Dissolved matter fluxes in the inner delta of the River Niger

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Abstract This study is part of the EQUANIS programme, the objectives of which are (a) estimating inputs from the River Niger to the inner Delta; (b) computing the hydrological balance; and (c) monitoring the quality of water in the central lacustrine basin. Eleven sampling locations were selected near gauging stations, both on the Niger River and its main tributary, the Bani River. Those sites have been sampled weekly since July 1990. The inner delta of the Niger River is a system particularly subject to sahelian and sub-desert climatic conditions and characterized by large flood plains. Time series of input water volumes in the inner delta, and of the water losses within it, show that the water losses are high, due to the intense evaporation, and vary from 6 to 40 km^3. The water losses reach their maximum during the wettest years—up to 47%, and minimum during the driest years—only 32%, due to the reduction of the flooded area. The surface of the flooded area is inferred from the hydrological balance. The preliminary results of this study indicate that the Niger and Bani rivers have low levels of dissolved element concentrations. The mean conductivity values, ranging from 50–80 $\mu S\ cm^{-1}$, increase regularly during the low water stage and decrease drastically with rising water. The pH values are slightly basic, ranging from 7.1 to 8. Silica and bicarbonates are the main dissolved species; they always represent more than 75% of TDS. In May, when the rising water stage begins, the waters are poorly mineralized at the input of the delta, while they have been enriched during the dry season in the delta. A good mass balance is found between inputs and outputs through the delta. However, a disequilibrium appears at the sampling sites within the basin, which could be partially linked to poor mixing between the Niger and Bani river waters. The first results from the upper basin and below the inner delta, show low concentrations of matter. The specific dissolved loads vary between 10–12 t km^{-2} $year^{-1}$ for the Niger River and 2.5 t km^{-2} $year^{-1}$ for the Bani River. The annual input in the inner delta was about 2.2×10^6 t in 1992–1993. Chemical budgets show a saline deposit of 0.3×10^6 t in the inner delta. Seasonal variations of the dissolved matter fluxes are very different between the upper and lower parts of the inner delta, due to the breaking of the annual flood and to the more important flood plains in the upper delta.

Los flujos de materiales disueltos en el delta inerior del Níger

Resumen Es presente estudio forma parte del programa EQUANIS, cuyos objetivos son (a) estimación de los aportes del río Níger al delta interior, (b) cómputo del balance gídrico, y (c) monitoreo de la calidad del agua en la cuenca lacustre central. Se seleccionaron once sitios de muestreo próximos a las estaciones de aforo tanto en el Níger como en su principal afluente, el Bani. Desde julio de 1990 se llevaron a cabo allí muestreos semanales. El delta interior del Níger is us sistema particular sometido a condiciones climáticas "sahelianas" y subdesérticas, y se caracteriza por grandes planicies de inundación. Las series temporales de aporte hídrico in il delta interior, y de pérdidas de agua en is mismo, muestran que las pérdidas son elevadas debido a la evaporación intensa, y fluctúan entre 40 y 6 km^3. Las pérdidas de agua son máximas durante los años más húmedos (hasta un 47%) y mínimas durante los años más socos (solo 32%) debido a la reducción de las áreas inundadas. La superficie inundada se deduce del balance hídrico. Los resultados preliminares del estudio indican que los ríos Níger y Bani tienen un bajo nivel de concentración de elementos en disolución. Los valores medios de conductividad que van de 50 a 80 $\mu S\ cm^{-1}$ se incrementan regularmente durante el período de estiaje y disminuyen drásticamente en períodos de avenidas y variacíon de niveles. Los valores de pH son ligeramente básicos, de 7.1 a 8. Los principales materiales dusueltos son el sílice y los bicarbonatos; siempre representan más del 75% del TDS. En mayo, cuando se inicia el período de crecida, las aguas contienen pocos minerales en la entrada del delta mientras que se han concentrado durante la estación seca del delta. Se observa un buen balance de masa en el delta entre los aportes y descargas, pero aparece un desequilibrio en los sitios de muestreo dentro de la cuenca, que puede atribuirse parcialmente a una mala mezcla entre las aguals del Níger y del Bani. Los primeros resultados en la cuenca superior y baja del delta interior muestran bajas concentraciones de material. Las cargas disueltas específicas fluctúan entre 10 y 12 t km^{-2} $año^{-1}$ para el río Níger y 2.5 t km^{-2} $año^{-1}$ para el río Bani. El aporte anual en el delta interior fue de unos 2.2×10^6 t en 1992–1993. Los balances químicos presentan un depósito salino de 0.3×10^6 t en el delta interior. Las variaciones estacionales de los flujos de materiales son muy diferentes entre las partes alta y baja del delta interior, debido al inicio de la crecida anual y a las más importantes planicies de inundación en la parte superior del delta.

INTRODUCTION

Since 1990, the EQUANIS project on the environment and quality of contributions of the Niger River to the Sahel has been developed in Mali to establish a network of observation stations of flows of suspended and dissolved matter. The project has been gradually developing the theme of research of the PEGI programme (INSU, Institut National Scientifique de l'Univers; CNRS, Centre National de Recherche Scientifique; ORSTOM). This programme combines several subjects:

- the estimation of the solid and liquid contributions of the Niger River to the central delta;
- modelling of the water balance of the inner delta of the Niger using calculations of water losses and the evolution of concentration of dissolved matter to establish a relationship between flooded surface and duration of flood;
- the supervision of the environment and the water quality to detect major alterations of the system;
- the establishment of relationships between renewable hydrological resources and renewable living resources.

The network depends on the knowledge of water transfers well identified by reference gauging stations (Brunet-Moret *et al.*, 1986). Measurement protocols have been adapted to particular conditions of the hydrographic system of the Niger River, notably in the lacustrine basin where flows are particularly slow and where the vast flood plains allow the observation of deposits and the evolution of dissolved matter flows.

The regime of export of dissolved matter of the basins is being studied at the Ké-Macina station (see Fig. 1)(after withdrawal of canal flows by the Office of Niger for

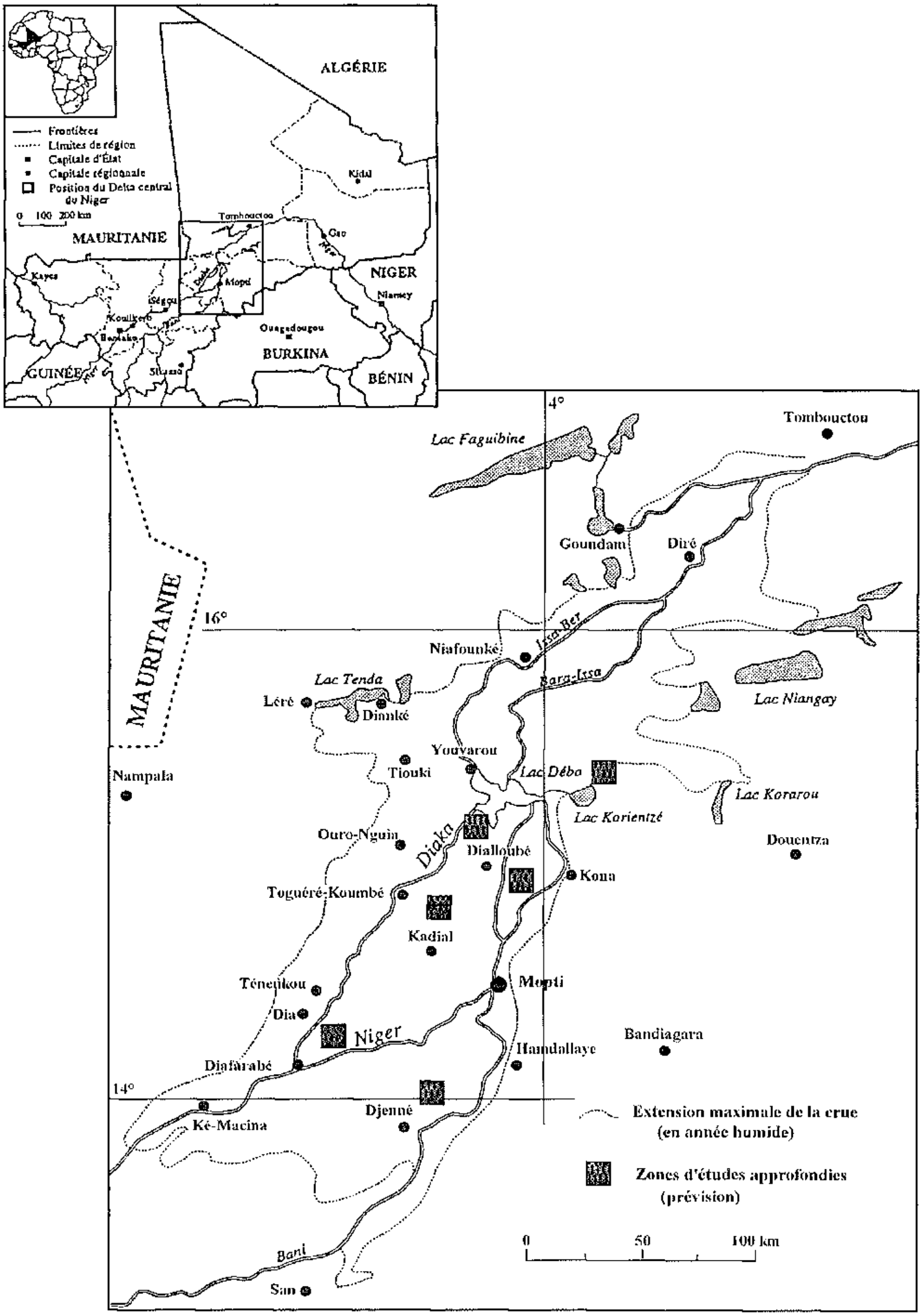

Fig. 1 EQUANIS project area, with maximum limit of the flooded area and permanent rivers.

irrigation, and by the Markala Dam), and at the Douna station on the Bani River, principal tributary of the Niger (basin of 102 000 km^2 in natural regime). These two stations have been retained as references of input flows in the lacustrine basin, i.e. the inner Delta of the Niger River.

The study of the main outflows of the Niger–Bani system in the inner Delta is assigned to Kara station on the Diaka River, Tilembeya and Mopti stations on the Niger River, Sofara station on the Bani River, before the waters of the upstream basin meet in Lake Débo.

A first budget for outputs from Lake Débo is calculated using the three outflows of the lake from Aka station on the Issa Ber, Awoye station on the Bara Issa and Korientze station on the Koli-Koli. These three outflows form a unique reach level upstream to Diré; it is at this station that the total outputs of the inner delta are controlled.

STUDY SITE AND METHODOLOGY

The lacustrine basin of the Niger River

The Niger, a great African river, crosses right through Mali and, in the centre of the country, floods an area of some thousands of square kilometres. The river has its source on the humid Guinean plains and, downstream of Mopti, receives the Bani River coming from the less watered regions of Ivory Coast.

The long-term mean annual discharge values for the period 1935–1995 were 1200 m^3 s^{-1} at Ké-Macina, 335 m^3 s^{-1} at Douna (Bani), 992 m^3 s^{-1} at Mopti (junction of the two rivers) and 971 m^3 s^{-1} at the exit of the basin at Diré (Fig. 2). The hydrograph is tropical sudanian (Brunet-Moret *et al.*, 1986).

The hydraulic slope is 7 cm km^{-1} upstream of Ké-Macina and rapidly falls to 4 cm km^{-1}. The slope downstream of Lake Débo does not exceed 0.7 cm km^{-1}. This

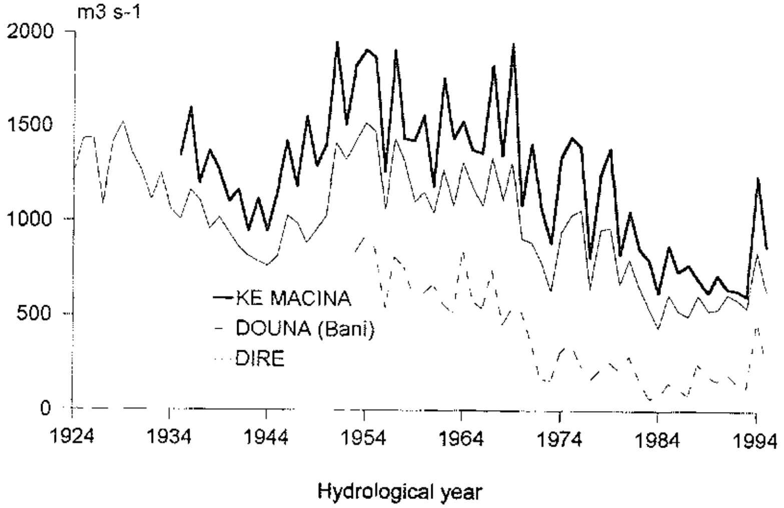

Fig. 2 Annual discharge variation for the Niger River basin.

provokes a slowing that, during the annual flood, gives rise to a deposit of the load and overflow of the waters. The lacustrine basin formed lies between latitude 13–17°N and longitude 3–5.3°W with variable peripheries according to the intensity of the flood and the rapidity of the inflow. The lakes in this region are not fed regularly and their volumes vary markedly according to the season and the magnitude of the flood.

In this basin, the evaporation from the free water surface is between 1900 and 2300 mm $year^{-1}$. Evaporation is at a maximum at the end of the dry season when the land is partly out of the water. Climatic factors remain very favourable to evaporation at the maximum flood. The temperature is raised, the continental trade winds (Harmattan) blow regularly and the air humidity is low. The region undergoes a gradient of regime from a sudanian climate to the south passing through a sub-sahelian climate to the north, and then desert. On the actual inner basin, annual rainfall averages are 200 and 600 mm with rainfall mainly in July–October. The month of August is the wettest. The dry season of December–April lengthens toward the north.

Methodology

Since July 1990, several observation stations have been installed on various branches of the river in the lacustrine basin. Sampling points have been chosen so as to cover the entire basin and so that they are near a gauging station whose daily budgets are recorded by the Direction Nationale de l'Hydraulique et de l'Energie (DNHE, National Board of Hydraulics and Energy of Mali).

Three litres of water were collected weekly at each of these stations (from the left, middle and right of the waterway). Samples were taken to a depth of 60 cm. Bottles were brought to the ORSTOM centre at Bamako every three months. After measuring the conductivity and pH, the water was filtered on membranes of 0.20 μm pore size. A volume of 250 ml of the filtered water was sent to the ORSTOM centre at Bondy (France) for chemical analysis.

RESULTS AND DISCUSSION

Hydrology

Ké-Macina represents an inlet to the inner delta. On the Bani River, between Douna and Sofara, many branches leave to rejoin the Niger River upstream of Mopti. The station of Douna that is located upstream of the flood zone was therefore preferred for the solid and liquid budget calculations.

In the delta, the three stations that have been taken in to account at the exit of Lake Débo are Aka, Awoye and Korientze, which represent respectively 558, 61 and 21 $m^3 s^{-1}$ of annual mean discharge, being 87, 10 and 3% of the water discharge. At the exit of the delta, at Diré station, a discharge of 546 $m^3 s^{-1}$ indicates that 26% of the water that entered the delta has evaporated, which represents 6.2×10^9 m^3 annually (DNHE, 1990, 1991).

Regime of dissolved matter export from the upstream Niger basin

The waters of the Niger between Ké-Macina and Diré are poorly mineralized. Dissolved concentrations are between 30 and 80 mg l^{-1} for the Niger River at Ké-Macina (Fig. 3) and 20–100 mg l^{-1} for the Bani at Douna. The behaviour of the annual dissolved concentrations is similar to that of other sahelian rivers (Orange, 1992; Gourcy, 1994). The strongest concentrations occur at the end of the dry season with a minimum from the beginning of the flood period, so that the runoff phase is the most intense in relative value as compared to the delayed flow. The progressive increase of concentrations during the annual flood converts into an increasing contribution of underground waters (Gourcy, 1994). At the end of the flood abatement, when the superficial flow has ended, the phase of depletion is marked by a stronger increase in concentrations.

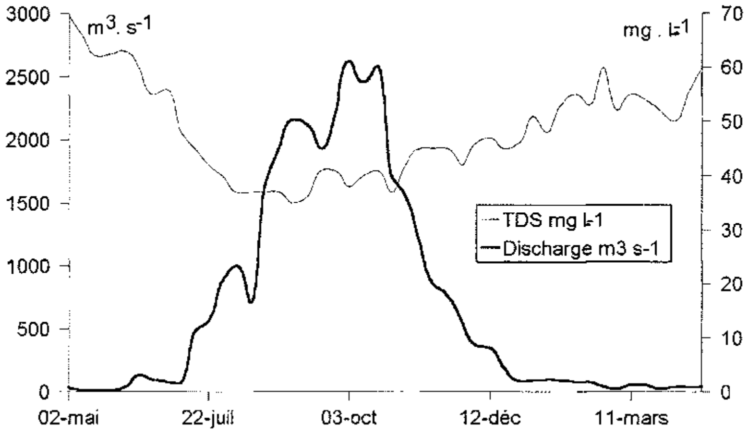

Fig. 3 Example of the relation between discharge and TDS concentration (Ké-Macina on the Niger River, 1992–1993).

The pH of the water is slightly basic all year (between 7 and 8). The pH of the Bani River ranges from 7.1 in August to 7.9 in May–June. The average is 7.5, while on the Niger at Ké-Macina it is 7.3. The most basic pH values are observed in periods of low water.

The amplitude of concentration variations is smaller for the Niger River at Ké-Macina. Indeed, dry season discharges are sustained by releases from the Sélingué dam (stocking volume 2×10^9 m^3); and these dam waters (origin essentially linked to superficial flows of the preceding rain season) are less concentrated in dissolved elements.

Silica represents between 9 and 38% of the total weight of dissolved elements (see Fig. 4). These high contents are explained by the geology of the basin crossed by the river, which is usual for river waters in west Africa (Gac, 1980; Probst, 1992; Orange, 1992). Furthermore, the raised temperature of the water, 20–25° in the winter period and 25–30° in the dry season, increases the solubility of the silica (Berner & Berner, 1987; Meybeck, 1979).

Bicarbonates represent 41–68% of dissolved elements. The contribution is essentially atmospheric and can come equally from the oxidation of organic matter

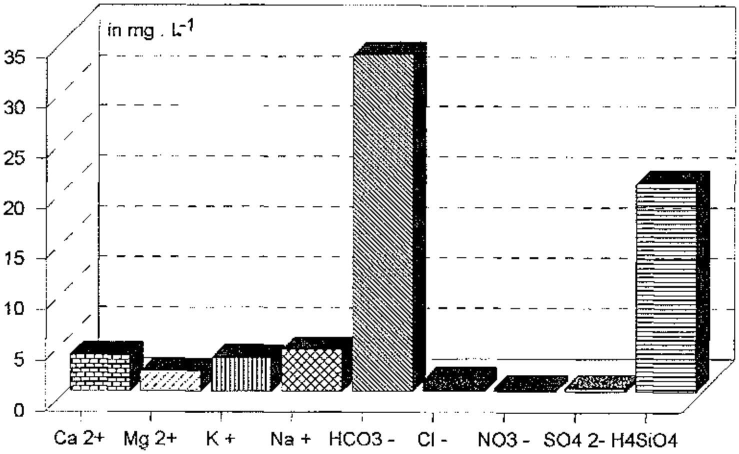

Fig. 4 Mean chemical composition of the water in the inner delta.

accompanied by an increase in the content of bicarbonates and protons (H^+) (Pickering, 1989).

Sulphate and nitrate contents represent only 0–2% of total dissolved elements but are not significant considering the time of sample storage. The proportion of each element remains stable all the year. Only bicarbonates increase during the low water season in contrast to the silica values. The pH values are also clearly more basic. Waters are less basic at the beginning of the flood, up to the moment where the waters are high (Lowe-McConnel, 1985; Gourcy, 1994).

The concentrations of dissolved elements increase steadily during the dry season and then, from the beginning of the flood, decrease rapidly. Waters concentrate then during the decrease. The concentrations of Ca^{2+}, Na^+ and HCO_3^- are strongly related to discharge ($R < -0.84$). Similarly, Mg^{2+} evolves conversely to the discharge but the correlation is less good. Chloride ions, potassium and silica have an evolution that is not related to discharge (Gourcy, 1994).

In contrast to the River Niger, the waters of the River Bani have stronger concentrations in calcium and bicarbonate and weaker concentrations in silica and sodium. The silica does not represent more than 25% of the dissolved elements.

BUDGET AND VARIATION OF DISSOLVED MATTER IN THE LACUSTRINE BASIN

The Niger River crosses the lacustrine basin and the inner delta with very slow flows. So its flood plains do not noticeably modify the load of dissolved elements of the river. One can distinguish two parts in the inner delta:

- an upstream part: a vast spreading zone, again largely flooded by the annual flood despite the water deficit, that ends at Lake Débo, a major and permanent aneurysm of the hydrographic system of the region (Fig. 5(a));
- a downstream part: where the very different geomorphology is characterized by the superposition of anterior deltaic forms of Holocene erg pipe, oriented east–

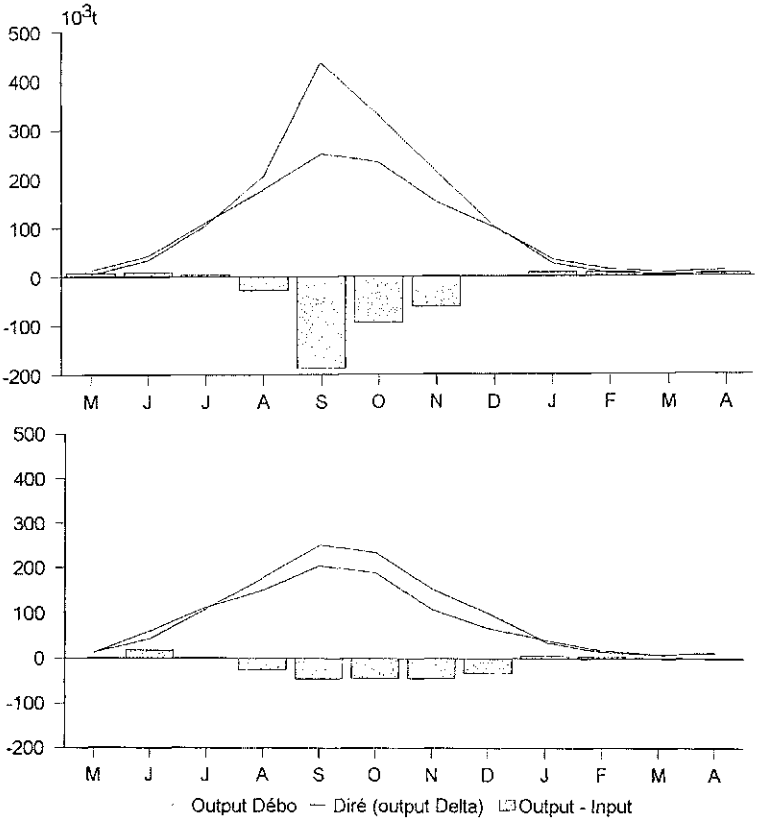

Fig. 5 Monthly balance of the dissolved load fluxes in the inner delta, 1992–1993: (a) upper part, and (b) lower part.

west, to show a very diffuse hydrographic system, often ordered by sandhill furrows, with zones of more reduced flood (Fig. 5(b)).

The study is based on observations undertaken at upper entries of the delta (Ké-Macina and Douna stations), at the exits of Lake Débo, and at the exits of the downstream delta at Diré station.

Annual flow budget of dissolved matter in the inner delta

The Niger and Bani rivers have brought to the delta a mean annual dissolved matter flow of 1–1.2 $\times 10^6$ t. The general budget of the evolution of these flows calculated for the hydrological year 1992–1993 show that the global load measured at Diré station falls was 890 000 t of dissolved matter. The total inner delta has retained 300 000 t of salts.

Table 1 gives details of the annual loss observed in 1992–1993. Intermediate measures undertaken at the exits of Lake Débo show a very different behaviour of upper and downstream parts of the inner delta. The average concentrations of dissolved matter essentially have not varied in the traverse of the inner delta. A deposit of 300 000 t of salts in the lacustrine basin, with more than two-thirds in the

Table 1 Water balance and dissolved matters budget in the inner delta (year 1992–1993).

	Flow (10^9 m^3)	Dissolved matter tonnage (10^3 t)	Concentration (g m^{-3})
Inputs Ké-Macina + Douna	24.22	1189	(49.1)
Upstream losses	3.72	213	
Outputs Lake Débo	20.5	976	(47.6)
Downstream losses	2.46	87	
Output to Diré	18.04	889	(49.2)
Total losses	6.18	300	

upper part, represents only a layer one hundredth of a millimetre thick over the area of zones flooded in the current deficient period, but the long-term consequences of such deposits would have to be perceptible. It is clearly demonstrated in records of average conductivity of the superficial water table, established by the National Board of Hydraulics (Mali), where an enrichment in salt is clearly shown in external water tables of the zone; in addition, in straight bank lakes of the Niger deposits and saline encrusting are found. It is not excluded that a functioning of the typical Lake Chad (dunes of the Kanem) similarly limits the impact of the losses in salts in the actual delta (Roche, 1973; Gac, 1980). The monthly flow variations of matter provide some complementary information on the hydrodynamic functioning of the Niger in its crossing of the Delta.

Seasonal flow variations of matter in the inner delta

Monthly flow variations of dissolved matter show a diagram less differentiated between the two parts of the inner delta. In the upstream part, losses are maximum in September, the month in which water is deposited in the flood plains of the lacustrine basin, with 240 000 t; losses in October reach 55 000 t. In November, December and January, a return to the river of part of the volume of the flood waters returns an excess of dissolved load as compared to inputs, that does not exceed the total 40 000 t.

In the downstream part, losses are more obvious between August and December, with a maximum in September limited to 40 000 t.

At the Ké-Macina and Douna stations, the increase of concentrations begins before the flood has reached its maximum. The superficial water table and the flow of subsurface waters influence the water quality. There is evaporation on the part above the water table during the dry season. The first rains that infiltrate move through a ground enriched in salts. These two types of waters arrive with a slight delay in the flood. At Kara station, until the outputs of Lake Débo, the increase of concentrations in dissolved elements begins after the flood maximum has passed. On the other hand, at Ké-Macina and Douna stations, the significant evaporation on the superficial water table, and on marshes and lakes, entails a gap between the flood and the increase of concentrations in dissolved elements.

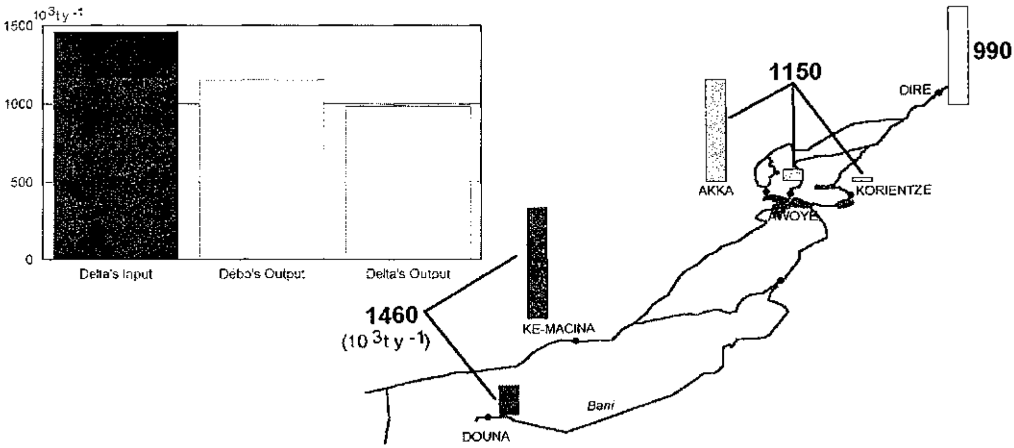

Fig. 6 Budget of dissolved matter fluxes through the inner delta of the Niger River.

CONCLUSION

After five years of flow and water quality measurements in the inner delta of the Niger River, it emerges that the complexity and diversity of the hydrographic system in this sahelian region renders input-output studies of the flood zone particularly difficult. Two sectors can be distinguished, the downstream and the upstream of Lake Débo. The entries are Douna and Ké-Macina, and the exits of Lake Débo are at Aka, Awoye and Korientze stations (Fig. 6).

Currently, the flood occurs essentially on the upstream part of the Débo and notably along the Diaka River.

The effect of evaporation is certainly a predominant factor. But the weak concentrations of dissolved elements in the river waters and their very small variations do not allow a fine analysis of the functioning of the delta.

During the hydrological cycle in the marshes, salts are probably taken up by the vegetation and accumulated in sediments of lakes and temporary pools. Some may be picked up by winds when lakes dry (Grove, 1972). Salts follow a complex cycle that is emphasized by a constant regression of the height of the flood. In order to better analyse the hydrochemical functioning of the inner delta and to calculate models of dilution, the observations at main stations need to be maintained with a regular frequency, especially during flood times.

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