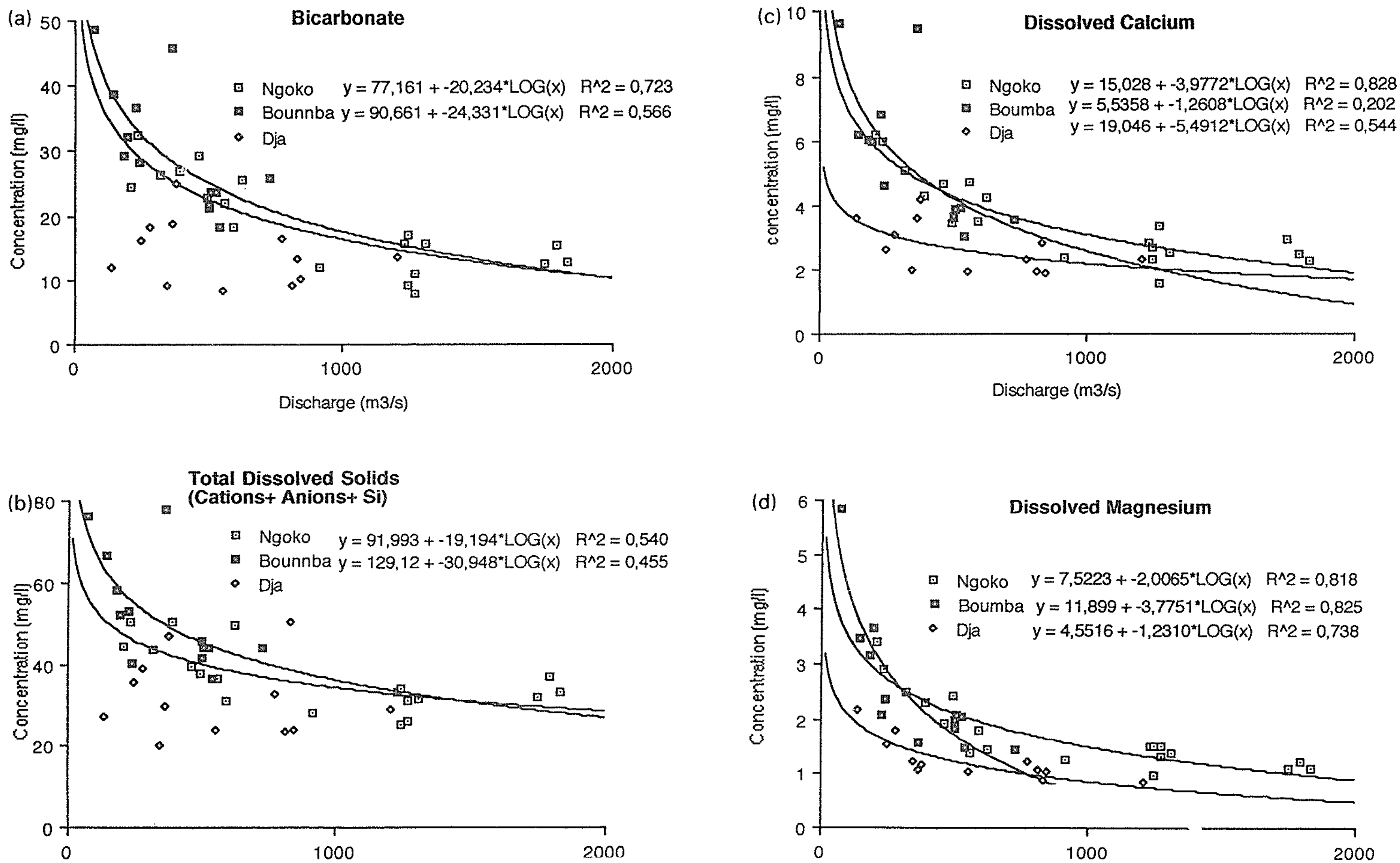

Fig. 9 Relationship between chemical concentrations and discharge for the Boumba, Dja and Ngoko Rivers. (a) Bicarbonate; (b) total dissolved solids; (c) calcium, and (d) magnesium.

the lowest concentrations generally associated with high discharge (Fig. 10(a)). Except for chloride, these elements have multiple origins, i.e. atmosphere, vegetation and bedrock.

Since there is essentially no chloride in the igneous substratum of the drainage basin, it is likely that all chloride in the waters comes from precipitation. Oceanic precipitations also bring sodium and sulphate, but no evident relationship is found between Na^+ and Cl^-, and SO_4^{2-} and Cl^-. The ratio Na/Cl is maximum during low flow (mean 1.16) and it decreases when the discharge increases (0.64). These results suggest that these components have a dual origin, atmospheric and lithospheric for sodium, atmospherical and biological for sulphate. According to Kennedy & Malcolm (1977), sulphate is released by the mineralization of organic matter. Potassium concentrations in streamwaters generally do not show a strong correlation with discharge (Feller & Kimmins, 1979). Potassium comes originally from weathering of mineral particles (mainly clay minerals) but it is also an important nutrient that is taken up and released by growing vegetation (Johnson *et al.*, 1969; Borman *et al.*; 1969).

The third type of pattern is found for nitrate, concentrations of which increase with increasing discharge (Fig. 10(b)). According to Cleaves *et al.* (1970) and Meybeck (1983) such behaviour occurs when the concentration of a chemical species is higher in soil leachates than in groundwaters. It is usually the case for dissolved organic carbon, ammonium, nitrate and phosphate, suggesting that those elements are flushed by surficial flow during the high discharge.

The relative constancy of dissolved silica observed in the Boumba, Dja and Ngoko streamwaters (Fig. 10(c)) is not always found on other Rivers (e.g. Deronde & Symoens, 1980; Wright, 1982; Meybeck, 1983). The absence of correlation reported here between dissolved silica and discharge may be due to several simultaneous processes, including biological and solid-liquid exchange processes during transport. In the Rivers studied here, we suggest that surficial waters that contribute to the peak discharge contain high concentrations of dissolved silica.

Precipitation chemistry and chemical budgets

Precipitation chemistry Table 5 summarizes the chemical data of rainfall samples collected during the hydrological years 1989-1990 and 1990-1991. Coefficients of variation of these data are also reported. We considered that pH and potassium measurements were good indices of purity of samples. When either of these were abnormally high, we suspected a contamination and the samples were rejected.

Elemental concentrations do not shown significant difference from sites to sites, except at the Djoum station, for which extremely high concentrations were measured in all the samples. The Djoum station is one of the meteorological network stations, located in the vicinity of a large unasphalted road. We suspect that the contamination is due to artificial weathering resulting in the road traffic.

With the exception of this station, pH ranges from 5.37 to 6.89, values usually found in equatorial precipitation (Lacaux *et al.*, 1992). Concentrations of most chemical species are lower than those found in temperate regions (Meybeck, 1990), but are similar to those found in the equatorial regions (Galloway *et al.*, 1982; Stallard & Edmond, 1981; Andreae *et al.*, 1990; Lacaux *et al.*, 1992).

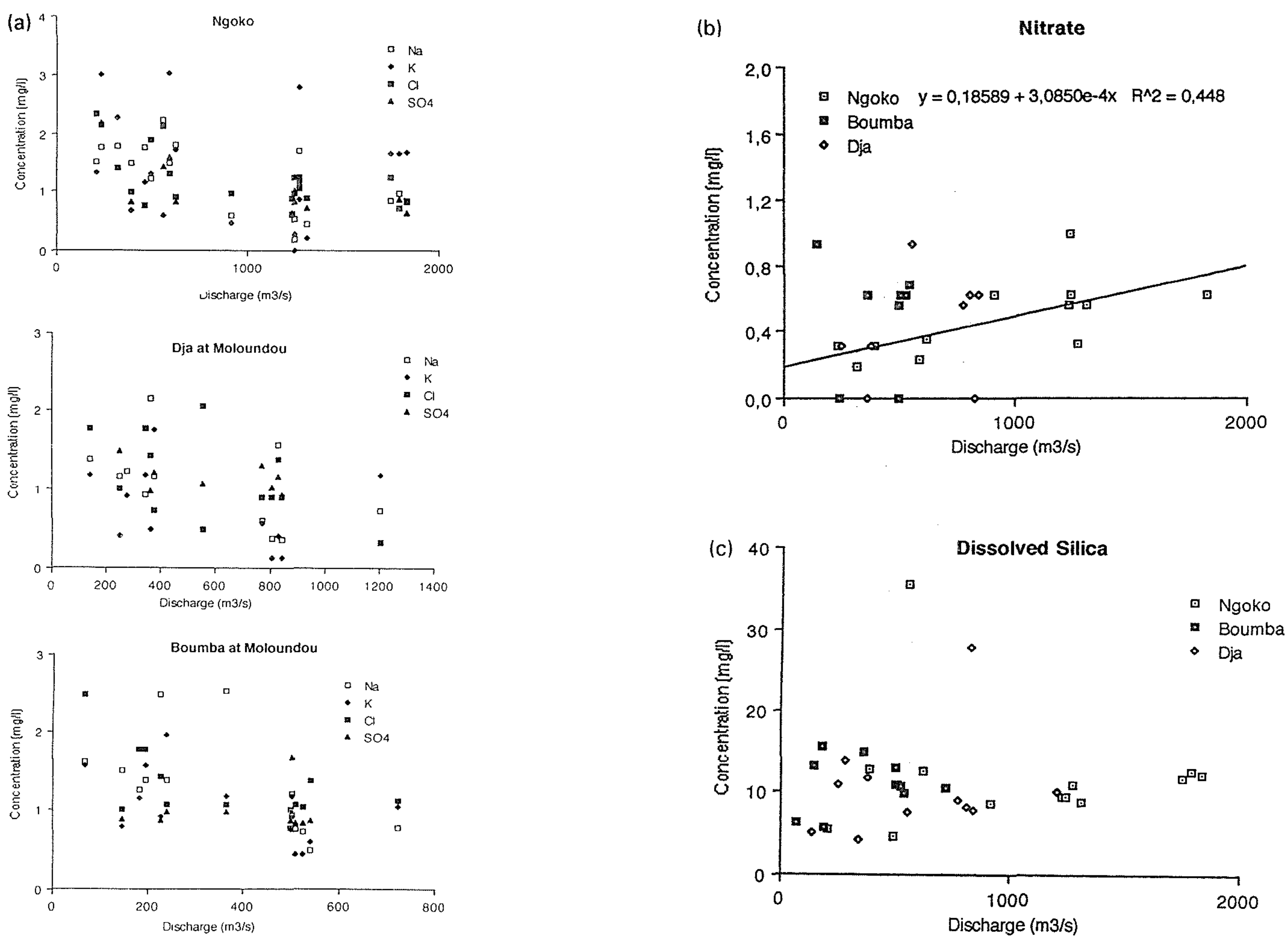

Fig. 10 (a) Sodium, potassium, chloride and sulphate concentrations versus Dja, Boumba and Ngoko discharges; (b) nitrate concentration versus rivers discharges; (c) dissolved silica versus rivers discharges.

Table 5 Total precipitation chemistry at the raingauging stations. Data are averaged over the 1989-90 and 1990-91 water years. SD: standard deviation.

STATION		pH	Ca	Mg	Na	K	Cl	SO4	NO3	SiO2	TDS
			mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}	mg l^{-1}
MOLOUNDOU	MEAN	6,43	0,16	0,21	0,32	0,15	0,51	0,58	0,11	0,246	2,29
	SD	0,31	0,13	0,15	0,31	0,14	0,28	0,43	0,01	1,126	2,57
YOKADOUMA	MEAN	6,89	0,33	0,12	0,43	0,13	0,43	0,87	0,20	0,626	3,14
BIWALA	MEAN	*6,05*	*0,19*	*0,23*	*0,16*	*0,16*	*0,43*	*0,87*	*0,44*	*0,115*	*2,59*
	SD	0,78	0,10	0,08	0,06	0,13	0,04	0,41	0,45	0,146	1,41
GARI GOMBO	MEAN	5,37	0,19	0,35	0,49	0,45	0,50	2,46	0,16	0,845	5,45
BI	MEAN	5,51	0,25	0,25	0,14	0,19	0,48	0,97	0,13	0,363	2,76
	SD	0,71	0,14	0,12		0,37	0,05	0,46			1,14
LOMIE	MEAN	6,86	0,20	0,23	0,49	0,09	0,24	2,12	NA	0,475	3,83
	SD			0,11	0,49	0,08	0,17	1,45		0,407	2,70
SOMALOMO	MEAN	6,13	0,24	0,41	0,45	NA	0,42	1,45	0,61	0,315	3,89
	SD	0,25	0,20	0,45	0,49		0,31	1,27	0,52	0,280	3,52
SANGMELIMA	MEAN	6,68	0,38	0,31	0,14	0,46	0,47	0,13	0,14	0,657	2,69
DJOUM	MEAN	7,78	6,71	0,27	6,56	0,92	1,02	7,11	10,64	57,08	134,46
	SD		4,79	0,07	5,48	0,63	0,33	6,73	7,41	29,44	48,29

Chemical budgets Rainfall input of chemical elements were first calculated for each station by multiplying depth of rainfall by mean chemical concentration in precipitation. The total input is then computed using the Thiessen polygon method (Table 6). Stream output were determined by multiplying the annual water discharge measured at the streamgauge stations by mean chemical concentration in streamwater (Table 7).

Examination of the loading charge in precipitation shows that sulphate flux is consistently greater than the others. Meybeck (1983) reported sulphate flux from precipitation ranging from 0.6 to 2.2 t km^{-2} $year^{-1}$. If the input flux reported here (1.2 t km^{-2} $year^{-1}$) is representative of the zone studied, then the net gain for the Ngoko basin is 0.63 t km^{-2} $year^{-1}$. As suggested by Kling (1987) the rainforest area may act as a sink for sulphate.

Table 6 Mean annual rainfall (mm) and chemical load (t km^{-2} $year^{-1}$) in total precipitation at the raingauge stations.

STATION	AREA	RAIN	Ca	Mg	Na	K	Cl	SO4	NO3	SiO2
	% OF TOTAL	mm								
MOLOUNDOU	26,15	1167	0,19	0,25	0,37	0,18	0,59	0,68	0,13	0,29
YOKADOUMA	7,42	1569	0,38	0,14	0,51	0,15	0,50	1,02	0,23	0,73
BIWALA	16,01	1415	0,22	0,27	0,18	0,19	0,50	1,02	0,51	0,13
GARI GOMBO	1,8	1730	0,22	0,41	0,58	0,52	0,59	2,87	0,19	0,99
BI	9,63	1570	0,29	0,29	0,16	0,22	0,56	1,13	0,16	0,42
LOMIE	18,83	1570	0,23	0,27	0,57	0,10	0,28	2,47		0,55
SOMALOMO	10,68	1465	0,27	0,48	0,53		0,49	1,69	0,71	0,37
SANGMELIMA	4,4	1598	0,44	0,36	0,16	0,54	0,55	0,15	0,16	0,77
TOTAL	94,82	1575	0,26	0,29	0,37	0,19	0,49	1,24	0,24	0,4

Table 7 Mean annual specific discharge (l s^{-1} km^{-2}) and chemical load (t km^{-2} $year^{-1}$) in the rivers at the streamgauging stations.

RIVER	STATION	q	Ca	Mg	Na	K	Cl	SO4	NO3	SiO2	TDS
		l s^{-1} km^{-2}									
DJA	SOMALOMO	13,90	0,60	0,27	0,35	0,21	0,50	0,26	0,15	4,82	10,04
DJA	BI	13,70	0,59	0,29	0,32	0,47	0,24	0,22	0,07	3,56	8,80
DJA	MOLOUNDOU-SOTREF	11,85	1,01	0,47	0,37	0,27	0,45	0,42	0,28	4,64	13,00
		S D	0,29	0,15	0,20	0,19	0,20	0,07	0,14	3,29	4,86
BOUMBA	BIWALA	10,90	0,97	0,48	0,50	0,34	0,55	0,24	0,68	4,85	13,28
		S D	0,33	0,09	0,21	0,15	0,20	0,10	1,08	3,79	6,03
BOUMBA	MOLOUNDOU-BAC	10,65	1,83	0,85	0,43	0,35	0,44	0,33	0,21	4,50	18,64
		S D	0,75	0,42	0,22	0,16	0,16	0,09	0,17	3,02	6,02
NGOKO	MOLOUNDOU	11,25	1,27	0,62	0,43	0,47	0,45	0,61	0,26	4,74	14,36
		S D	0,47	0,24	0,21	0,33	0,18	0,65	0,21	3,30	5,00

On the other hand, input and output of chloride, sodium and nitrogen are well balanced, suggesting that the whole budget is reasonably adequate. Losses of calcium, magnesium and potassium and dissolved silica observed in the Ngoko basin are commonly found in the budget studies in tropical regions (Nkounkou & Probst, 1987), as well as in temperate regions (references in Feller & Kimmins, 1979).

Net gains and losses for the entire Ngoko basin are reported Table 8. Atmosphere is the major contributor for sulphate (contribution of forest fires?), chloride and sodium. Magnesium and potassium are supplied equally by the atmospheric and terrestrial sources. Dissolved silica and calcium have a terrestrial origin.

The total quantity of dissolved material carried by the Ngoko averaged 1.23 10^6 t for the water-years 1989-1990 and 1990-1991. After atmospheric correction, calculated net flux is 1.14 10^6 t $year^{-1}$, i.e. a chemical erosion rate of 17 t km^{-2} $year^{-1}$. This value can be compared to the mechanical erosion rate above calculated, of 8.6 t km^{-2} $year^{-1}$. Net losses of dissolved silica (4.3 t km^{-2} $year^{-1}$) and bicarbonate (6.5 t km^{-2} $year^{-1}$) account for 60% of the total dissolved output. Total denudation rate (sum of chemical and mechanical erosion rate) is estimated at 25.6 t km^{-2} $year^{-1}$.

Table 8 Chemical mass balance between total precipitation and stream loads for the entire Ngoko basin (t km^{-2} $year^{-1}$).

		Ca	Mg	Na	K	Cl	SO4	NO3	SiO2
INPUT		0,26	0,29	0,37	0,19	0,49	1,24	0,24	0,43
OUTPUT		1,27	0,62	0,43	0,47	0,45	0,61	0,26	4,74
LOSS		1,01	0,36	0,06	0,28			0,02	4,31
GAIN						0,04	0,63		
SOURCES	ATMOSPHERIC (%)	20	46	86	40	108	203	92	9
	TERRESTRIAL (%)	80	54	14	60	0	0	8	91

CONCLUSION

The Ngoko basin in Cameroon, essentially forested and, up to now, pristine, constitutes an interesting model to study the natural biogeochemical processes in equatorial ecosystem. The hydrological balance, the mechanical and chemical weathering processes are greatly influenced by the forested cover. The chemical erosion rate characterizes the weathering of the equatorial environment. After correction of atmospheric inputs, the chemical erosion represents 66% of the total denudation rate.

If we consider the Ngoko ecosystem in equilibrium with actual climatic conditions, the soil deepening rate can be estimated at 6.4 mm per 1000 years (mean specific gravity of metamorphic rocks is 2.65) and the surficial erosion rate by scouring at 4.3 mm per 1000 years (mean specific gravity of soils is 2.0).

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Incidences de l'instabilité des ressources en eau sur la gestion d'un système d'eau aménagé. Cas du Sassandra en Côte d'Ivoire

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Résumé Après avoir constaté la diminution des ressources en eau de surface observée depuis une vingtaine d'années en Afrique de l'Ouest, on décrit les aménagements projetés sur le bassin du Sassandra, zone d'étude retenue. Les méthodes utilisées pour générer les chroniques de deux cents ans d'apports aux différents ouvrages sont ensuite présentées. Ces chroniques permettent de procéder à des simulations de fonctionnement sur de longues durées dans des cas de figures correspondant aux contextes climatiques observés avant et depuis la sécheresse de la fin des années soixante. Les résultats montrent une nette baisse des performances du système d'eau en relation avec les conditions qui règnent depuis le début de la sécheresse. Les conclusions tirées de ces comparaisons et analyses mettent en évidence que, si la situation actuelle devait se prolonger en Afrique de l'Ouest, les ressources en eau de surface ne seraient plus en correspondance avec des besoins déterminés et planifiés à partir de chroniques de données présentant des caractéristiques différentes de celles observées aujourd'hui. Les fréquences de défaillances seraient alors beaucoup plus élevées provoquant d'importantes chutes de production des aménagements réalisés. Les modifications apportées au fonctionnement du barrage de Buyo sont également analysées.

INTRODUCTION

L'activité économique de la Côte d'Ivoire est principalement liée à l'agriculture, et à un degré moindre à une relative industrialisation dont l'énergie est tirée à 60% de l'hydroélectricité. C'est dire l'importance considérable que revêt la disponibilité des ressources en eau. Parallèlement, les études réalisées dans les domaines de l'aménagement et de la gestion de cette ressource tablent, en général, sur l'hypothèse de stationnarité des chroniques de données climatologiques et hydrologiques. Or, l'analyse de ces données (Sircoulon, 1990) montre qu'en certains endroits, et en Afrique de l'Ouest en particulier, cette hypothèse pourrait ne plus être vérifiée; les effets tangibles en étant la persistance des déficits pluviométriques aux conséquences dramatiques. Une telle instabilité, si elle se vérifie, pose alors le problème de ses conséquences sur les performances des équipements et conduit à envisager une nouvelle démarche en matière de planification des aménagements et de gestion de la ressource. En nous basant sur les projets agricoles et hydroélectriques envisageables à moyen terme sur le bassin du Sassandra en amont de Buyo, aujourd'hui très faiblement équipé, nous avons cherché à évaluer quelle pourrait être l'incidence de cette instabilité des ressources en eau sur le fonctionnement d'un système d'eau aménagé.

SCHEMA D'AMENAGEMENT RETENU ET DONNEES GENEREES

Schéma d'aménagement retenu pour le bassin du Sassandra

Le bassin versant du Sassandra en amont de Buyo, importante retenue de quelques 9 milliards de m^3 à vocation exclusivement hydroélectrique, couvre près de 45 000 km^2. C'est une zone qui, aujourd'hui encore, est très faiblement aménagée et dont les données hydrométriques disponibles peuvent être considérées comme représentatives de l'état naturel. A partir des reconnaissances de sites de retenues qui avaient été effectuées par EDF dans les années 1970, et des projets de développement envisageables à moyen terme, nous avons élaboré un schéma réaliste d'aménagement hydraulique de cette région.

Le nord du bassin, situé en zone de savane et pour lequel on observe une saison des pluies unique est une zone à vocation agro-pastorale. Les trois ouvrages que nous y avons situés sont donc de capacité relativement réduite et à utilisation principalement agricole. Le Sud du bassin, quant à lui, est déjà en zone de forêt et présente deux saisons des pluies dans l'année. Les aménagements retenus pour cette zone sont d'une dimension beaucoup plus importante, et à vocation hydroélectrique en priorité.

Le Tableau 1 présente les différentes caractéristiques et contraintes de gestion de ces ouvrages. Un premier essai avait été effectué avec un barrage supplémentaire

Tableau 1 Caractéristiques du système d'eau aménagé.

Retenue	Capacité (Mm^3)	Module interann.	Objectif	Débit réservé	Besoins en irrigation	Production hydroélectrique
1	62	5 m^3 s^{-1}	Agricole	0.32 m^3 s^{-1}	12000 ha soja en amont	-
2	32.5	35 m^3 s^{-1}	Agricole	2.3 m^3 s^{-1}	10000 ha de canne à sucre en amont	-
3	30	65 m^3 s^{-1}	Agri/Elec	3 m^3 s^{-1}	500 ha de riz 2 cultures/an 250 ha vivrier	2 turbines $Q = 40$ m^3 s^{-1}
5	5000	247 m^3 s^{-1}	Electricité	10 m^3 s^{-1}	-	2 turbines $Q = 160$ m^3 s^{-1} turbinage continu
6	1450	65 m m^3 s^{-1}	Agri/Elec	3.5 m^3 s^{-1}	1000 ha de riz 200 ha vivrier	2 turbines $Q = 50$ m^3 s^{-1}

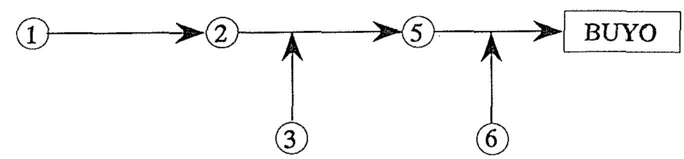

Fig. 1 Relations fonctionnelles des différents ouvrages composant le schéma d'aménagement retenu pour le bassin du Sassandra en amont de Buyo.

portant le numéro 4, mais cette hypothèse, peu réaliste, a été abandonnée. Par contre, la numérotation des retenues n'a pas été modifiée par la suite. Les relations fonctionnelles des ouvrages, entre eux, ont été représentées en Fig. 1.

Données générées

Pour simuler le fonctionnement de ce système d'eau, nous avons été amenés à générer deux séries de deux cents ans de données décadaires de pluies et de débits en différents points du bassin versant, correspondant à cinq postes pluviométriques du réseau ivoirien et aux stations hydrométriques contrôlant les sites potentiellement aménagés. La génération de ces données a été précédée d'une étude visant à confirmer l'instabilité des chroniques de précipitations et à fixer l'année de la "rupture" observée dans ces séries chronologiques. Nous étions alors en mesure de générer une série de deux cents ans ayant les caractéristiques observées avant cette date, et une autre série, de même longueur, représentative de ce qui est observé depuis.

Etude de l'instabilité des séries pluviométriques Les travaux de Nicholson *et al.* (1988) permettent d'apprécier commodément les variations pluviométriques depuis le début du siècle en zone sahélienne, en s'appuyant simplement sur les écarts

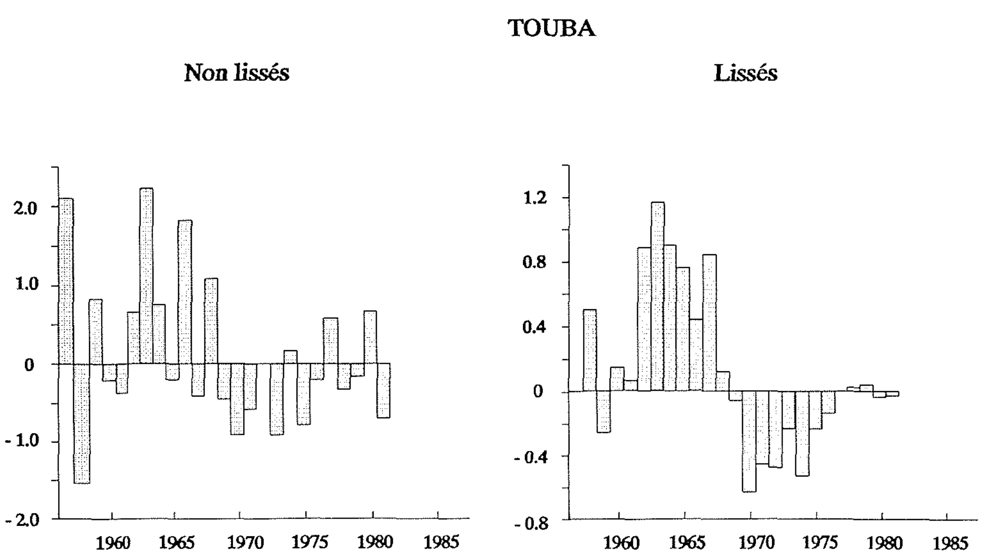

Fig. 2 Indices pluviométriques réduits $((x_i - x)/s)$ à la station de Touba.

pluviométriques annuels standardisés. Nous avons utilisé la même méthode pour tenter de détecter une éventuelle rupture des séries climatiques dont nous disposons et qui concernent les postes d'Odiénné, Man, Touba, Guiglo et Duékoué dont la période d'observation commune débute en 1957. Sur la période 1957-1987, nous avons donc calculé pour chaque poste et annuellement, la variable $(x_i - x)/s$ (x_i: pluviométrie de l'année i; x: pluviométrie annuelle moyenne; s: écart-type). L'examen des tracés qui en résultent fait apparaître des "ruptures" qui varient entre 1968 et 1971. Ces ruptures apparaissent plus nettement encore lorsque les variables sont lissées par l'utilisation d'une moyenne mobile. La Fig. 2 présente, à titre d'exemple, le cas de la station de Touba. A l'issue de cette étude, nous distinguerons donc la période "avant 1969" et la période "après 1969", ce qui est en accord avec les résultats présentés par Sircoulon (1990) et Hubert *et al.* (1989).

Génération de la pluviométrie décadaire Notre objectif n'était pas de mettre au point un modèle stochastique complet de génération de chroniques de données pluviométriques décadaires, mais de fabriquer des chroniques d'apports réalistes. Nous avons donc opté pour une procédure simplifiée dont les résultats se sont montrés suffisamment représentatifs.

Pour chacun des postes pluviométriques, une loi des fuites a été ajustée pour chaque décade à partir des données observées. Puis, par tirage au hasard dans ces différentes lois ajustées, nous avons généré deux cents ans de pluviométrie décadaire. De manière à conserver au système une certaine cohérence (une année à tendance sèche est ressentie de façon à peu près identique sur l'ensemble de la région, et il en va de même pour les années pluvieuses), ce sont les mêmes séries de nombres tirés au hasard qui ont été utilisées en chacun des postes pour générer les chroniques de données par tirage dans les lois des fuites. De même, pour respecter l'alternance des périodes sèches et humides et n'avoir à juger que de l'incidence de la diminution de la ressource, les mêmes séries ont été utilisées "avant 1969" et "après 1969". En procédant ainsi, nous avons obtenu des séries générées dont les caractéristiques sont très voisines des séries observées tout en offrant un éventail de situations variées (Sakho, 1991).

Génération des apports naturels aux stations hydrométriques de référence Disposant des séries pluviométriques générées, nous avons choisi de représenter la relation pluie-débit à l'aide de modèles autorégressifs et corrélatifs, fonctionnant au pas de temps décadaire. Les coefficients de corrélation des différentes équations établies pour générer les chroniques de débits étaient tous supérieurs à 0.80, voire à 0.90 pour les stations aval du Sassandra, ce qui est satisfaisant au vu des objectifs visés par cette étude.

L'ensemble des hypothèses qui ont été faites, tant au niveau de la génération des pluies qu'au niveau des débits n'a pas pour effet de "dénaturer" le régime des eaux au point de lisser les écarts ou au contraire de créer des différences fictives. Elles permettent, en fait, de reconstituer des chroniques "plausibles", qui sont compatibles avec ce que l'on connaît, et qui se résume à une information pluie-débit concomitante très réduite.

LE MODELE DE SIMULATION DE FONCTIONNEMENT

Le modèle de simulation de fonctionnement du système d'eau aménagé doit prendre en compte, essentiellement, deux types de besoins, tout en tenant compte d'un débit garanti aval:

(a) Irrigation: en amont de la retenue (le pompage est alors effectué directement dans la retenue), ou en aval de la retenue avec, cette fois, un pompage au fil de l'eau dans le bief aval.

(b) Hydroélectricité: certaines des retenues envisagées devant en effet être équipées de turbines.

En établissant un bilan complet sur chacune des retenues, le modèle doit être en mesure de fournir, à chaque pas de temps (donc à chaque décade), l'état de chacun des ouvrages et les niveaux de satisfaction des différentes contraintes de gestion. Il sera alors possible de mettre en évidence et de mesurer l'incidence de ressources en eau moins abondantes sur les performances de ces ouvrages en établissant, par exemple, des comparaisons en terme de défaillances.

Organisation générale et fonctionnement du modèle de simulation

Nous ne donnerons ici qu'une rapide description de l'organisation du modèle, décrit par ailleurs (Sakho, 1991). A chaque pas de temps, les six retenues sont traitées successivement, de l'amont vers l'aval. Pour un ouvrage donné, le modèle effectue un bilan complet des entrées-sorties sur la retenue au pas de temps considéré. Il détermine, selon les cas, les volumes fournis à l'agriculture amont, la lâchure (qui est la somme du débit garanti et du volume fourni par l'agriculture aval), les éventuels débordements et la production électrique. A l'issue de cet ensemble de calculs, on connaît l'état de la retenue (c'est à dire la cote du plan d'eau) à la fin du pas de temps.

ANALYSE DES REPONSES DU SYSTEME D'EAU AMENAGE AUX SIMULATIONS DE FONCTIONNEMENT

Le fonctionnement du système d'eau aménagé a été simulé au pas de temps décadaire durant deux cents années dans les conditions de type "avant 1969" et après "1969". L'analyse des résultats s'est effectuée selon des niveaux de complexité et de détails croissants:

(a) analyse globale des réactions du système dans chacun des cas,

(b) analyse globale par ouvrage,

(c) analyse de quelques cas particuliers de défaillances.

Notre étude nous a également conduits à considérer l'impact de l'aménagement de ce système d'eau sur le barrage de Buyo existant, à vocation hydroélectrique, et dont le fonctionnement est aujourd'hui satisfaisant.

Analyse globale des réactions

Le modèle de simulation permet de calculer les apports à chaque retenue en l'état aménagé du système d'eau pour chacune des situations. Les différences sont très marquées et, bien entendu, à l'avantage de la série "avant 1969". Elles s'accroissent en valeur absolue avec la superficie des bassins, et du Nord vers le Sud. Sur les barrages 5 et 6, ces écarts entre apports "avant 1969" et "après 1969" peuvent atteindre jusqu'à plusieurs centaines de millions de m^3 par an. Les volumes annuels de déversement s'inscrivent également dans la logique de la diminution de la ressource "après 1969", puisque les débordements constatés pour cette simulation sont systématiquement les plus faibles. Dans le cas du barrage 6, par exemple, on n'y observe pratiquement jamais de déversement alors qu'ils oscillaient régulièrement autour de 150 millions de m^3 par an "avant 1969". L'algorithme utilisé permet d'estimer, par une méthode simplifiée (Sakho, 1991), des volumes de pertes dans le bief situé en aval de la retenue. Elles apparaissent plus importantes pour la série "après 1969" que pour la série "avant 1969", et ce pour les barrages à faible capacité (barrages 1 et 2), indiquant par là que la diminution des ressources induit une baisse du niveau des lâchures au sens large; ce qui entraîne une diminution des volumes qui transitent dans les biefs situés en aval des retenues à faible capacité. Ces pertes restent cependant relativement faibles en valeur absolue.

Analyse des défaillances au regard des contraintes

Satisfaction de la demande agricole L'évaluation des performances du système par rapport à cette contrainte est faite à partir des moyennes décadaires des 200 années de simulation et exprimée en pourcentage de satisfaction. Les ouvrages du nord du bassin (1, 2 et 3), dont la vocation est hydro-agricole, présentent des défaillances vers fin mars/début avril. Ces défaillances prennent beaucoup d'ampleur pour la série des apports "après 1969". Les retenues situées en tête de bassin ont des réactions brutales à la diminution des apports, la cote du plan d'eau chutant très rapidement. Cela est dû à la faible capacité de ces ouvrages, ce qui ne leur permet pas de jouer un rôle tampon lorsque les apports diminuent au plus fort de la saison sèche.

Débit garanti La satisfaction de la contrainte débit garanti est liée à celle des besoins agricoles. Cependant, le niveau de défaillance est moindre (seuls les barrages 1 et 2 montrent des défaillances) dans la mesure où ,dans le modèle de simulation, une priorité a été affectée au débit garanti par rapport aux besoins hydro-agricoles. La gestion de la pénurie se fait donc au détriment de l'agriculture, mais plus sévèrement "après 1969" qu'"avant 1969".

Production hydroélectrique La production d'hydroélectricité est grande consommatrice des ressources en eau. Par comparaison avec l'agriculture, on peut donc s'attendre à une plus grande sensibilité du système face à la diminution des ressources. Sur les trois barrages équipés de turbines (3, 5 et 6), des déficits de production hydroélectrique apparaissent de façon beaucoup plus accentués dans la période "après 1969". Le barrage 3 a la production la plus stable et la plus proche de son niveau nominal tout au long de l'année. En effet, c'est de janvier à fin mars, que l'on assiste aux défaillances de cet ouvrage qui peuvent atteindre 25% sur la période "après 1969" au plus fort de la saison sèche, alors qu'elles dépassent à peine 10% "avant 1969". Le barrage 5 présente une baisse de performance systématique, de

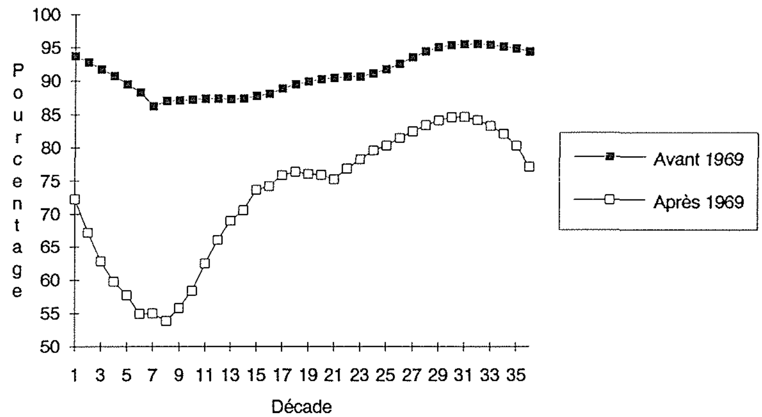

Fig. 3 Niveau moyen décadaire de satisfaction de la production électrique pour le barrage 6 (niveau nominal 100%).

l'ordre de 5% en moyenne par décade sur toute l'année, de la série "après 1969" par rapport à la série "avant 1969". Le barrage 6 illustre, quant à lui, le cas le plus criant de contre-performance due à la diminution de la ressource (cf. Fig. 3). "Avant 1969", la production est plus ou moins constante et se situe autour de 90% de satisfaction de la contrainte hydroélectrique. "Après 1969", à la fin de la saison sèche, on se trouve, en moyenne, à peine à 55% de satisfaction de la production décadaire nominale, ce qui représente un déficit de l'ordre de 30% par rapport à la série d'"avant 1969". En outre, la courbe de production hydroélectrique de la série "après 1969" ne dépasse que très rarement les 80% de la production nominale. On observe également, et toujours pour cette série, aux alentours de la 21ème décade, une légère diminution de la production, conséquence de la petite saison sèche qui s'observe dans le Sud du pays. De plus, la production montre une grande variabilité tout au long de l'année, pouvant atteindre une amplitude de 25% entre les valeurs les plus basses et les valeurs les plus élevées, alors qu'elle n'est que de 10% "avant 1969".

Etude de quelques défaillances particulières

Nous nous sommes particulièrement intéressés à certaines années des séries chronologiques générées afin de tenter de mieux appréhender les situations pouvant conduire à des défaillances du système. Elles ont été choisies parmi celles qui présentent le plus grand nombre de décades défaillantes consécutives, ce qui a pour effet d'augmenter leur sévérité. Cette étude était possible dans la mesure où le système que nous avons mis en place offre "avant 1969" et "après 1969" les mêmes successions d'années sèches et humides du fait de la génération des données à partir des mêmes séries de nombres au hasard. Cette analyse a montré (Sakho, 1991) que pour les barrages à faible capacité la différence est très minime qui fait passer d'une situation satisfaisante à une défaillance. Généralement la chute est brutale, les retenues ne pouvant jouer un véritable rôle de tampon. En cas d'apports déficitaires prolongés, la situation persiste, occasionnant principalement de sérieuses difficultés à l'agriculture irriguée. Pour les barrages à capacité plus importante, la progressivité des défaillances est plus accentuée, les retenues pouvant compenser quelques temps la faiblesse des apports. Cependant, aucun seuil d'apports minimum sur une période donnée, en dessous duquel se produisent rupture et défaillance, n'a pu réellement être mis en évidence.

Impact de l'aménagement amont sur Buyo

La réalisation d'un aménagement du type de celui que nous venons de décrire pourrait avoir un sérieux impact sur le fonctionnement du barrage de Buyo (9 milliards de m^3 et un productible garanti de 610 GWh). Les apports de cette retenue avaient été évalués à partir des données des stations du N'Zo à Guiglo et du Sassandra à Guessabo sur la période 1955-1974, c'est à dire avant la période de sécheresse. Dans le cadre du système d'eau aménagé, les sorties des barrages 5 et 6 correspondent respectivement à ces deux stations. Ne disposant pas des consignes de turbinage propres à Buyo, nous n'avons pas pu évaluer l'impact de l'aménagement à partir de la production électrique correspondant aux différents cas envisagés: pas d'aménagement amont, aménagement amont et apports type "avant 1969", aménagement amont et apports type "après 1969". Nous avons donc fait porter la comparaison sur les apports, cherchant à évaluer et à chiffrer l'impact de l'aménagement sur la régularité et l'abondance des ressources disponibles pour Buyo dans les différents cas de figure.

Les apports au barrage de Buyo, issus des aménagements, ont été calculés pour les années décennales sèches et humides (cf. Tableau 2). Ils ont ensuite été comparés aux conditions moyennes de fonctionnement de Buyo. L'aménagement du bassin versant du Sassandra en amont de Buyo entraînerait d'une manière générale une forte diminution de la variabilité des apports annuels, ce que confirment les Figs 4 et 5. La série de type "avant 1969" entraîne, en effet, une nette régularisation des apports mensuels, en particulier en saison sèche, pour un niveau de performance global comparable, voire légèrement supérieur, à celui de l'état naturel. La série de type "après 1969" conduit, quant à elle, à un déficit d'apports de près d'un milliard de m^3 en année moyenne, ce qui ne serait pas sans conséquences sur le fonctionnement de l'ouvrage. Cette analyse de l'impact sur Buyo montre l'incidence que pourrait avoir, sur des aménagements déjà existants, une sécheresse qui irait en se prolongeant.

CONCLUSION

Cette étude menée à partir d'une situation réelle, s'est appuyée sur la nette diminution des ressources en eau constatée depuis la fin des années 1960 dans toute la zone intertropicale africaine. L'exemple choisi pour en mesurer l'impact a le mérite de figurer au nombre des futurs projets d'équipement de la Côte d'Ivoire, ce qui lui confère une forte connotation d'utilité dans le cadre de la gestion des ressources naturelles ivoiriennes.

Certes, pour pallier l'absence de données, des moyens qui ont pu paraître audacieux ont été utilisés (génération de la pluviométrie, modélisation pluie-débit); leur pertinence est peut-être discutable, mais en l'occurrence, la rigueur la plus absolue a dû laisser la place à la nécessité.

Tableau 2 Apports annuels à Buyo, en milliers de m³, pour différents cas de figure.

	Apports moyens annuels (Mm^3)	Année décennale humide (Mm^3)	Année décennale sèche (Mm^3)
Situation naturelle	9681	14 037	6100
Situation aménagée "avant 1969"	9858	11 528	8468
Situation aménagée "après 1969"	8790	9732	7594

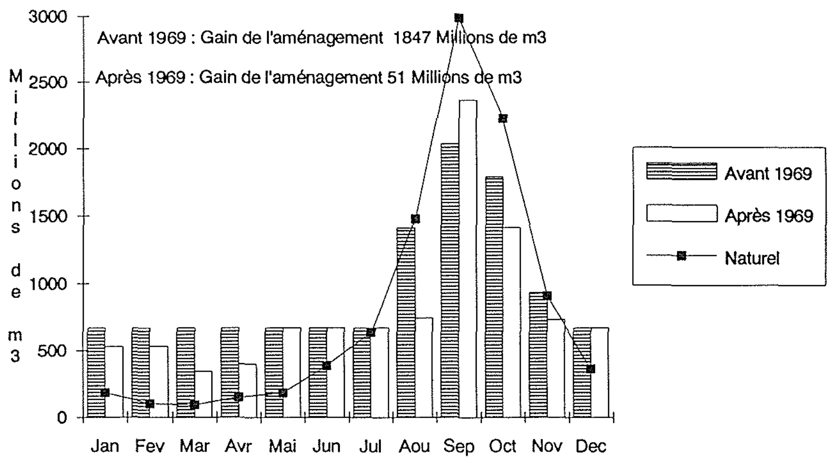

Fig. 4 Apports, dans le barrage de Buyo, de l'année décennale humide en situation de système d'eau aménagé comparés aux apports "naturels" moyens.

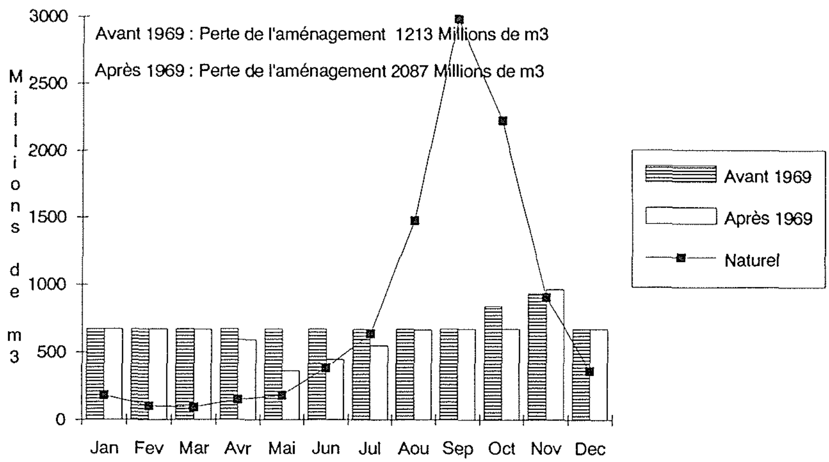

Fig. 5 Apports, dans le barrage de Buyo, de l'année décennale sèche en situation de système d'eau aménagé comparés aux apports "naturels" moyens.

On a alors pu montrer que la diminution des ressources, comme on l'obverse depuis la fin des années 1960, entraîne des défaillances plus sévères et plus longues au regard de contraintes qui, par contre, sont satisfaites lorsque les chroniques d'apports ont les caractéristiques des séries observées avant 1969. Ainsi, bien que la pluviométrie reste plus abondante et mieux répartie que plus au Nord en région sahélienne, la zone forestière humide présente, elle aussi, des situations critiques vis-à-vis de ressources en baisse, reflet de la tendance climatique générale observée aujourd'hui dans toute la région. Si la situation actuelle devait se prolonger en Afrique de l'Ouest, les ressources en eau de surface ne seraient plus en correspondance avec des besoins déterminés et planifiés à partir de chroniques de données présentant des caractéristiques différentes de celles observées aujourd'hui. Les fréquences de défaillances seraient alors beaucoup plus élevées provoquant d'importantes chutes de production des aménagements réalisés.

Au vu de ces fluctuations et des difficultés d'adaptation présentées par les ouvrages, il faudrait pouvoir développer une réflexion allant dans le sens d'une conception dynamique des systèmes d'eau qui intégrerait, en partie, cette instabilité. On s'orienterait, ainsi, vers une reformulation de la notion de "normes hydrologiques" dont le caractère figé apparaît aujourd'hui comme un sérieux handicap à la réalisation de nouveaux aménagements.

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Impacts of floods and drought on the development of water resources of Kenya: case studies of Nyando and Tana catchments

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Abstract With the rapidly growing population in Kenya at an estimated rate of 3.63% per annum and the resultant high rate of urbanization coupled with the fact that 75% of the country is either arid or semiarid, the proper management and therefore planning for water resources development is vital in order to maintain the use of water on a sustainable basis. The proper management and planning for the use of water resources calls for the evaluation of the water resources available within the country and the degree to which they can be exploited. This paper examines the magnitude of the problems of drought (water deficit) and floods (water surplus) within two catchment areas in Kenya: the Nyando and Tana. It is shown that, apart from meteorological and/or climatological factors, man has greatly influenced the severity of the two events within the study catchments. The anthropogenic influences such as large-scale deforestation programmes, damming of the rivers, urbanization and other development programmes, have to a large extent affected the return periods of these two events within the catchments. Various programmes that could be adopted in reducing the magnitude and/or severity of the two events have been suggested. Drought has been identified particularly with eastern Kenya which is comprised mainly of semiarid low-lying land, and the pastoral areas of northern and southern Kenya. Recently attention has been paid to climatic variability in the dry areas near Lake Victoria, settlement schemes in the Rift Valley and the coast province where too much rainfall and poor soils compound the problems. Flooding is particularly characteristic of western Kenya in the Lake Victoria drainage basin, the Lower Tana and Athi River reaches and more recently the city of Nairobi is showing increased vulnerability to floods.

SOCIAL ECONOMIC BACKGROUND

Kenya has an area of about 580 000 km^2 located on the equator lying in between the Indian Ocean and Lake Victoria. The country has between 10 and 12% high potential agricultural areas mainly in the Central and Western highlands of where the crops grown include maize as the staple crop and coffee and tea as the main cash crops. Most of the remaining parts in the northern district, southern Rift Valley and the eastern highlands which is either arid or semiarid is used by nomadic or semi-nomadic pastoralists and about 5.5% of the land area is devoted to National parks.

The country's population is concentrated around the high potential agriculture areas, but the population of the country is growing so rapidly such that its expected to reach 37 million in the year 2008 as opposed to the present 24 million, and thus people have been forced to move into the marginal areas.

RAINFALL PATTERNS IN KENYA

The average rainfall in Kenya varies from less than 100 mm to over 2000 mm on Mt Kenya. Most of the country experiences two rainy seasons, the long rains between March and May and the short rains between October and December.

The weather in most of East Africa is related to the large-scale atmospheric circulation. Some of the synoptic features that influence the weather in this region include the inter-tropical convergence zone (ITCZ), easterly waves, tropical storms, low-level troughs, jet streams and extra-tropical weather systems (Downing *et al.*, 1989).

In sub-saharan Africa the drought years are accompanied by increased subsidence and decreased low-level convergence, decreased moisture flux and reduced upper-level easterlies flow into the region. In East Africa, anomalies in the wind field were related to the abnormally wet conditions of 1961 and abnormally dry 1984. Kenya seems to depend greatly on moisture advection encouraged by the circulation systems in the Indian ocean and central Africa as well as convective processes brought about by the ITCZ and unstable conditions from the west. The two rainfall seasons in Kenya are controlled mainly by the southward and northward movement of the sun. The sun is over the equator approximately in March. Due to high temperatures the equatorial region forms a low pressure belt, coinciding approximately with the intertropical convergence zone which is formed a month later; hence the high rainfall over most of Kenya in April. The spatial variation in rainfall is mostly a product of topography, distance from the Indian ocean and Lake Victoria at the heart of East Africa.

The formation of the tropical convergence zone results in the convergence of southeasterly and northwesterly winds alternatively tumultuous and poorly organized. The result is vertical movement of air leading to condensation and precipitation.

The seasonal rainfall patterns dependent on the ITCZ are usually modified by anomalies in the semi-permanent anticyclones. Development of tropical storms may introduce such anomalies. Tropical cyclones typically occur from November to April in the southern Indian Ocean.

AN OVERVIEW OF THE FLOOD AND DROUGHT SITUATION

Major floods in certain low-lying parts of the Lake Victoria catchment and Tana basin in particular occurred in March 1925, 1937, 1947, 1951, 1957, 1958, 1961, 1962 and 1978. In the Lake Victoria basin there has a major flood annually or twice annually since 1982, suggesting that the flood situation is worsening.

Among the floods mentioned above, the exceptionally heavy rainfall of 1961 resulted in unusually severe floods in many areas of Kenya. The floods covered large areas of the Kano Plains, Yala swamps and other low-lying areas of the lake basin. Lake Victoria rose by 1.25 m in 1962 over that of the previous year. The lake water level actually started rising in November 1961 and reached its peak in 1964.

The worst drought occurred in the period 1933-1934 in central Kenya while the second worst was in 1942-1944. In the last two decades severe droughts occurred in 1971-1975 and 1981-1985. Both climatological records and oral knowledge show that major droughts with serious results to man, livestock and game occurred in 1928, 1933, 1934, 1942, 1944, 1952, 1955-1960.

THE NYANDO CATCHMENT

The Nyando River runs a total length of 170 km and drains a total catchment area of 3618 km^2. The flood zone lies in the lowlands of the Lake Victoria drainage basin, and forms part of the lake shore lowlands and lies within the Nyanza rift valley in what is known as the Kano Plains. Most of these flood plains lie between 1120 and 1150 m. In terms of climate the Nyando catchment can be divided into two major regions by temperature and rainfall characteristics. The highland source regions receives an annual average of about 1835 mm; the mean annual maximum temperature is 27°C, the mean annual temperature about 9°C. The lowland region forming the flood plain receives a mean annual rainfall of about 1000 mm with great variability, the mean annual maximum temperature being about 30°C and a mean annual minimum of about 18°C.

Ojany & Ogendo (1986) state that rains in western Kenya are partly due to the unstable Congo airstream and partly from convection thunderstorms associated with breezes introduced by the pressure of Lake Victoria and augmented by the Congo airstream.

The differences in climatic conditions between the lowland surrounding Lake Victoria and highlands beyond are mainly a consequence of the topographic differences. The lowlands lie in the rain shadow of the highlands on the eastern shoulder of the rift valley. By the time the winds descend the rift valley scarp they are relatively dry. Most of the flood waters of the Nyando River originate in the highlands. The soils are generally medium to heavy clays which have a low infiltration capacity. The main activity here is arable agriculture with irrigation schemes for rice, maize, and sorghum as the main crops.

THE FLOOD OCCURRENCE

In March 1925 very heavy rains occurred and many homes were abandoned. The situation did not last long and after a few years life returned to normal along the shores of lake Victoria. The real trouble started with the rains of 1961. Since then the lake level has remained relatively high at approximately 1136 m which combined with the peak flood of 1963, 1968, 1977, 1979 and 1985 have had the cumulative effects of turning lands at the deltas of the river into permanent swamps. The amount of flood water in the river is related to the amount of rainfall received by the catchment area. The flood is, however, not so much due to the amount of discharge carried by the river but more to do with capacities of different sections of the river. Overtopping of the banks occurs at fairly low discharges at sections which have low capacity . In the case of Nyando, the channel capacity is frequently exceeded in the lower 30 km, but most seriously in the last 8-12 km from the lake.

ADJUSTMENT TO FLOODING IN THE NYANDO CATCHMENT

It is estimated that between 1963 and 1964, 8000 ha were flooded in the Kano Plains. Most of the plain suffers from impeded drainage. The mean lost production per year for the crops has been estimated at US $1.3 million because of flooding and impounded drainage (Lake Basin Development Authority, 1986). The total area of the Kano plains is about 70 000 ha out of which 28 500 ha are cropped. The total value of production is estimated at US $3.5 million. Flood control may release the remaining over 40 000 ha for annual cultivation and increase the agricultural income nearly three times. The floods normally occur annually. The cost of moving people from one area to another and of other relief efforts is quite high. During such events public institutions have to be closed down.

It can be stated therefore that flood control would result in direct economic savings and would greatly enhance the general welfare of the population living in the Nyando River basin region.

Studies by Denga(1990) showed that most of the response by the affected public is in terms of reinforcing the buildings to withstand the flood waters. This include raising the floor and building barrages outside the houses, and digging diversion canals round the houses. It is, however, accepted that moving away from the flood plain during such events is a must and the houses are mainly reinforced so that on their return of the occupants, they will still be there. Denga (1990) found that the people continued to occupy the flood plain as all or most of their economic activities were centred there – including fishing, irrigated rice cultivation and other cultivation. Other factors which affect individual adjustment include income levels, hazard exposure and levels of education.

The institutional response from the central Kenya government has been coordinated mainly by the Lake Basin Development Authority set up in 1978. Studies by Alexander Gibbs and Partners 1954-1956 and 1961-1962 led to the establishment of two rice irrigation schemes: Ahero and West Kano pilot schemes.

The National Irrigation Board, after experiencing some flooding of the Ahero Scheme, constructed some flood protection bounds on the Nyando side. The West Kano pilot scheme was built in the form of a polder right from the start for flood protection purposes.

The Ministry of Agriculture has implemented two projects with assistance from the EEC and the Dutch Government aimed at protecting land for irrigation.

There is also a flood control unit of the Ministry of Water Development which is constructing flood protection dykes along the Nyando River. A larger scale project is in plan and will involve the construction of flood protection works consisting of following:

(a) Construction of flood protection dykes over a total length of 24 km of the River Nyando on both banks increasing its height at a later stage.
(b) Earlier investigations proposed five storage sites within the Nyando sub-catchment with a total storage capacity 80 million cubic metres. However no systemic studies

of sedimentation rates have been taken. This is important because high rates of sedimentation would reduce the economic life of these reservoirs. It is to be observed here that an important element in flood studies is the quantification of land use changes in the highland catchments and the relationship of these to the increasing flood frequency on the Nyando catchment. It is in this connection that flood control should emphasize within channel measures. It is necessary to emphasize adjustments of non-structural approaches.

DROUGHT INCIDENCE, TRENDS AND PREDICTION

Table 1 shows the major drought occurrences and the areas in which they occurred. Table 2 shows seasonal drought probabilities in two towns within the Tana catchment.

Impacts of drought in the Tana catchment

The lower Tana catchment is essentially a grazing area with low rainfall totals as has already been discussed before. Drought affects the hydrology of the area. With decreasing rainfall, surface runoff becomes sparse, subsurface water is not recharged and the local aquifers become dry. The pastoralists concentrate their livestock near the reliable water sources such as boreholes. These areas are already under a high grazing pressure. During drought the water levels fall and crops under irrigation are affected. In some instances, the area cultivated is reduced. In other cases irrigation is halted and all the water available is used for domestic purposes. Essential food commodities such as maize, beans and flour become scarce and sell at exorbitant prices. Many of the livestock (cows and goats) die, while others have to be sold for cash for food or school fees (Downing *et al.*, 1989).

Table 1 Droughts in Kenya.

Year	Region
1883	Coast
1889-1890	Coast
1894-1895	Coast
1896-1900	Extended over most of East Africa
1907-1911	Lake Victoria area, Machakos, Kitui, coast
1913-1919	Ethiopia, Kamba Lands, coast
1921	Coast
1925	Kerio Valley, coast
1933-1934	Coast, Kikuyu Lands
1942-1944	Kenya, Uganda
1947-1950	Kikuyu Lands, coast
1952-1955	Kitui and other districts
1969-1961	Maasai Lands, Machakos Kitui, Rift Valley
1981	Eastern Province
1983	Coast, Kitui, Machakos, Meru, Kakamega, Nyanza.
1984	Kenya

Table 2 Seasonal drought probabilities.

	Machakos	Makindu
March-May (long) rains		
No. of years	91	81
Mild drought	0.25	0.43
Moderate drought	0.20	0.23
Severe drought	0.05	0.06
October-December (short) rains		
No. of years	90	80
Mild drought	0.49	0.56
Moderate drought	0.26	0.40
Severe drought	0.11	0.11

Source: Akanga *et al.* (1987).

Notes: Probabilities based on a normalized drought index:

No drought	DI > -0.2
Mild drought	DI ≤ -0.2
Moderate drought	DI ≤ -0.5
Severe drought	DI ≤ -0.8

where DI $= (P - X)/S$; P = seasonal precipitation; X = long-term average from that season; S = seasonal standard deviation of P.

Drought mitigation

One important solution to this problem was envisaged as water storage. Ongwenyi (1987) suggests possibilities of underground storage. It is important that this be looked at with long-term goals to solve desertification problems. Procedures have been developed by the Department of Resource surveys and remote sensing to predict crop yields mainly using aerial photography and radiometry. This is important in warning about expected yields in order to set mechanisms to offset the food shortages that may occur during droughts. The Central Bureau of Statistics (CBS) also runs an independent crop forecast survey. This is dependent on data collection from the district levels based on questionnaires to farmers and historical data. The monitoring system includes an agroclimate crop yield model, processing of data collected in crop forecast surveys, monitoring market prices, analysis of trends in health and nutrition and analysis of food flows reported by the National Cereals and Produce Board. The CBS forecasts are based on meteorological data such as: normal precipitation, actual precipitation, number of days of rainfall and potential evapotranspiration and water reserves in the soil.

The two case studies referred to above show that Kenya has a serious problem of water and precipitation distribution in both space and time. The Lake Victoria drainage basin has an annual and sometimes biennial flood problem. This water can be harnessed in a system of reservoirs. It could then be pumped through the western shoulders of the great Rift Valley and allowed to flow to the drylands from the eastern shoulders of the Rift Valley to the eastern part of the country which is more drought prone. This would increase the chances for irrigation and lessen the dangers of desertification and starvation in the arid and semiarid areas of Kenya. The complexity here is that the lake waters are international and are protected by riparian law.If proper quantification studies are made, however, it is believed this could be done without inconveniencing the riparian users and reduce the pressure on the marginal areas of the country being placed on them by the ever increasing population.

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Forest clearcutting and site preparation on a saline soil in East Texas: impact of element movement

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Abstract A study was conducted on a saline soil in the Davy Crockett National Forest near Apple Springs, Texas to monitor movements of 17 elements under three forest conditions, i.e. an undisturbed forest, a commercial clearcutting, and a clearcutting with stumps sheared and windrowed. Element losses were measured from runoff samples and sediment deposited in plot-watersheds (water years 1989-1990). Also, vertical water and element movement were monitored at four depths in the soil profile. Total concentrations (mg l^{-1}) of 17 elements in surface runoff were higher in the forested and cleared plots than that in the sheared plot. But, total element losses (kg ha^{-1}) were greater in plots with greater forest disturbances. Soil and soil-water electrical conductivity (EC) were greatly affected by the treatments. Differences in EC among the treatments were most significant first at the surface horizons, then gradually reaching the deeper horizons. Of the 17 elements in soil-water analysed, only the average concentrations of Na and Al were significant at the 0.05 alpha level. Calculated % Na ranged from 55 to 90% and was responsible for slow permeability of the study soil. None of the elements in the soil-water had a concentration high enough to cause adverse effects on plants.

INTRODUCTION

There are more than 120 000 ha of somewhat poorly drained, upland saline soils in central East Texas. The soils contain a high concentration of aeolian sediments deposited over impervious mudstone high in pyroclastic sediments. Vegetation is dominated by mature loblolly and shortleaf pines with scattered hardwood species. After clearcutting the forest, artificial pine regeneration on these soils is extremely difficult (three attempts in some areas). Examination of scattered pine seedlings naturally regenerated in clearcut sites show J-shaped root-systems at about 15 cm below the surface with little lateral-root development. It is not clear that if the poor root system along with mortality of pine seedlings in the clearcut are due to high water tables caused by the removal of vegetation, salt concentrations toxic to seedlings, nutrient imbalance near the surface, or combinations of the three.

Geographically, these saline soils lie between Sam Rayburn Reservoir in the northeast and Lake Livingston in the southwest. How surface runoff from these soils, especially in areas with no forest-cover protection, affect stream sediment and water quality is not known since no studies have been. The main objective of this research is to study the effects of forest harvesting and site preparation on soil physical and chemical properties along with soil, water and element losses on a poorly drained saline soil in East Texas. Such information is essential in developing artificial regeneration techniques for southern pine species and in nonpoint sources of water pollution management in the problem area. Results on sediment-loss have been reported by Chang *et al.* (1992); this report only deals with element movement.

METHODS AND PROCEDURES

Study area and treatments

The study was conducted during the water years 1989 and 1990 in the Davy Crockett National Forest near Apple Springs, Texas, about 200 km north of Houston and 250 km southeast of Dallas. The area has a humid subtropical climate with prevailing winds from the southerly directions. Precipitation recorded at the study site was 1245 mm for the 1989 and 1349 mm for the 1990 water year years, much higher than the normal (1951-1980) annual precipitation of 1054 mm observed at Lufkin Airport about 22 km northeast of the study area. The soil of the study site, with slopes ranging from 2-20%, is Fuller fine sandy loam, a member of the fine loamy siliceous, thermic family of Albic Glossic Natraqualfs. The saline nature of these soils was derived from volcanic ash blown from the Cook Mountain Formation during the Eocene epoch and deposited on siltstones or mudstones. Ocean water inundated the area and compacted the volcanic ash, and silty materials were blown from the west to settle on top of the compacted ash. Vegetation was dominated by loblolly (*P. taeda*) and shortleaf pines (*P. echinata*) with a mixture of hardwood species. Merchantable trees ranged from 30 to 55 years of age in 1988 with an average height 28.5 m, DBH 25 cm, site index 27 m, and basal area 21.81 m^2 ha^{-1}.

Three treatments were employed in the study: (1) undisturbed forest with full crown closure as a control, (2) commercial clearcut with all merchantable timber removed, other vegetation left intact, and (3) clearcut, all vegetation removed, stumps sheared with V-blade D6 crawler tractor, and debris windrowed, vegetation was prevent from regrowth, by shearing, with no disturbance to the soil for two years. All treatments were located within an area of 3.24 ha with each treatment separated by a small 1st-order drainage ditch, they all have the same soil (Fuller soil) and comparable environmental conditions in terms of vegetation, slope, aspect, and climatic characteristics. The size of each treatment was about 0.5 ha; the cutting was conducted on 23-24 July, and shearing on 26 August 1988.

Plot watersheds, measurements and chemical analysis

A surface plot, 9.14 m wide × 22.13 m long, was centrally located in each treatment to monitor surface runoff and soil and element losses generated by storms. Each plot was bordered by a plywood barrier 8 cm below and 7 cm above the ground surface.

At end of each plot, an apron, an approach section, a 15.4 cm H-flume, a stilling well equipped with an FW-1 automatic water-level recorder, a Coshocton N-1 runoff sampler, and a storage tank were sequentially connected together. The runoff sampler diverts about 1% of the surface runoff into a small storage tank with two compartments confined in the large tank for element concentration analysis. Samples of surface runoff were collected at the end of each storm for laboratory analyses. The determined element-concentrations in mg l^{-1} were later converted into element losses in g ha^{-1}.

Element vertical movement in the soil was examined by *in situ* measurement of soil electrical conductivity (EC) and the EC, pH, and concentrations of 17 other chemical elements of soil water, both at four depth levels in the soil profile. A set of four SCT soil salinity bedding sensors (Martek Instrument Inc., Irvine, California) was buried in the soil to provide *in situ* monitoring of apparent soil salinity conductivity (EC_a) at the 30, 60, 90, and 120 cm depths of each plot. The readings were taken weekly using a Martek SCT Module (Rhoades, 1978) and further converted into EC through a pre-calibration procedure conducted in the field (Sayok, 1991). Soil temperatures required to adjust EC_a readings from standard 20°C were obtained from a soil temperature sensor (Omega ON-401-pp thermistor) installed at each depth and monitored using an Omega 450 ATH thermistor thermometer. Missing soil temperature data were estimated using air temperature in a periodic regression model developed for the study sites (Juin, 1991). Samples of soil water required for laboratory analyses were obtained from a set of four soil water samplers (piezometers), Model 1900, Soilmoisture Equipment Corp., Santa Barbara, California, installed at the same four depth levels in each plot. Prior to installation, the ceramic cup of each piezometer was cleaned with soap and water, then soaked in 1 N HCl for two days and in distilled water for another two days. After that distilled water was sucked through each cup until pH of the water passing through the cup was stable. Soil-water in each piezometer was sucked into a container for laboratory analyses using a test hand-pump, Model 1900K, Soilmoisture Equipment Corp.

Chemical analyses of soil water included electrical conductivity (EC), pH, and 17 chemical elements. Of the 17 elements, nitrate, nitrite, ammonium, chloride, carbonate, sulphate, orthophosphate, and total Kjeldahl nitrogen were determined according to procedures given by Hach Co. (1984), bicarbonate by APHA *et al.* (1985), and cations Na, Ca, Mg, K, Cu, Fe, Zn, and Mn by Dewis & Freitas (1976). Electrical conductivity was determined by YSI Model 32FL conductance/temperature meter, pH was determined using glass-and-calomel electrode in 1:2 soil and water suspension solution (Peech, 1965).

RESULTS AND DISCUSSION

Element concentration in surface runoff

Losses of elements in surface runoff may come from three sources: deposited, suspended, and dissolved, and the sum of dissolved and suspended elements contribute to element concentration in surface runoff. During the first treatment year (October 1988-September 1989) the surface-runoff concentrations of all 17 elements were higher in the clearcut and undisturbed forest plots than that in the sheared plot. For individual elements, however, only concentrations of dissolved HCO_3 and Na in the forest plot were significantly higher than the sheared plot at the 0.05 alpha level. Higher element concentration in the undisturbed forest than that of the clearcut and sheared plots was probably due to the effects of leaching of ions from the vegetation and forest floor. On the other hand, greater runoff caused by the reduction in evapotranspiration may have diluted element concentrations in the sheared plot.

In the second year, the element concentrations were generally lower than that in the first year. Precipitation in the second year was about 10% greater than the first year which caused surface runoff 44%, 72%, and 320% greater in the sheared, clearcut, and undisturbed forest plots, respectively. The lower concentrations in the second year might have caused by dilution effect of surface runoff. Among concentrations of the 17 elements, the deposited sources of Al, Mn, and Cl were significantly greater and TKN significantly less in the sheared plot than that in the clearcut and undisturbed plots. Differences in dissolved and suspended concentrations among the three treatments were insignificant at the 0.05 alpha level. During the two year period only the concentrations of PO_4 exceeded the Environmental Protection Agency's (1976) standard for water entering streams. Average concentrations of the 17 elements for the 2-year period are given in Table 1.

Element losses

Total losses of the 17 elements during the first post-treatment year were 18.1, 80.5, and 230.3 kg ha^{-1} for the undisturbed forest, commercial clearcut, and sheared plots,

Table 1 Mean concentrations of 17 elements in surface runoff in the study area.

Element	Undisturbed forest:			Commercial clearcutting:			Sheared:		
	Diss	Susp	Dept	Diss	Susp	Dept	Diss	Susp	Dept
Ca	2.54	1.44	139.54	2.71	1.10	110.16	2.45	1.15	107.55
Mg	1.55	0.76	32.39	1.64	1.03	31.15	1.58	1.10	22.68
Na	12.21	3.74	43.32	12.17	3.30	43.53	9.58	4.47	44.36
K	3.82	1.30	40.39	5.06	1.02	33.03	4.11	1.29	28.03
TKN	4.79	1.24	869.57	4.18	2.00	878.58	3.54	1.30	785.28
Al	0.20	0.16	3.93	0.30	0.30	4.04	0.31	0.20	7.04
Mn	0.09	0.07	2.50	0.15	0.14	2.91	0.14	0.17	4.43
Fe	0.23	0.43	4.13	0.44	0.56	3.92	0.36	0.37	6.42
Zn	0.32	0.21	3.13	0.51	0.30	3.29	0.47	0.33	2.58
Cu	0.21	0.09	0.73	0.20	0.17	0.97	0.23	0.31	1.32
NH_4	2.64	0.88	6.68	2.63	1.18	7.84	2.32	0.70	7.55
NO_2	0.04	0.04	0.19	0.04	0.06	0.19	0.12	0.11	0.18
NO_3	0.27	0.07	0.85	0.28	0.08	1.08	0.24	0.18	0.99
HCO_3	36.90	7.96	36.89	39.93	10.63	43.63	23.81	8.54	41.44
SO_4	24.45	11.43	70.07	21.42	9.34	80.72	16.98	10.00	79.13
Cl	13.69	3.45	10.76	14.90	5.50	12.33	13.20	4.72	17.71
PO_4	1.99	0.96	3.18	2.57	1.38	2.92	1.84	1.04	3.85
Sum	108.87	34.23	1268.19	109.09	38.06	1260.25	81.22	35.52	1160.50

Notes: (1) Data covered water years 1989-1990. (2) Dissolved (Diss) and suspended (Susp) elements are in mg l^{-1}, while deposited (Dept) elements are in ppm.

respectively. The average losses for each storm ranged from 0.31 kg ha^{-1} for the undisturbed forest to 3.67 kg ha^{-1} for the sheared plot with an average of 3.3 kg ha^{-1} for the three treatments. Differences in element losses among the three treatments were highly significant at the 0.05 alpha level. They increased substantially with increasing severity of site disturbance. Compared to the undisturbed forest, clearcutting increased total element losses by 4.4 times while shearing by 12.7 times. Total losses for each individual element among the three forest treatments followed the same pattern for losses of all element combined. The largest storm in the first year was 123.7 mm or 9.4% of annual total which generated about 3.6 kg ha^{-1} (20% of annual total), 10.6 kg ha^{-1} (13%), and 38.19 kg ha^{-1} (17%) element losses from the undisturbed forest, clearcut, and sheared plots, respectively. In other words, shearing can generate element loss in a single storm about twice that of the annual total losses from the undisturbed forest

In the second year, total element losses were 44.4 kg ha^{-1} from the undisturbed forest , 67.2 kg ha^{-1} from the clearcut, and 323.5 kg ha^{-1} from the sheared plot. Again, they were significantly different between any pair of treatments at the 0.05 alpha level. Losses in both the undisturbed forest and sheared plots were higher than that in the previous year. This was due to the greater precipitation and surface runoff in the second year along with a 50% reduction of forest canopy caused by a tornado strike through the undisturbed forest plot on 19 January 1990. In the clearcut plot, however, there was a reduction in element losses during the second year. This could be caused by the heavy uptake of elements by luxuriant sprouting vegetation and grasses. Average annual losses of the 17 elements during the two years study period are given in Table 2. Of the three element sources, those that attached to deposited sediment contributed less than 1%, while dissolved form contributed about 70%.

Table 2 Annual losses (kg ha^{-1}) of the 17 elements in the study area.

Sources	Undisturbed forest	Commercial clearcut	Sheared
1989			
Dissolved	15.107	60.393	156.726
Suspended	4.458	18.652	69.891
Deposited	0.064	0.499	0.976
Total	19.629	79.544	227.593
1990			
Dissolved	29.563	45.286	218.730
Suspended	15.370	21.545	104.518
Deposited	0.040	0.069	0.251
Total	44.973	66.900	323.499
Average			
Dissolved	22.335	52.840	187.728
Suspended	9.914	20.099	87.205
Deposited	0.052	0.284	0.614
Total	32.301	73.222	275.547

Fluctuations of soil electrical conductivity

Soil electrical conductivity (EC), monitored through Martek's salinity-conductivity

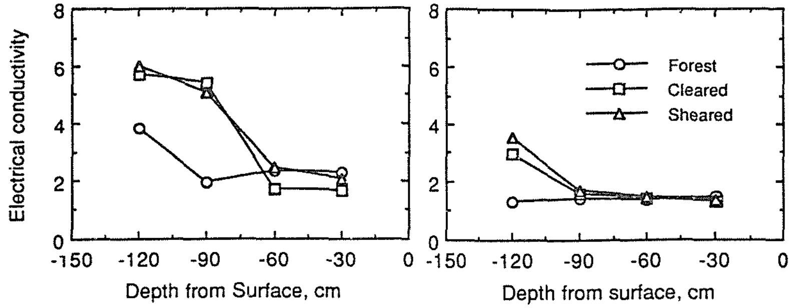

Fig. 1 Soil electrical conductivity (mS cm^{-1}) in the Fuller soil 6th (left-side) and 18th (right-side) months after treatments.

sensors, generally increased with depth in the soil profile in response to increasing concentrations of total ions. A saline soil is one with EC exceeding 4 mS cm^{-1}, sodium present but not excessively high in proportion to calcium and magnesium. This level of EC was usually found at or below 85 cm depth in the study area. Of the three treatments, EC was generally the highest in the sheared plot, except in the surface 30 cm depth. However, EC values were largely reduced, in all three plots, in the second year after treatment. The average EC values for the 6th and 18th month after treatment for the three forest conditions are plotted in Fig. 1.

The increasing trend of EC in the sheared and cleared plots in the first year may indicate that more salts were dissolved from the soil as more water became available due to the reduction of evapotranspiration. Element uptake by plants was also reduced in the treated plots. As the increase in water in the soil profile continues, elements may be diluted as shown in the second year (Geraldson, 1957). However, it is interesting to find that soil EC in the 30 cm depth of the forest plot was generally the highest of the three. The additional ions in surface layer of the forest plot might have come from dry and wet depositions through forest canopy. Further study is needed.

Fluctuations of soil-water electrical conductivity

Based on 271 samples collected between January 1989 and December 1990, the average values of soil-water electrical conductivity (EC) for the three forest conditions

Table 3 Mean electrical conductivities (mS cm^{-1}) of soil-water in the study area.

Depth (cm)	Undisturbed forest	Commercial clearcut	Sheared
30	0.728[a]	0.580[a]	1.280[b]
60	0.540[a]	1.140[b]	1.270[b]
90	0.992[a]	1.660[b]	1.490[b]
120	1.891[a]	2.560[b]	1.407[a]

Notes:

(1) Average values among treatments at each depth indexed by the same letter are not significantly different at the 0.05 alpha level as determined by Duncan's multiple range test.

(2) Data were collected bi-weekly between January 1989 and December 1990.

are given in Table 3. Generally, the soil-water electrical conductivity (EC) increased with depth from the surface and was the lowest in the undisturbed forest plot. At the 30 cm depth, the average EC was 1.28 mS cm^{-1} in the sheared plot, significantly greater than the commercial clearcut (0.580) and undisturbed forest (0.728) plots at the 0.05 alpha level. However, the commercial clearcut plot had a much higher EC (2.560 mS cm^{-1}) than the sheared (1.407) and undisturbed forest (1.891) plots at the 120 cm depth. Differences in EC between the sheared and the commercial clearcut plots in the middle horizons of the soil profile were insignificant at the 0.05 alpha level. Again, all these reveal the increase in release of elements and the decrease in element uptake by plants in the treatment plots.

Element concentration in soil water

Of the 17 elements analysed during the two year period, only the average concentrations of Na and Al were significantly different among the three treatments at the 0.05 alpha level. Forest clearcutting followed by intensive site preparation did not significantly affect four nitrogen elements, K, PO_4 and other elements throughout the soil profile.

The concentrations of Na and Al were lower in the undisturbed forest plot and progressively increased with the intensity of forest disturbances. At the 30 cm depth, the average Na concentration was 39.64 mg l^{-1} in the forest plot, and 50.65 and 76.25 mg l^{-1} for the commercial clearcutting and sheared plots, respectively. This increasing pattern was observed throughout the entire soil profile except at the bottom level. As for the Al concentrations at the 30 cm level, they were 0.31 mg l^{-1} for the sheared plot, 0.06 mg l^{-1} for the commercial clearcut, and 0.14 mg l^{-1} for the undisturbed forest. Differences in Al concentrations at the 90 cm depth among the treatments were not significant at the 0.05 alpha level.

The increases in concentrations of Na and Al in the soil profile of the treated plots seemed to result from the combined effects of evapotranspiration reduction and lack of elements uptake by plants. These elements were dissolved from the soil as more water was remained in the soil due to reduction in transpiration. Average concentrations of the three major cations, i.e. Ca, Mg, and K, ranging from 2.93 to

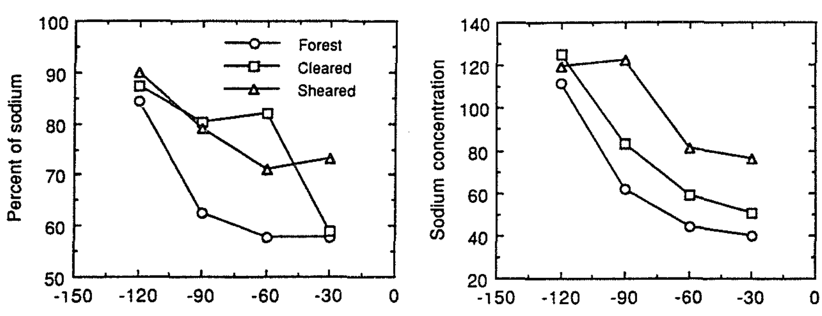

Fig. 2 Sodium as % of four major cations in soil-water vacuumed at various depths in the soil profile (left-side), and average sodium concentration in mS cm^{-1} of the soil-water (right-side), both covered water years 1989-1990.

12.59 ppm, were much lower than Na. This made Na the predominate cation in the soil profile. Calculated % Na ranged from 55 to 90 (Fig. 3), an imbalance in respect to the major cations which could produce a soil having poor tilth and structure (McKee & Wolf, 1963; Suarez *et al.*, 1984). This may explain why permeability of the study soil (fine sandy loam) is so slow (saturated hydraulic conductivity 6.0 cm h^{-1}) although its sand composition is as high as 78-82%.

Rendig & Taylor (1989) stated that an Al concentration of as high as 0.24-5.62 ppm in topsoils did not inhibit the root development of soybeans and cottons. The aluminium concentrations in the study soil should not adversely affect root growth of loblolly-shortleaf pines and other hardwood species, especially when the soil-water pH is around 6.6. Cl^- and SO_4^{--} are the other two most abundant ions in saline soils. The average concentrations of Cl^- and SO_4^{--} at the 30 cm depth of the three study plots were 23.01 and 38.82 ppm, respectively. These concentrations are not likely to impose toxic effects to plants (KcKee & Wolf, 1963).

CONCLUSIONS

Although surface-runoff concentrations of 17 elements in the sheared and cleared plots were not as high as that in the undisturbed forest, total element losses in mass per unit area increased substantially with increasing severity of site disturbance. Soil and soil-water electrical conductivities (EC) generally increased with depth in the soil profile, and were the highest in the sheared plot. Of the 17 elements in soil-water analysed, only Na and Al were significantly different at the 0.05 alpha level. Sodium is the predominate cation, responsible for slow permeability of the study soil. None of the elements in the soil-water analysed had a concentration high enough to cause adverse effects on plants. It is suggested that after timber in salt problem soils is harvested, the area be fallowed for a few years to let the excess salts in the upper soil be absorbed by herbs and grasses before pine seedlings are planted.

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Evaluation of the impact of deforestation to inflow regime of the Hoa Binh Reservoir in Vietnam

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Abstract Hoa Binh Reservoir – the largest reservoir in Vietnam has been established on the Da River. The problems in runoff calculation, erosion and sedimentation, planning and management for this reservoir are important. The author shows the results of evaluating the impact of deforestation to its inflow regime as well as the variation of sediment concentration which was caused by deforestation in this basin.

INTRODUCTION

The Da River is the largest river of the Red River System. This basin is situated in three countries, China, Laos and Vietnam. It is the most important river and its flooding often threatens the Bac Bo Plain and Hanoi – the capital of Vietnam. Its sediment has had an essential role in creating the Red River Delta and in establishing the complex river-bed process in this delta. In recent years, the largest reservoir in Vietnam – Hoa Binh Reservoir – has been established on the Da River: its maximum storage capacity is 9.45 billion cubic metres and the water surface at operating level area is 208 km^2. The main objectives of this reservoir were flood control and to produce hydropower (the average power production has been 7.56 million kWh $year^{-1}$). It has a very important role in transportation (the navigable length of the main river is more than 200 km); in fishery (the yield is thousands of tons per year). It is also the main water source for irrigation in the dry season at Bac Bo Plain and making good conditions to develop socio-economic situation as well as for the environment in the northwest region of Vietnam (tourism, health etc.).

Geographical conditions

The total area of the basin is 52 900 km^2 (31% the total area of Red River basin). The area inside Vietnam is about 26 800 km^2. The Da River basin is situated in a northwest-southeast direction, from latitude 20°40′N to 25°00′N and from longitude 100°22′E to 105°24′E. The average length of basin is 690 km, with a width of 76 km. The main characteristic of relief is mountainous and highland forms which is rather high and divided. The main slope direction of relief is northwest-southeast with an average altitude of 965 m. The river cross sections are narrow and have a V-form.

Climate

There are three regions:

- The upper basin (from starting point to the China-Vietnam border): the mean annual temperature is 15-18°C, the maximum temperature (in July) is about 30°C and the minimum temperature (in January) is about 0°C. The mean relative humidity is 82-86%. The annual rainfall is 1000-1600 mm.
- The middle basin (from the China-Vietnam border to Ta Khoa town): the mean annual temperature is 21-23°C, the annual rainfall is high (2000-3000 mm) on the left of river bank area but it is low on the right – from 1200 to 2000 mm.
- The lower basin (from Ta Khoa town to the river's mouth): it is influenced by the northeast and southwest monsoons and even typhoons coming from the Bien Dong Sea every year. The mean annual temperature is 18-23°C. Three months having maximum rainfall are July, August and September. The daily maximum rainfall was 573.0 mm (Muong Te, 5 August 1967). The rainfall intensity is high, sometimes it exceeds 20 mm in 5 minutes.

Soil and forest cover

Red-yellow feralite soil is the main component which occupies the lower mountainous relief (less than 600-700 m elevation) along the Da River valley. The slope relief, rainfall with high intensity and the forest cover which was destroyed are the main reasons for generating erosion in the reservoir's basin.

Hydrological characteristics

The Da River runoff is abundant. The annual average total volume of runoff is 53.5 km^3 (at Hoa Binh cross section) which is equivalent to a discharge of 1690 $m^3\ s^{-1}$ and module of runoff at 32.6 litres $s^{-1}\ km^{-2}$. The distribution of river density is not uniform: in the karst regions, the river density is very low (less than 0.5 km km^{-2}, such as Nam Sap catchment) but in the high mountainous regions, river density is high (it reaches 1.67 km km^{-2}, e.g. Nam Mu catchment). The number of rivers longer than 10 km is 223. There are 148 rivers with catchment areas less than 100 km^2.

The Da River flooding is highest in the Red River system. The flood volume measured at the Hoa Binh cross section is 47% of the flood volume of the Red River

Table 1 The variation of sediment concentration in the long-term periods (unit: g m^{-3}).

Station	1st period	2nd period	3rd period
Thac Moc	43.3	106	144
Nam Mu	55.5	203	291
Suoi Sap	76.0	99	132
Thac Vai	86.7	226	274
Lai Chau	785	1500	1590
Ta Bu	712	1520	1420
Hoa Binh	562	1430	1130

system measured at the Son Tay cross section. Flood module is equal to 2 times that of the annual runoff module. Runoff in the flood season (June-October) is about 77.6% of the total annual runoff, 23% in August alone. Flooding of Da River is due to the mountainous flood: its discharge changes quickly (water level amplitude has reached 30 m at the Lai Chau cross section). Runoff calculation and forecasting are difficult tasks.

EVALUATION THE IMPACT OF DEFORESTATION TO INFLOW REGIME OF HOA BINH RESERVOIR

The relationship between the forest cover area and the natural regulation capability

The forest cover area in the Hoa Binh Reservoir basin changed as follows: it was 77.44% the basin total area in 1943, but reduced to 14.13% in 1972 and 8.9% in 1981.

Based on the hydrological data at the Hoa Binh cross section (1965-1984), values of the natural regulation coefficient were calculated as follows:

$$\alpha = \int_0^1 p\,\mathrm{d}K$$

in which: p is the frequency of discharge Q_i; K is the ratio between Q_i and Q_o; and Q_o is the mean annual discharge ($m^3\ s^{-1}$). α is the ratio of the volume of runoff passing over the cross-section having discharge values smaller than the annual average discharge and the mean annual volume. So, if α is large then the basin has good regulation, and vice versa. It can be seen that when the forest cover area was reduced the natural regulation capacity of the basin was also reduced.

The relationship between the forest cover area and the runoff hydrograph

By using the model, the relationship between the forest cover area and the runoff hydrograph is shown to be as follows:

- When the forest cover area changed from 100% to 0%, the peak discharge and the total of runoff volume increased clearly (with the same total of rainfall and distribution).
- The time to the peak discharge was longer when the forest cover was in a natural condition (no deforestation).

Forest cover and the variation of sediment concentration in the long term

In order to find the relationship between erosion and land use processes in the basin, analyses were made of the long-term series of sediment concentration data in the Da River and other rivers in the Red River system.

Based on these data series, the average values of sediment concentration were calculated for three periods: the first period was from the beginning of those data series (when the sediment stations were established) to 1968; the second one: to 1973 and the third: to 1985. The results are presented in Table 1.

From Table 1, the following can be concluded:

(a) Comparing two periods (from beginning to 1968 and to 1973) shows an increased tendency of the sediment concentration in almost all of the Da system. The main reason for that was deforestation, which developed quickly in the basin, especially in the highland areas.

(b) Looking at the third period, it can be seen that the sediment concentration in the Da River system was increasing in almost all of the tributaries. But it was decreasing in the main river because the reservoir was established.

CONCLUSION

The Hoa Binh Reservoir is the largest reservoir in Vietnam at this time. The Da River is a large transboundary river which has important influences on many socio-economic sectors, so the relationship between the forest cover and runoff/sediment regimes needs to be understood. Soil loss in the Da River basin is rather high even in the areas of moderate topography. The main reason for that has been deforestation and unscientific cultivation methods. The protection of the headwater forests is very important for soil conservation in the Da River and for the Hoa Binh Reservoir. Thus, the environmentally-sound management of the river and reservoir basin is one of the most important problems. Watershed management is a problem that should be solved as soon as possible.

At the same time, there is a need for an international project to be established to support research, planning and management of the whole basin in order to permit the sound exploitation of the water resources. The results of the project would be good not only for the management of the Hoa Binh Reservoir but also for other reservoirs in Vietnam.

Algorithme non récursif et récursif: application à la prévision des crues du haut-bassin du Fleuve Sénégal

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Résumé L'irrégularité des crues du Fleuve Sénégal et le peu d'informations disponibles rendent difficile le suivi de leur évolution dans l'espace et dans le temps à l'aide de modèles déterministes. Un modèle linéaire à plusieurs entrées et une sortie a été mis au point. L'analyse des paramètres calculés par la méthode des moindres carrés ordinaire sur 20 crues montre qu'ils varient d'une année à l'autre, suivant les caractéristiques de l'écoulement. Une procédure adaptative permettant de recalibrer le modèle à partir de l'information récente en vue de la prévision en temps réel a été alors utilisée. La comparaison des résultats obtenus par les deux méthodes à l'aide des fonctions de répartition de l'écart quadratique moyen, et de l'erreur relative de pointe d'une part, et en utilisant les graphes calculés et observés d'autre part, a permis de mettre en évidence l'amélioration apporté par le modèle adaptatif.

INTRODUCTION

Le problème de la prévision des crues du Fleuve Sénégal est devenu d'actualité depuis que les barrages de Manantali (dans le haut-bassin) et Diama (dans le delta) ont été construits pour répondre à la baisse persistance de la pluviométrie constatée dans le Sahel. Cependant, la difficulté d'obtenir des données hydrauliques complètes dans la partie amont, et l'incertitude inhérente aux données hydrologiques rendent coûteux l'élaboration d'un modèle déterministe, qui par ailleurs risquerait d'être trop précis pour la qualité de l'information disponible.

Le présent travail vise à fournir un outil simple de prévision en temps réel des crues dans le haut-bassin basé sur la théorie du modèle linéaire. Il fait suite aux travaux menés sur la prévision des crues dans la vallée du Fleuve Sénégal (Sambou, 1989; Thirriot *et al.*, 1990).

CONSTRUCTION DU MODELE

Un bassin versant comportant n stations de mesures peut être décrit par un modèle linéaire de la forme:

$$X(t) = \phi\,(B^l)\,X(t) + \Lambda(B^k)\,U(t) + w(t)$$

où: $X(t)$ est le vecteur état représentant le débit à l'exutoire (ici Bakel); $U(t)$ vecteur des entrées aux stations explicatrices du bassin qu'on peut mettre sous la forme d'un vecteur partitionné pour tenir compte des apports des différents affluents:

B opérateur de différence arrière agissant sur $X(t)$ et $U(t)$,

l et k ordres de l'opérateur,

ϕ et Λ matrices de coefficients du modèle,

$W(t)$ vecteur des erreurs entre valeurs calculées et observées.

Cette relation permet de calculer le débit en un point quelconque du bassin versant choisi comme exutoire à la date $t + \delta$ à partir d'observations faites en d'autres endroits du bassin par:

$$Q_{av}(t+\delta) = \sum_{i=1}^{l} \alpha_i Q_{av}(t-i) + \sum_{j=1}^{n_0} \sum_{m-1}^{kj} \beta_{mj} Q_{amj}(t-\tau_j-m) + w(t)$$

où:

n_0 est le nombre de stations amonts explicatrices;

k_j le nombre de données à la station amont j antérieures à τ_j;

l le nombre de données à la station aval;

δ le délai de prévision.

Pour des raisons de simplicité, on peut la mettre sous la forme condensée d'un modèle linéaire global ci dessous:

$$Y = \Phi\, X_N + W$$

où:

Φ $(1,N)$ vecteur des coefficients du modèle;

$Y(N,1)$ le vecteur des débits à l'aval;

X_N (N,p) matrice des débits amont;

$W(N,1)$ vecteur des erreurs.

On a: $p = 1 + \Sigma\, k_j, j = 1, \ldots, n_0$.

$$X_N = |U_0\!: U_1\!: U_2\!: \ldots\!: U_p|^T$$

$$Y = |Q_{av}(t + \delta), \ldots, Q_{av}(t + \delta - N)|^T$$

avec

$$U_0 = \begin{vmatrix} Q_{av}(t) & . & Q_{av}(t-l) \\ Q_{av}(t-1) & . & Q_{av}(t-l-1) \\ . & & . \\ . & . & . \\ Q_{av}(t-N) & . & Q_{av}(t-l-N) \end{vmatrix}$$

$$U_i = \begin{vmatrix} Q_{am}(t-\tau_i) & Q_{am}(t-\tau_i-1) & . & Q_{am}(t-\tau_i-k_i) \\ Q_{am}(t-\tau_i-1) & Q_{am}(t-\tau_i-2) & . & Q_{am}(i-\tau_i-k_i-1) \\ . & . & . & . \\ . & . & . & . \\ Q_{am}(t-\tau_i-N) & Q_{am}(t-\tau_i-1-N) & . & Q_{am}(t-\tau_i-k_i-N) \end{vmatrix}$$

$$\Phi = |\alpha_1, \ldots, \alpha_2 \quad \beta_{1,1}, \ldots, \beta_{1,k1}, \ldots, \beta_{n0,1}, \ldots, \beta_{n0,kn0}|$$

DETERMINATION DU MODELE

La détermination du modèle va consister à chercher les valeurs de n_0, k_j, t_j, p ainsi que la matrice Φ des coefficients.

Estimation des temps de propagation

En toute rigueur, le temps de propagation est une fonction du débit. Cependant, on peut le considérer en moyenne comme étant égal au maximum du corrélogramme croisé entre deux séries de débits à deux stations voisines. Les temps trouvés par cette méthode varient d'une année à l'autre en fonction des caractéristiques de la crue.

Estimation de l'ordre du modèle p

Différentes combinaisons de l, et k_j, $j = 1 \ldots n_0$ ont été utilisées pour faire des essais de prévisions. A chaque fois l'écart quadratique moyen ϵ a été calculé. Nous avons choisi comme combinaison finale celle donnant la plus faible valeur de ϵ. Du fait de l'irrégularité interannuelle des crues, le p-uplet optimal (l, k_j, $j = 1 \ldots n_0$) varie d'une année à l'autre.

Estimation du vecteur Φ

Dans cette étude, on a d'abord utilisé la méthode des moindres carrés ordinaire. Puis un caractère récursif a été ensuite introduit, en utilisant l'information la plus récente pour recalibrer les coefficients du modèle.

Cette dernière méthode a été utilisée dans le but de tenir compte de la non-linéarité du modèle et des opérations en temps réel.

Rappels théoriques: méthode des moindres carrés ordinaire L'estimation de Φ par la méthode des moindres carrés ordinaire conduit à minimiser le produit scalaire $W\,W^T$ en annulant les dérivées partielles premières. En utilisant la notation matricielle, on a:

$$\frac{\partial(W^T W)}{\partial \Phi} = 0$$

ce qui donne la condition d'extremum:

$$\hat{\Phi} = C_N^{-1} X_N^T Y$$

avec:

$$C_N = X_N^T X_N$$

Ràppel théorique: estimation récursive Le vecteur des paramètres précédent Φ_N est supposé constant tout au long des essais de prévisions. Dans le cas où la prévision s'effectue en temps réel, on peut utiliser à chaque fois les observations arrivées fraîchement sur le système pour recalibrer les paramètres du modèle, ou pour corriger les calculs. Une procédure récursive adaptative est alors utilisée. Parmi les techniques existant, celles des moindres carrés est très répandue (Bolzern *et al.*, 1982; Young, 1986; Delleur, 1991).

Supposons la matrice X_N décrivant la série des mesures de débit du système connue jusqu'à la date k. Cette information doit être utilisée pour calculer le vecteur $\hat{\Phi}$ pour le pas de calcul suivant. Pour ce faire, il convient d'établir une relation récursive entre Φ_k et Φ_{k-1}.

Posons $P_k = C_k^{-1}$, P_k^{-1} peut être décomposé en deux matrices:

$$P_k^{-1} = P_{k-1}^{-1} + B_k$$

De même Y_k peut être décomposé en deux vecteurs: Y_{k-1} et M_k:

$$Y_k = Y_{k-1} + M_k$$

Le vecteur Φ_k des paramètres peut alors s'estimer par la relation:

$$\Phi_k = P_k Y_k$$

On peut exprimer P_k en fonction de P_{k-1} en utilisant le lemme d'inversion matricielle ci-dessous:

$$(A + B\,C\,D)^{-1} = A^{-1} - A^{-1}B\,(C^{-1} + DA^{-1}B)^{-1}\,DA^{-1}$$

et en posant:

$$A = P_k^{-1};\ B = X_k;\ C = 1;\ D = X_k^T$$

Ce qui donne:

$$P_k = (P_k^{-1} + X_k X_k^T)^{-1} = P_{k-1} - P_{k-1}X_k(1 + X_k^T P_{k-1} X_k)^{-1} X_k^T P_{k-1}$$

En remplaçant dans l'expression de Φ_k, il vient:

$$\Phi_k = \Phi_{k-1} + K_k (Y_k - Y_c)$$

avec:

$$K_k = P_{k-1}X_k(1 + X_k^T P_{k-1}X_k)^{-1}$$

est appelé gain, Y_c étant le vecteur calculé à partir de Φ_{k-1}.

COMPARAISON DES DEUX ALGORITHMES: CRITERES DE QUALITE

Parmi les critères utilisés dans la littérature (Green & Stephenson, 1986), nous en retiendrons deux, bien connus (Thirriot & Habaieb, 1986)
- l'erreur relative de pointe,
- l'écart quadratique moyen qui va permettre de mesurer la dispersion des valeurs calculées par rapport aux valeurs observées.

APPLICATION AU HAUT-BASSIN DU FLEUVE SENEGAL

Le haut-bassin en amont de Bakel (Fig. 1), a une superficie de 218 000 km^2. Il se situe dans une région de relief plus contrasté avec, du sud au nord, une succession de plateaux entaillés de vallées étroites. La pluviométrie plus abondante varie de 1200 mm à proximité de la source (climat tropical guinéen) à 700 mm à Bakel (climat tropical sahélien). Le fleuve est formé de la rencontre du Bafing sa branche maîtresse, et du Bakoye. Il reçoit ensuite à la rive droite le Karakoro et le Kolombiné, et à la rive gauche la Falémé.

Pour la construction du modèle, le haut-bassin a été considéré comme un système entrée-sorties reliées par une fonction de transfert, avec trois entrées qui sont les débits aux stations extrêmes: Dakka-Saidou sur le Bafing, Toukoto sur le Bakoye, Fadougou sur la Falémé, et une sortie qui est Bakel sur le Fleuve Sénégal. Pour éviter l'encombrement et diminuer le temps de calcul, nous avons utilisé uniquement les observations effectuées aux stations explicatrices amont. Le modèle a été mis sous la forme simplifiée:

$$Y = X\,\Phi + W$$

où Y vecteur $(N,1)$ des débits à l'exutoire (Bakel); X matrice $(N,3)$ des entrées aux stations amont situées sur les affluents décalés de leur temps de propagation respectif; $\Phi(N,1)$ est le vecteur des paramètres du modèle; $W(N,1)$ vecteur des erreurs de prévision.

Les essais ont été effectués sur un échantillon de crues qui s'étale de 1961 à 1980. Pour chacune de ces crues une simulation des prévisions a été effectuée en utilisant d'abord l'algorithme des moindres carrés récursif. Les temps de propagation jusqu'à l'exutoire de Bakel ont été respectivement choisis égaux à quatre jours pour la station de Dakka-Saidou, trois jours pour celle de Toukoto, et quatre jours pour Fadougou. Pour chaque essai nous avons calculé les critères de qualité définis plus haut.

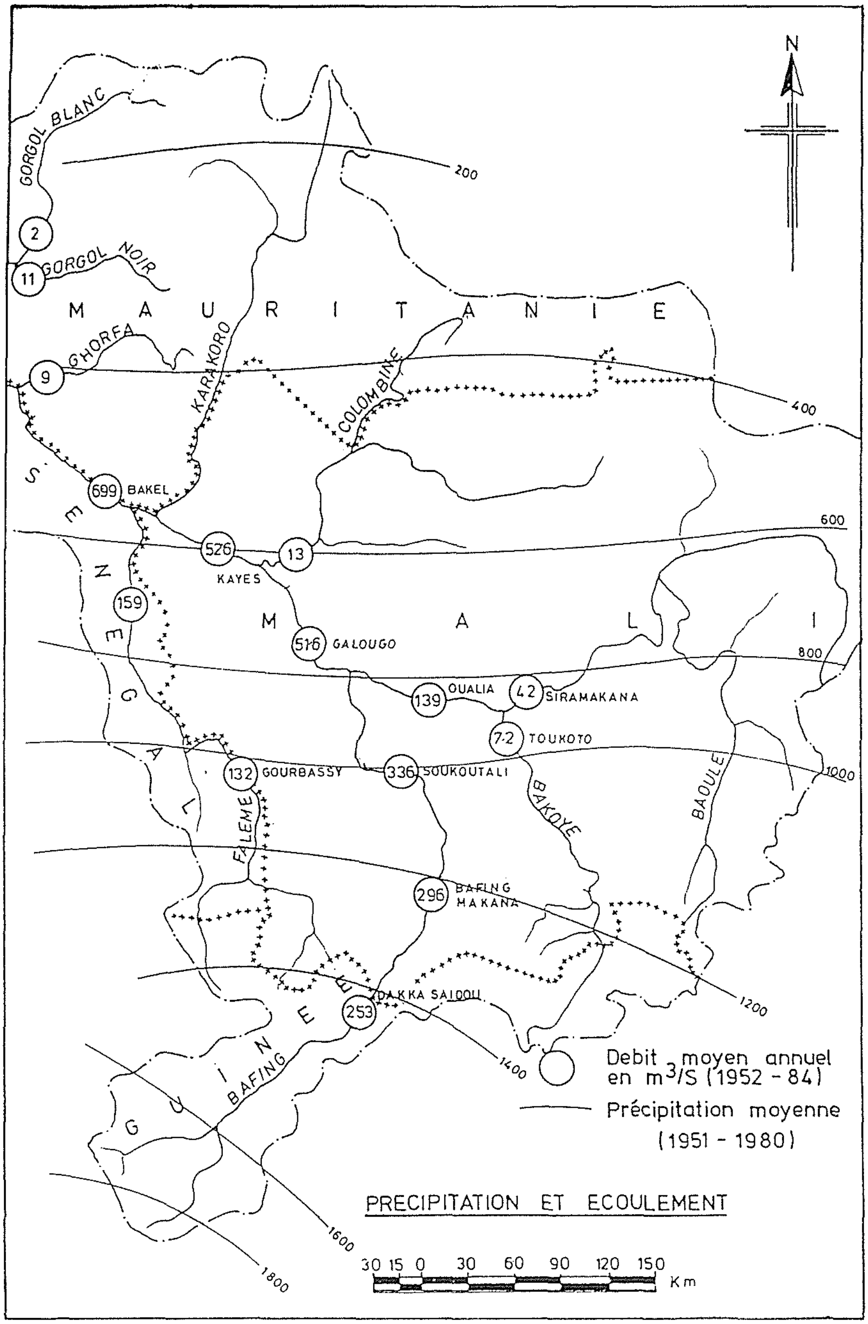

Fig. 1 Carte du haut-bassin du Fleuve Sénégal.

RESULTATS

L'amélioration apportée par le modèle adaptatif sur l'erreur relative de pointe est

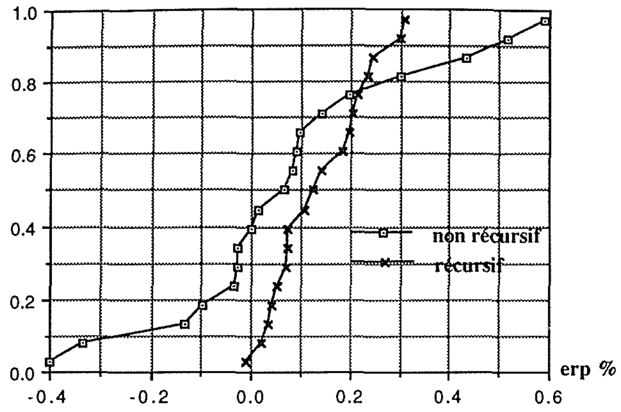

Fig. 2 Fonction de répartition des erreurs relatives de pointe.

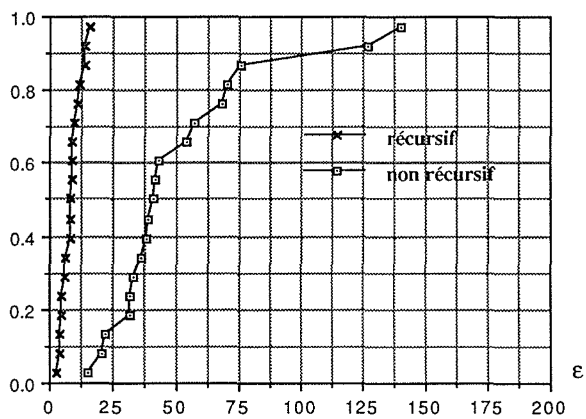

Fig. 3 Fonction de répartition des écarts quadratiques moyens.

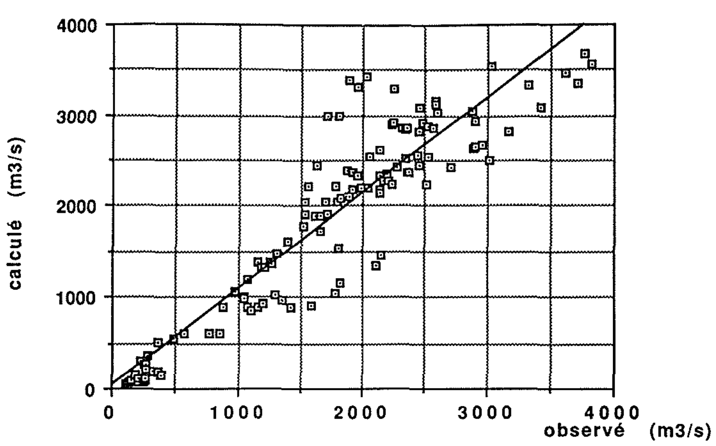

Fig. 4 Estimation non récursive. Graphe calculé-observé.

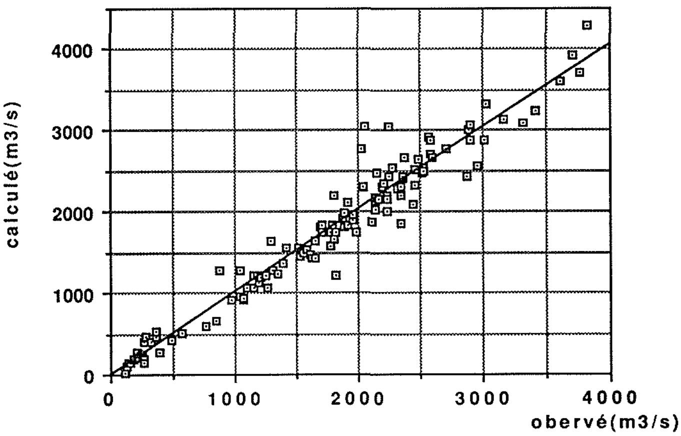

Fig. 5 Estimation récursive. Graphe calculé-observé.

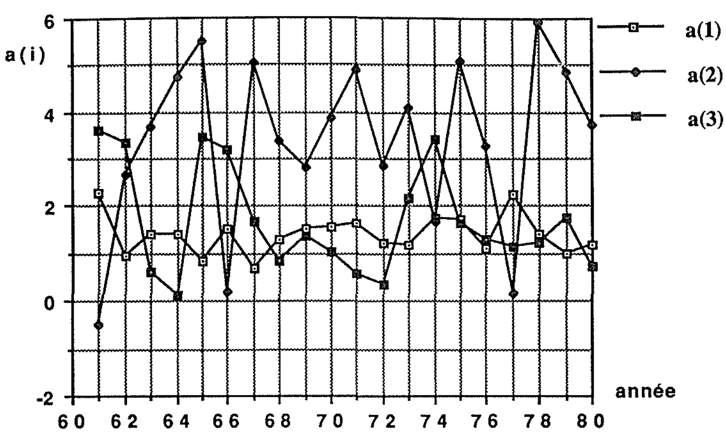

Fig. 6 Estimation non récursive. Variation des paramètres en fonction des crues.

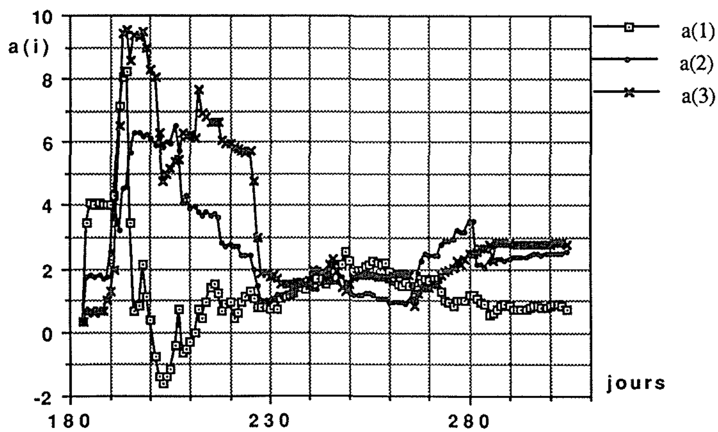

Fig. 7 Bakel 1963. Estimation récursive. Evolution des paramètres.

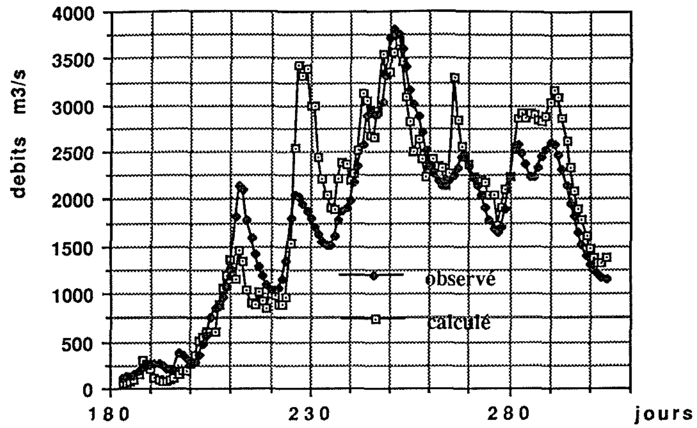

Fig. 8 Bakel 1963. Estimation non récursive.

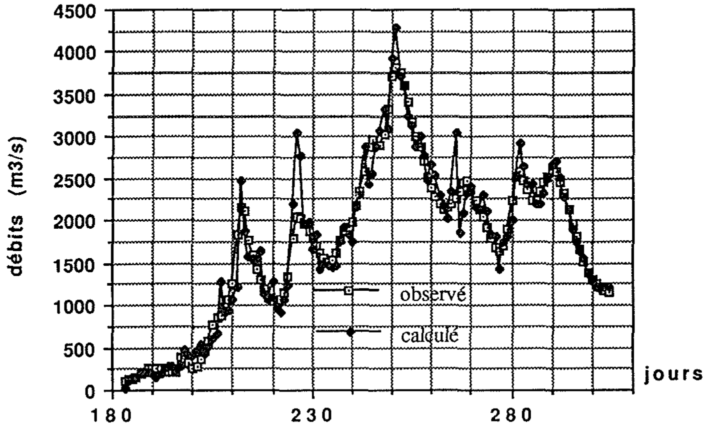

Fig. 9 Bakel 1963. Estimation récursive.

moins importante. Ce dernier ne réagit pas assez vite à l'inversion de tendance (Fig. 2).

Par contre (Fig. 3), l'écart quadratique moyen est beaucoup plus faible, mettant en évidence la correction du décalage entre hydrogrammes calculés et observés par suite du recalibrage des paramètres à chaque pas de calcul. Ce résultat se traduit sur les Figs 4 et 5 par la diminution de la dispersion des graphes calculés – observés pour l'algorithme récursif.

Sur la Fig. 6, les paramètres calculés sur 20 crues varient d'une année sur l'autre, mais avec des amplitudes différentes. Le coefficient $a(1)$ varie peu, parceque la station de Dakka Saidou située sur le Bafing est mieux corrélée avec celle de Bakel; par contre $a(2)$ et $a(3)$ qui tiennent compte des apports des affluents ont des fluctuations plus importantes, en rapport avec les contributions de ces différents affluents suivant l'importance de la pluviométrie.

L'évolution des paramètres sur la crue test de 1963 est indiquée sur la Fig. 7. Elle montre deux tendances distinctes. Pendant le début de la crue, on observe une grande instabilité des paramètres, en étroite relation avec la forte variation des débits. Au voisinage du maximum, et en décrue les inversions de tendance de l'écoulement sont moins fréquentes, ce qui se traduit par des "paliers".

La Fig. 8 représente les hydrogrammes calculés et observés à Bakel pour la crue de 1963. Les paramètres ont été calculés sur la crue de 1962 qui est plus importante, d'où une surestimation des débits calculés par rapport aux débits observés. La Fig. 9 représente les mêmes hydrogrammes pour la même crue, avec cependant estimation récursif des paramètres. Les amplitudes des écarts ont diminué, mais l'erreur sur le maximum est plus importante.

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The impact of converting grassland to pine forest on water yield in Viti Levu, Fiji

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Abstract Evapotranspiration (ET) in 6-year-old and mature pine plantations and natural grassland in southwest Viti Levu, Fiji, were compared. Dry season ET (Bowen ratio energy balance method) of the young pine stand over 145 days in 1990 was 3.6 $\pm$ 1.0 mm day^{-1}. The corresponding value for the mature stand over 1990 (basin water balance) was 4.3 mm day^{-1}. Penman open water evaporation (E_0) for 1990 was 1812 mm, suggesting ET/E_0 = 0.86 for mature pine. Average ET for grassland over 131 days during the dry season of 1991 was 1.0 $\pm$ 0.3 mm day^{-1} (Penman-Monteith), with a corresponding E_0 of 3.7 $\pm$ 1.0 mm day^{-1}. The resulting low value for ET/E_0 (0.25) was attributed to the gradual dying of the grass as the dry season progressed. Because of the large difference in dry season ET between grassland and pine forest, the reafforestation of Fijian grasslands will produce a significant decrease in water yield during a time of year when water is already scarce.

NOTATION

c_p	Specific heat of air at constant pressure	[J kg^{-1} K^{-1}]
d	Zero plane displacement length	[m]
e	Actual vapour pressure	[mbar]
e_s	Saturation vapour pressure	[mbar]
G	Flux density of heat into the soil (positive if downwards)	[W m^{-2}]
k	Von Kármán's constant, set at 0.4	
R_n	Net radiation	[W m^{-2}]
R_g	Flux density of short-wave solar radiation	[W m^{-1}]
r_a	Aerodynamic resistance	[s m^{-1}]
r_c	Canopy resistance	[s m^{-1}]
U_z	Wind speed at height z above the surface	[m s^{-1}]
z_0	Aerodynamic roughness length	[m]
Δ	Rate of change of saturation vapour pressure with temperature	[mbar K^{-1}]
λ	Latent heat of vaporization of water	[J kg^{-1}]

ρ	Density of air	[kg m^{-3}]
γ	Psychrometric constant	[mbar K^{-1}]

INTRODUCTION

The area covered by degraded and largely unproductive grasslands in the tropics is growing. In view of increasing demands for timber and perceived environmental improvement, calls for the reafforestation of such land are becoming more frequent. On the other hand, work in warm-temperate areas has suggested large drops in water yield after maturation of forest planted on former grasslands, particularly during the dry season (Van Lill *et al.*, 1980). Despite the urgency of the issue, virtually no sound information is available to date with respect to the hydrological consequences of reafforesting degraded grassland to fast-growing evergreens in the humid tropics (Bruijnzeel, 1990). To partly fill this gap a study of the water and nutrient dynamics of an age series of *Pinus caribaea* plantation forests and, to a lesser extent, *Pennisetum polystachyon* grassland was initiated in late 1989 in Nabou, about 25 km south of Nadi in the western part of Viti Levu, Fiji. The study was a collaborative effort of the Free University of Amsterdam, the Netherlands, and Fiji Pine Limited.

During the wet season, ET rates for forest and grassland will differ somewhat as a result of differences in albedo (0.19 for grass *vs.* 0.10 for pine forest; Waterloo, 1993) and rainfall interception. In the study area, the contrast in forest and grassland ET can be expected to become more pronounced during the dry season since most of the grass normally dies off, with the dead leaves effectively shading the ground and suppressing evaporation from the soil. The larger rooting depth of the pines (1-2 m *vs.* less than 0.7 m for the grass), on the other hand, will enable the trees to continue to extract water from the subsoil even though the surface layer may have reached wilting point. Therefore, the present paper will pay particular attention to ET for pine forest and grassland during the dry season.

STUDY AREA

The three study sites were located within the Nabou Forest Estate in southwestern Viti Levu (18°S, 177°E) at elevations of 115 m (Tulasewa site, 6-year-old pines), 110-250 (Oleolega basin, 15-year-old pines) and 90 m a.m.s.l. (Nabou, grassland). Topography at Oleolega was steeply dissected but gently undulating at the two other sites. Soils were generally shallow (0.5-1.5 m) and derived from andesitic to dacitic lavas and tuffs. Average annual rainfall at Nabou (1980-1991) was 1578 ± 416 mm, with a

Table 1 Average monthly rainfall amounts and standard deviations (mm) for Nabou weather station (1980-1991). Source: Fiji Meteorological Service, Nadi.

Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Average	251	265	240	162	78	72	57	67	74	80	88	145
St. dev.	138	135	164	133	107	61	38	48	53	50	48	98

distinct dry season from May to October during which period average monthly rainfall ranges between 57 and 80 mm (Table 1).

Mean monthly temperatures (1960-1975) at nearby Nadi airport ranged from about 23°C in July (southern winter, dry season) to 26.5°C in January (Coulter, 1981). Average monthly relative humidities at Nabou station (1974-1985, 8:00 a.m.) varied from 67% (beginning of rainy season) to 79% (height of rainy season) with intermediate values during the dry season (Basher, 1986). Similarly, average daily sunshine durations at Nabou (1974-1988) ranged between 5.6 h day^{-1} in March and 7.1 h day^{-1} in November (Coulter, 1982; Reddy, 1989). Easterly to southeasterly trade winds blow throughout the year. Wind speeds are generally low (about 2 m s^{-1}) and slightly higher during the dry season. However, two or three major hurricanes pass through Fiji per decade, often causing severe damage to the forests, as occurred on 29 November 1990 when cyclone Sina struck the study basin (see below).

The pines at Tulasewa had been planted in 1984 and had reached an average height of 12.4 m by mid 1990. Stocking was 837 trees ha^{-1} and leaf area index 3.6 $\pm$ 1.5 m^2 m^{-2} (Waterloo, 1993). The trees showed vigorous growth and undergrowth was dominated by Mission grass. The pines of the 60-ha study basin were planted in 1975 over 83% of the area, the remainder being occupied by grass, reeds and native forest in the riparian zone. Average height of the pine trees in 1990 was *c.* 18.5 m at a stocking of about 600 trees ha^{-1}. The Nabou grassland site was dominated by 1.8 m tall Mission grass (*Pennisetum polystachyon*) with minor contributions of ferns and other grasses (*Mimosa pudica, Sporobolus indicus*). The area had not been burned in the last 5 years. This type of vegetation shows active growth during the wet season (December-April), a flowering period at the start of the dry season (May-June) and a gradual dying off during the dry season (July-October) (Waterloo, 1993).

INSTRUMENTATION AND METHODS

Tulasewa site (6-year-old pines)

A 21.85 m meteorological tower was equipped with instrumentation to measure temperature, humidity and wind speed at 4 levels, viz. at 21, 17, 13 and 6 m (no anemometer at the lowest level). Of the three types of instruments available for the measurement of temperature and humidity (see Vugts *et al.*, 1993), only the Rotronic sensors at 13 and 21 m have been used here for the derivation of Bowen ratios (Angus & Watts, 1984). A pyranometer, an albedometer and a net radiometer were installed at 13 m to determine radiation characteristics whilst rainfall was measured using a tipping bucket recorder, also at 13 m. All instruments were calibrated before and at the start of the experiment, with subsequent intercalibration of sensors on several occasions. The soil heat flux was measured with two heat flux plates placed 2 cm below the surface. Equipment was sampled every 30 s and average values plus their standard deviations were calculated for 30-min periods using a micrologger system. The tower experienced a fetch of about 1 km towards ESE (the prevailing wind direction) and of 1.5-2.5 km in other directions. Throughfall was determined by means of 20 randomly located standard gauges which were re-randomized after every sampling event. Rainfall interception was approximated by subtracting mean throughfall values from corresponding totals of incident rainfall as measured with a standard gauge in a nearby clearing. Stemflow was not measured.

Oleolega drainage basin (15-year-old pines)

Rainfall and discharge measurements were made throughout 1990. Rainfall was measured with a tipping bucket recorder (0.4 mm resolution) placed at the basin outlet and by three standard gauges placed along the basin perimeter. Areal averages were obtained using the Thiessen method. Discharge was measured by volumetric, dilution and current meter techniques in conjunction with a water-level recorder placed 2.5 m upstream from a culvert which acted as a flume. Due to maintenance work on the culvert, water-level data was missing from 22 February until 8 March 1990. Streamflow amounts for this period were simulated by means of a model developed by Schellekens (1992).

Nabou grassland site

Daily rainfall was measured with a standard raingauge at Nabou station situated 100 m from the site. A pre-calibrated capacitance probe (Didcot Instruments) was used to measure soil moisture profiles between 28 March/24 April (access tubes 1/2) and 4 October 1991 at least once a week at 2 cm intervals down to a depth of 1.1 m. ET was calculated as total soil moisture loss above a divergent zero flux plane during periods without drainage (Wellings & Bell, 1980). Daily totals of grassland ET were also computed by summing two-hourly averages calculated with the Penman-Monteith equation (Monteith, 1965):

$$\lambda E = [\Delta(R_n - G) + \rho c_p(e_s - e)/r_a]/[\Delta + \gamma(1 + r_s/r_a)]$$

Meteorological observations commenced on 10 May when part of the grass was just starting to turn yellow and were terminated on 21 September when most of the grass had died. Wind speed and direction were measured at 5.9 m above the surface with an anemometer and a wind vane. Temperature and relative humidity were measured at 5.5 m using a thermo-hygrograph (regularly calibrated) housed in a Stevenson screen. Solar radiation was measured with a pyranometer above a mature pine forest about 4 km from the site whereas a pre-calibrated actinograph acted as a backup on the grassland site. In the absence of a continuous record of net radiation, a relationship was derived between net and shortwave radiation from synchronous measurements during 4 days in June and July at 15-min intervals between 0900 and 1800 h using a portable pre-calibrated net radiation indicator (Thornthwaite Associates). The resulting equation ($R_n = -77.7 \pm 27.2 + 0.76 \pm 0.03 * R_g$, $r^2 = 0.98$) was similar to those found for mixed prairie grassland in Canada (Ripley & Redman, 1976) or Amazonian ranchland (Wright *et al.*, 1992). Grassland albedo and a relationship between solar radiation (R_g) and soil heat flux (G) had been determined previously for another grassland site in February/March of 1991 using the same equipment as described for the Tulasewa site ($G = -2.5 \pm 3.2 + 0.015 \pm 0.002 * R_g$; $r = 0.81$). The aerodynamic resistance was calculated as:

$$r_a = \{\ln[(z-d)/z_0]\}^2/(k^2U_z)$$

where z_0 and d were assumed to be 0.12 and 0.75 times the grass height respectively (Thom, 1975). An automatic porometer (Delta T Instruments MK3) was used for the determination of stomatal resistances at 0.3, 1.0 and 1.5 m above the ground on 4 days between 18 June and 23 July. Grass biomass, specific leaf area (SLA; based on 50 fresh leaves) and leaf area index (LAI) were determined by destructive harvesting of three plots of 1 m^2 each on 10 May, 30 July and 1 September.

RESULTS AND DISCUSSION

Tulasewa

Average day-time net radiation (R_n) above the 6-year-old forest during the 145 days of observation was 309 ± 96 W m^{-2}, with typical maximum values of *c.* 650 W m^{-2} around noon on clear, sunny days and about half this value on cloudy days. Night-time minimum values were usually close to −30 W m^{-2}. The daytime storage of heat (both sensible and latent) in the soil and/or in the air column between the top of the canopy and the soil surface constituted on average about 3% of R_n (range 13%) and was, therefore, taken into account (Frumau, 1992). Bowen ratios were derived from temperature and humidity profiles between 13 and 21 m and were combined with corresponding values of available energy to determine daytime totals of ET (Fig. 1). An average value of 3.6 ± 1.0 mm day^{-1} was obtained. Dry-canopy evaporation rates at night were generally very low or nil (condensation) (Frumau, 1992). Since rainfall interception by the canopy over the period 9 May-28 September 1990 was estimated at 82 mm or 16% of total rainfall, water uptake by the vigorously growing pines (E_t) amounted to 507 mm (86% of total ET; 91% of corresponding Penman open water evaporation, E_0; Penman, 1956). The influence of soil water status on the magnitude of ET is clearly illustrated by Fig. 1.

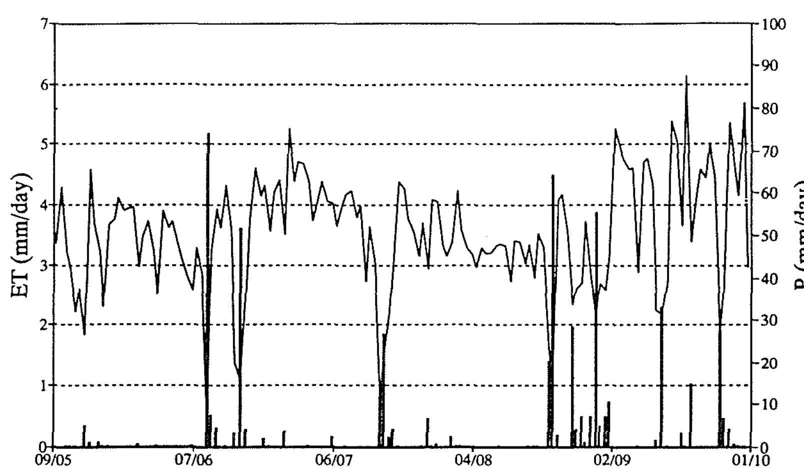

Fig. 1 Daytime evapotranspiration in a 6-year old stand of *Pinus caribaea* during 145 days in the dry season of 1990 as derived with the Bowen ratio energy balance method.

Oleolega

Total rainfall for 1990 amounted to 1847 mm, whereas streamflow was 293 mm (16% of rainfall). Some 115 mm (39%) was discharged as quickflow and 178 mm (61%) as baseflow. The overall change in groundwater storage was negligible (< 0.5 mm) while that in soil moisture was neglected as well (rainfall in December 1989 and 1990 being 67 and 84 mm, respectively). Total ET, calculated as the difference between rainfall and streamflow, was 1554 mm or 4.3 mm day^{-1}, which is slightly higher than that derived earlier for the 6-year-old forest. On the basis of throughfall data for a nearby 11-year-old stand (Waterloo, 1993), which may be considered representative for the situation at Oleolega as well, the partition of ET at Oleolega was estimated as follows. The mature pines intercepted 23% of the precipitation (*c.* 425 mm, or 27% of ET), leaving 1130 mm year^{-1} (by difference) for E_t and evaporation of water intercepted by the understorey and litter complex. Since E_0 for Nabou station in 1990 was 1812 mm, an average value of 0.86 is suggested for the ratio ET/E_0 for mature *Pinus caribaea* forest. It should be borne in mind, however, that the latter figure includes the (as yet unknown) water use by the broadleaved riparian forest (covering 17% of basin area).

Nabou

Grassland ET was derived from changes in soil moisture contents of the root zone (65 cm above a divergent zero flux plane. Any water losses below 65 cm were assumed to be due to drainage (Wellings & Bell, 1980). Changes in soil moisture with time down to 110 cm as measured in two access tubes are shown in Fig. 2. As expected, the range in concentrations was smaller for the subsoil (0.04 cm^3 cm^{-3}, drainage only) than that within the root zone (0.06 cm^3 cm^{-3}; removal of moisture by both drainage and evapotranspiration). An average value for ET of 0.9 ± 0.2 mm day^{-1} over 48 days when a divergent zero flux plane had developed around both access tubes was found.

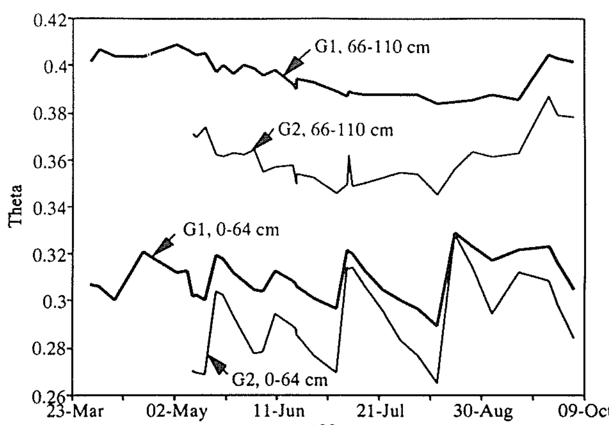

Fig. 2 Changes in soil moisture content (theta) within and below the rooting zone of a natural grassland during 131 days in the dry season of 1991 as measured in two access tubes.

To calculate daytime ET for the whole period, use was made of the Penman-Monteith equation, taking ET obtained from the depletion of soil moisture during specific periods (ET_{sm}) as a reference to derive representative values for the variation with time of r_c, the canopy (or surface) resistance of the grassland. A good fit ($ET_{p\text{-}m} = 0.9 \pm 0.3$ mm day^{-1} *vs.* $ET_{sm} = 0.9 \pm 0.2$ mm day^{-1}) was obtained when using the function:

$$r_c = 441 - 282 * \mathrm{LAI}) \qquad r^2 = 0.6, \quad n = 7$$

where LAI is the leaf area index (m^2 m^{-2}). With LAI decreasing linearly from 1.3 m^2 m^{-2} in May to 0.2 m^2 m^{-2} in September, corresponding values of day-time r_c ranged from 74 to 385 s m^{-1}. To smoothen the transition from day-time to night-time conditions (stomatal closure), nocturnal values for r_c were arbitrarily set at $1000*e/e_s$ and ranged from 500 to 1000 s m^{-1}. Finally, r_c was assumed to be zero during and immediately after rainfall events (Monteith 1965). Calculated day-time r_c values for May and June, when the grass started to die off, were within the general range for grass (60-200 s m^{-1}) given by Rowntree (1990) and similar to dry season values reported by Wright *et al.* (1992) for Amazonian ranchland. The high values derived for August and September are not unrealistic in view of the fact that most of the vegetation had died by then. Mean day-time stomatal resistances generally were quite high at 187-330 s m^{-1} above a height of 70 cm *vs.* 1240-1675 s m^{-1} between ground level and 70 cm (Waterloo, 1993).

Daily rainfall totals as well as changes in E_0, $ET_{p\text{-}m}$ (24-h totals) and ET_{sm} with time are given in Fig. 3. An average value of 1.0 ± 0.3 mm day^{-1} was obtained for $ET_{p\text{-}m}$ for the period 11 May until 19 September 1991. Since E_0 over the same period amounted to 3.7 ± 1.0 mm day^{-1}, the ratio ET/E_0 attained the low value of 0.26, reflecting the gradual dying of the grass as the dry season progressed. Total ET from the grassland over the above period was 128 mm (40% of rainfall).

The present data confirm the circumstantial evidence reported by Kammer & Raj (1979) of strong reductions in dry season flows in western Viti Levu following

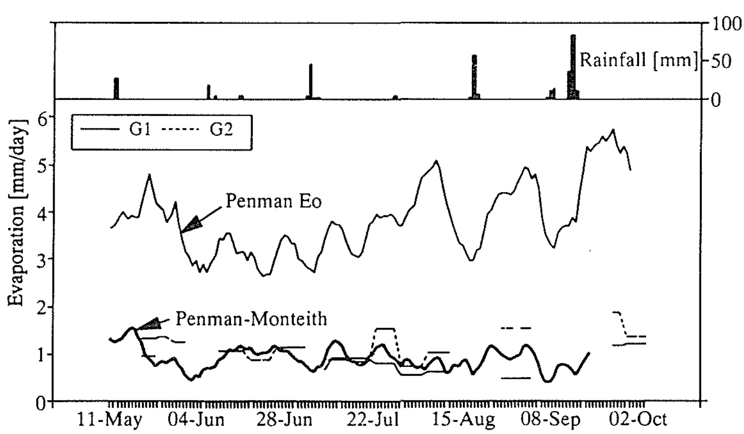

Fig. 3 Amounts of daily rainfall and evapotranspiration in natural grassland based on soil water depletion rates (access tubes G1 and 2) and the Penman-Monteith model. Penman open water evaporation added for comparison ($ET_{p\text{-}m}$ and E_0 represent 5-day moving averages).

afforestation of degraded grassland with pines. Total ET during the dry season from both young and mature pine plantations were much higher (by *c.* 3 mm day^{-1}) than that observed for natural grassland. Although our observations pertained to two different dry seasons with marked contrasts in rainfall (533 mm during 145 days in 1990 *vs.* 319 mm during 131 days in 1991), there can be little doubt that reafforestation of Fijian grasslands will produce a significant decrease in water yield during a period of year when water is already scarce.

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Geochemical characteristics of the major tropical rivers of India

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Abstract The tropical rivers, constituting a small part (960 000 km^2) of the great Indian river system are nevertheless important due to the area they drain and the density of population they serve. The annual transport of dissolved and particulate load of the ten major tropical rivers have been estimated to be around 57.5×10^6 t and 342×10^6 t respectively. The Godavari River alone transports nearly 50% of the sediment load of all the major tropical rivers. The rate of chemical erosion among these basins range from 22 t km^{-2} $year^{-1}$ to 199 t km^{-2} $year^{-1}$. Similarly, the rate of physical erosion ranged from 16 t km^{-2} $year^{-1}$ to 793 t km^{-2} $year^{-1}$. The chemistry of river water is partly controlled by chemical weathering and by monsoon precipitation and qualitatively by anthropogenic effects. Sediment chemistry indicates that Cauvery River sediments are most siliceous while those of the Godavari are least siliceous. The geology of the basins is one of the main controlling factor of the sediment transport of the tropical rivers. Sediment erosion in the basins reflect man's interference with natural processes.

INTRODUCTION

River particulate matter and dissolved salts play a significant role in geochemical cycles. The river sediment fluxes represent about three-quarters of the total denudation of the continents under present-day conditions. River sediments also adsorb and transport a number of aqueous ionic constituents. Recent compilations of the available data have estimated that the total annual discharge of river particulate and dissolved load to the coastal zones of the world under present-day conditions are 13.5×10^9 t and 3.87×10^9 t respectively (Milliman & Meade, 1983; Meybeck, 1979). The estimates for the individual continents are listed in Table 1. The suspended/ dissolved ratio reaches a maximum value of 10.45 for Oceanic and 4.04 for Asia, which mainly reflects the high suspended loads transported by rivers drawing such countries particularly Taiwan, New Guinea and New Zealand. The dissolved load exceed suspended sediment load only in Europe (Table 1).

The tropical rivers constituting a small part of the great Indian river system are nevertheless important due to the area they cover and density of population they serve.

Table 1 Dissolved and particulate loads carried by rivers to the ocean from individual continents.

Continent	Drainage area (km^2)	Dissolved load ($t \times 10^6$ $year^{-1}$)	Suspended load ($t \times 10^6$ $year^{-1}$)	Sediment yield ($t\ km^{-2}\ year^{-1}$)	Ratio of suspended /dissolved	Mean continental elevation (km)
Asia	16.88	1592	6433[a]	380	4.04	0.96
Oceania[b]	5.2	293	3062	~1000	10.45	~1.0
North America	17.5	758	1462	66	1.93	0.72
South America	17.9	603	1788	97	2.97	0.59
Africa	15.34	201	530	35	2.64	0.75
Europe	4.61	425	230	50	0.54	0.34

[a]Including value for Eurasian Arctic.
[b]Includes Pacific and Indian Ocean Islands – Japan, Indonesia, Taiwan, Philippines, New Guinea and New Zealand.
Sources: Meybeck (1979); Milliman & Meade (1983).

Major tropical rivers in India exist on the east coast, where the rivers discharge into the Bay of Bengal (Fig. 1). The present study of the major tropical rivers of India is an attempt to understand the dissolved and sediment fluxes and controlling factors involved. The general characteristics of water quality and suspended sediment for all the major tropical river basins, based on data generated in the last few years, are discussed together with some selected data from unpublished or published reports of the agencies.

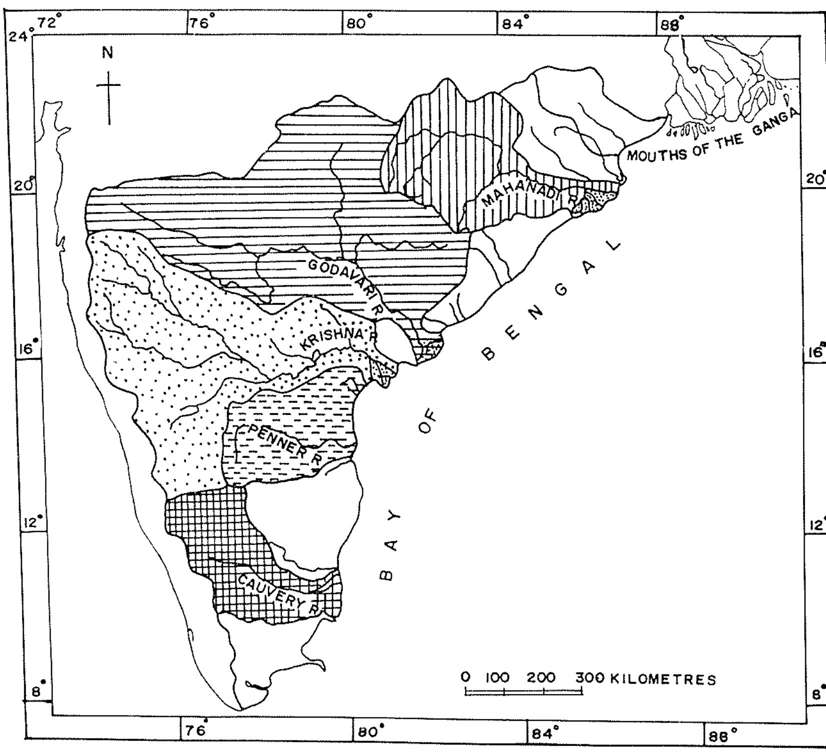

Fig. 1 (a) Map showing some of the major tropical rivers in India.

TROPICAL RIVER BASINS OF INDIA

The hydrological characteristics of major tropical river basins in India are summarized in Table 2. The total fresh-water runoff for the 10 river basins (Table 2) is 281 × 10^9 km^3 $year^{-1}$, which is about 17% of the water discharge from the Indian subcontinent. Unlike the large river system of the Amazon (water discharge 6340 km^3 $year^{-1}$) representing a single drainage network, the Indian rivers cover different climatological, geographical and geological formations. The Godavari, Krishna and Cauvery river basins together account for over 60% of the tropical Indian river system (Fig. 1). These rivers rise in the Western Ghats and flow about 1000 km before discharging into the Bay of Bengal. The Godavari and Krishna river basins are under the influence of a semiarid climate. The Cauvery crosses different climatic zones. The northwestern side of the basin is bounded by per-humid climate. After passing from northwest to east, the river crosses humid, moist humid, dry sub-humid and semiarid climate zones. Drainage and the geological formation of these rivers as well Pennar and Mahanadi Rivers is provided in Fig. 1(a) and 1(b).

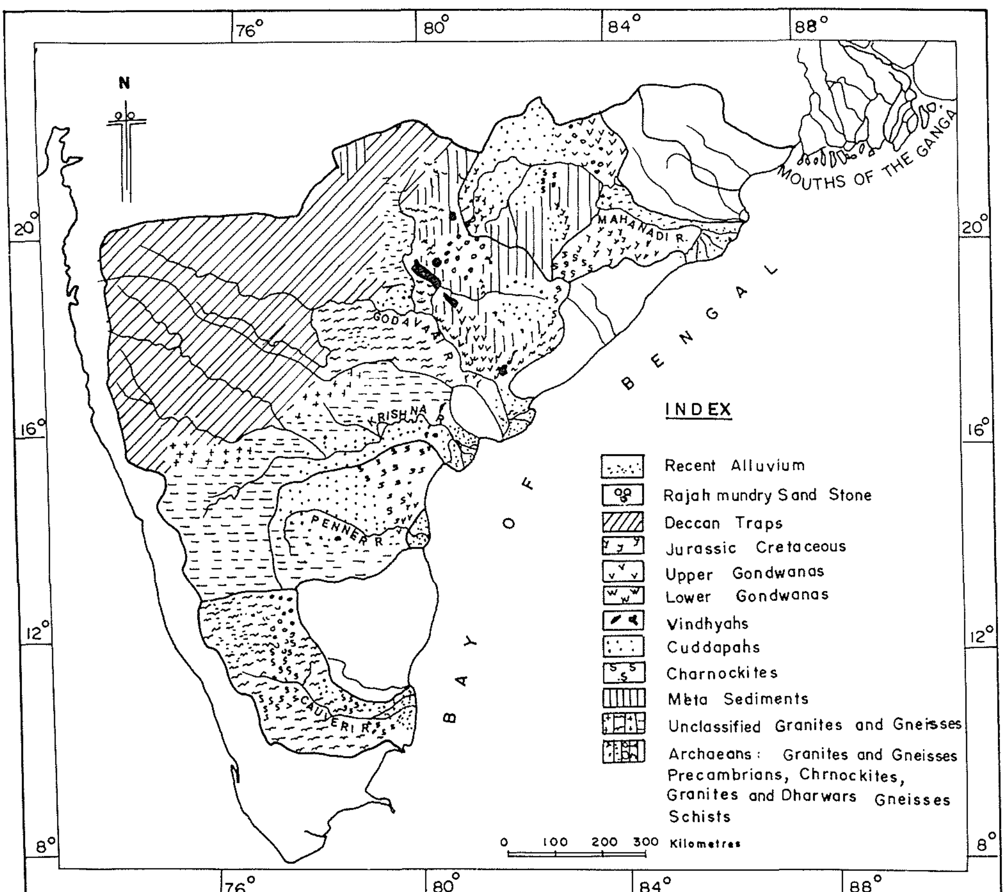

Fig. 1 (b) Map showing geological formations in some of the major tropical rivers in India.

Table 2 Mean discharge, transport and erosion rates of the major tropical rivers of India.

River	Station	Drainage area (km^2)	Annual runoff (10^6 m^3)	TDS (mg l^{-1})	TSM (mg l^{-1})	Chemical load (10^6 t $year^{-1}$)	Sediment load (10^6 t $year^{-1}$)	Total load (10^6 t $year^{-1}$)	Chemical erosion rate (t km^{-2} $year^{-1}$)	Sediment erosion rate (t km^{-2} $year^{-1}$)	Total erosion rate (t km^{-2} $year^{-1}$)	Ratio of sediment/ chemical loads
Godavari	Rajhamundry	313 147	92 245	181	1845	16.7	170	186.7	53.3	543	596	10.2
Krishna	Vijayawada	251 360	32 397	360	122	11.7	4	15.7	46.4	16	62	0.34
Cauvery	Musiri	87 990	11 510	172	120	2.0	1.4	3.4	22.5	16	39	0.71
Mahanadi	Tikarapara	88 320	54 431	149	563	8.1	30.6	38.7	91.8	347	439	3.8
Narmada	Garudeshwar	87 892	46 673	224	1494	10.5	69.7	80.2	119.0	793	912	6.7
Tapti	Savkheoa	49 136	9 713	294	2546	2.9	24.7	27.6	58.1	503	561	8.7
Pennar	Somasila	48 660	5 203	210	1322	1.1	6.9	8.0	22.5	142	165	6.3
Brahmani	Samal	28 200	16 340	72	1241	1.2	20.3	21.5	41.7	720	762	17.3
Mahi	Kadana	25 501	10 817	260	895	2.8	9.7	12.5	110.3	380	490	3.5
Sabarmathi	Valasana	14 176	1 450	352	3143	0.5	4.6	5.1	36	325	361	9.03
Total		994 292	280 779	-	-	57.5	341.9	399.4	58	344	402	5.9

TDS = total dissolved solids (discharge weighted average); TSM = total suspended matter.

METHODOLOGY

Water samples were collected mid-river from the Godavari, Krishna and Cauvery rivers and its major tributaries at least four times since 1982 to broadly cover the seasonal and annual variations. Suspended sediments were separated by 0.45 μm millepore filtration in the laboratory. Preservation of samples, laboratory processing and analytical methods were based on standard techniques and details have already been reported (Subramanian, 1979). Additional data on discharge chemistry and sediment load for other river basins (Tables 2, 3 and 4) obtained from several published/unpublished reports of government agencies in India.

Table 3 Chemical composition, fluxes and erosion rates of the dissolved constituents in the major tropical rivers of India.

River	HCO_3	Cl	SiO_2	SO_4	Ca	Mg	Na	K
Godavari	105[a]	17	8	16	22	5	12	3
	9.69[b]	1.57	0.74	1.48	2.03	0.46	1.11	0.28
	30.93[c]	5.01	2.36	4.71	6.48	1.47	3.53	0.88
Krishna	178	38	49	24	29	8.1	30	2.4
	5.77	1.23	1.58	0.78	0.94	0.26	0.97	0.08
	22.94	4.90	6.32	3.09	3.74	1.04	3.87	0.31
Cauvery	53.3	18	39	8.4	15.4	16	30	2.6
	0.61	0.21	0.45	0.10	0.18	0.18	0.35	0.30
	6.98	2.36	5.11	1.10	2.02	2.10	3.93	0.34
Mahanadi	66	11.7	NA	20.5	20	4.3	3.4	2.4
	3.59	0.64	-	1.12	1.09	0.23	0.19	0.13
	40.68	7.21	-	12.63	12.33	2.65	2.10	1.48
Narmada	108.4	30	20	21.4	17	12.4	9.0	6.6
	5.06	1.40	0.93	1.08	0.79	0.58	0.42	0.31
	57.56	15.93	10.62	11.36	9.03	6.58	4.78	3.50
Tapti	173.1	20.3	29.4	31	28.5	13.2	28.5	3.2
	1.68	0.20	0.29	0.30	0.28	0.13	0.28	0.03
	34.22	4.01	5.81	6.13	5.63	2.61	5.63	0.63
Pennar	116	32	NA	35	34.5	6.6	30.3	2.1
	0.60	0.17	-	0.18	0.18	0.03	0.16	0.01
	12.40	3.42	-	3.74	3.69	0.71	3.24	0.22
Brahmani	54	9	NA	28.5	11	3.5	5.7	2.3
	0.88	0.15	-	0.47	0.18	0.06	0.09	0.04
	31.29	5.21	-	16.51	6.37	2.03	3.30	1.33
Mahi	145	23	NA	5.5	39	9.5	12.5	1.7
	1.57	0.25	-	0.06	0.42	0.10	0.14	0.02
	61.51	9.76	-	2.33	16.54	4.03	5.30	0.72
Sabarmathi	1.55	51	NA	10.5	38.9	14	32.5	3.2
	0.22	0.07	-	0.02	0.06	0.02	0.05	0.01
	15.85	5.22	-	1.07	3.98	1.43	3.32	0.33

NA = not available.
[a] Chemical composition in mg l^{-1}.
[b] Dissolved flux in 10^6 t $year^{-1}$.
[c] Erosion rate in t km^{-2} $year^{-1}$.

Source: The values for Godavari, Krishna and Cauvery were measured by the authors and for other rivers from unpublished data of the author and also of the Central Water Commission (CWC).

Table 4 Major elemental composition, fluxes and erosion rates of five major tropical rivers of India.

Element	Godavari	Krishna	Cauvery	Narmada	Tapti
Si	220 000[a]	304 300	346 000	302 000	325 000
	37.4[b]	1.22	0.48	21.05	8.03
	119.4[c]	4.85	5.46	239.50	163.42
Al	43 100	22 500	44 400	28 900	44 400
	7.33	0.09	0.062	2.01	1.10
	23.4	0.36	0.71	22.87	22.39
Fe	57 100	25 100	17 600	31 400	109 000
	9.71	0.1	0.0246	2.19	2.69
	31.0	0.4	0.28	24.92	54.75
Mg	13 720	6 500	11 000	10 200	24 000
	2.3	0.026	0.0154	0.71	0.59
	7.34	0.1	0.18	8.08	12.01
Ca	45 780	24 100	15 000	20 100	81 600
	7.78	0.096	0.021	1.40	2.02
	24.84	0.38	0.24	15.92	41.11
Na	NA	55 600	NA	NA	NA
	-	0.222	-	-	-
	-	0.88	-	-	-
K	10 340	38 200	11 020	9 300	4 200
	1.76	0.153	0.015	0.65	0.104
	5.62	0.61	0.17	7.40	2.12
Ti	8 640	3 158	2 950	4 000	21 050
	1.47	0.013	0.004	0.28	0.52
	4.69	0.052	0.05	3.19	10.58
Mn	1 070	906	319	514	1300
	0.18	0.004	0.0005	0.036	0.032
	0.57	0.016	0.006	0.41	0.65

[a] Concentration in $\mu g/g^{-1}$.
[b] Flux in 10^6 t $year^{-1}$.
[c] Erosion rate in t km^{-2} $year^{-1}$.

RESULTS AND DISCUSSIONS

River water composition and fluxes

The discharge weighted mean chemical composition of the major ten rivers are presented in Table 3. Also shown are the dissolved flux and erosion rates of individual elements. The HCO_3^- ions are nearly more than 50% of the total dissolved solids (TDS) of the major tropical rivers. High TDS is generally reflected in higher alkalinity and Cl content. The dissolved K content in river water (except Narmada) is uniform for all the basins irrespective of size and location suggesting conservative behaviour in the river system. The high carbonate alkalinity may reflect intensive chemical weathering. Also, atmospherically regulated CO_2-water reactions, especially in the monsoon period, may further enhance the carbonate alkalinity. Gibbs (1970) classified world rivers into three categories: (i) those dominated by rock weathering; (ii) those controlled by precipitation and (iii) those controlled by evaporation. On a diagram developed by him, not shown here, various Indian tropical rivers are plotted and it shows that chemical weathering contributes the bulk of TDS. In addition to weathering, atmospheric contribution provide a major source of certain constituents, such as SO_4, in Indian tropical rivers. For example, in the Godavari river basin nearly 60% of the dissolved load is atmospherically recycled (Biksham & Subramanian, 1980).

The major Indian tropical rivers carry 57.5×10^6 t year^{-1} of solutes which is less than the load transported by the Ganges (76×10^6 t year^{-1} or Brahmaputra (76×10^6 t year^{-1}). It is well known that physical weathering is more dominant in Asian rivers (Gibbs, 1981) than chemical weathering. However, for the Krishna and Cauvery the chemical load is more dominant (Table 2) than sediment load. It should also be noted that the solute yield of Indian tropical rivers is higher than the global average (58 t km^{-2} year^{-1}).

Sediment transport and fluxes

The major tropical river basins are transporting about 342 million tonnes of sediments into the Bay of Bengal and the Arabian Sea (Table 2). Only the Godavari River

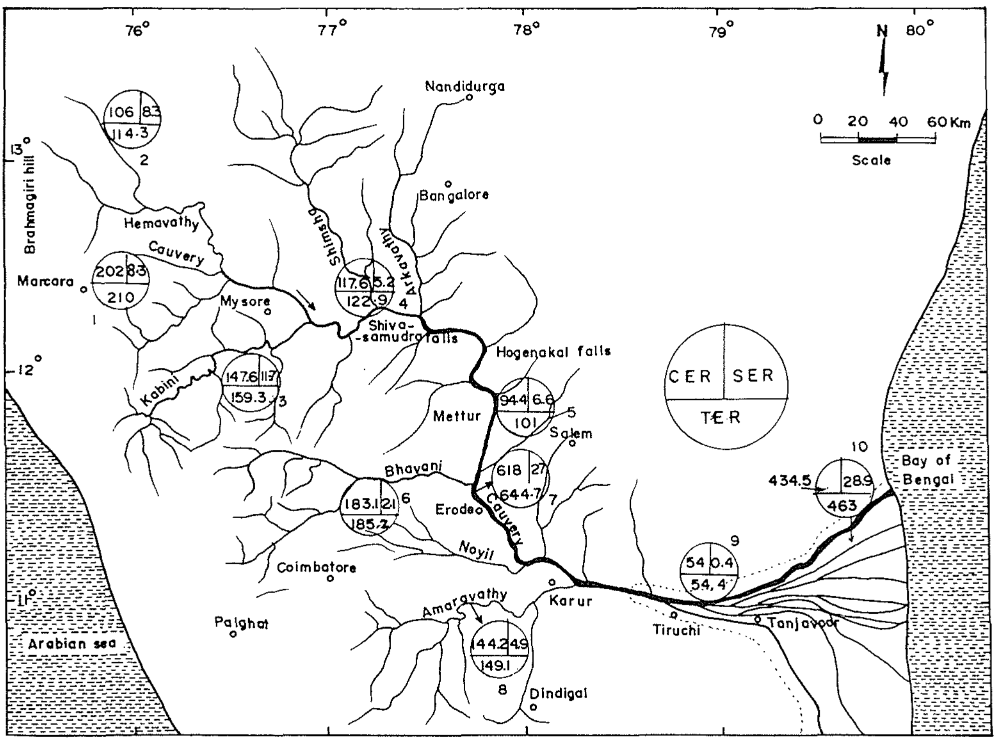

Fig. 2 Erosion rates in the Cauvery River basin (after Subramanian *et al.*, 1993). CER = chemical erosion rate; SER = sediment erosion rate; TER = total erosion rate.

contributes significant sediment load from tropical rivers. Nearly 90% of the sediment load in the Indian sub-continent is derived from the Ganges and Brahmaputra (1226 million t $year^{-1}$). The rivers are eroding at the rate of 344 t km^{-2} $year^{-1}$ which is very high compared to many world rivers (for example Amazon 146 t km^{-2} $year^{-1}$; Mekong 200 t km^{-2} $year^{-1}$; world average 150 t km^{-2} $year^{-1}$) of similar climatic, topographic and geological conditions. In the Krishna and Cauvery river basins, the major portion of the sediment load is being deposited behind dams located at river mouths. For example, Fig. 2 shows the nature of solute and sediment erosion rates prevalent in the entire Cauvery basin (Subramanian *et al.*, 1993). It will be evident from the figure that both the Krishnaraja Sagar Dam region and the Erode Mettur Dam region (locations 4 and 5) show abnormal erosion rates indicating the impact of man on natural rate processes. Similarly, in the estuary region of the river (location 10) involving extensive agricultural activities, the erosion rates are very high. Thus, the Cauvery River system no longer represents natural hydrological process.

Table 4 gives the chemical composition, annual flux of individual elements for the four major tropical rivers together with erosion rates. The annual flux of different elements ranged from 37.4×10^6 t for Si and 0.5×10^3 t for Mn. Fe, Ca and Ti contents in Tapti sediments are abnormally high relative to other tropical rivers. The Cauvery seems to carry highest siliceous materials compared to other rivers.

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