GLOBAL ENVIRONMENT FUND

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INTEGRATED MANAGEMENT OF LAKE CHAD

"B" preparatory assistance

RAF/95/G48

DIAGNOSTIC FILE
SUBJECT #1 : PHYSICAL HYDROSYSTEM

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Summary

FOREWORD

Our intervention takes place at the beginning of a preparatory assistance process of GEF, with UNDP as leader agency, and UNO-DADSG as executive agency. According to the terms of reference of this intervention in integrated management of water resources (complete text is in annex A), we were to:

1. to bring out a diagnosis on the Lake Chad waters and basin behavior;

2. to direct the preliminary assistance of the GEF future program in order to

   — take into account the known constraint linked to the mastery of international water resources, their variability and the identifiable risks,

   — give recommendations of complementary, realistic and major sub-programs.

The assignment in N'Djamena occurred from 18 to 26th of June for J.C. Olivry and from 21st to 30th of June for C. Leduc. Were present at the same time J.M. Chéné, project leader of UNO-DADSG and P. Harrisson, consultant in integrated and participative development. We could meet a lot of interlocutors, the list is given in annex. Despite unfavorable material conditions (power cuts all day long for instance), we could gather the most important documents that permitted us to draw up the requested synthesis.

Our recommendations mainly involve scientific common sense.

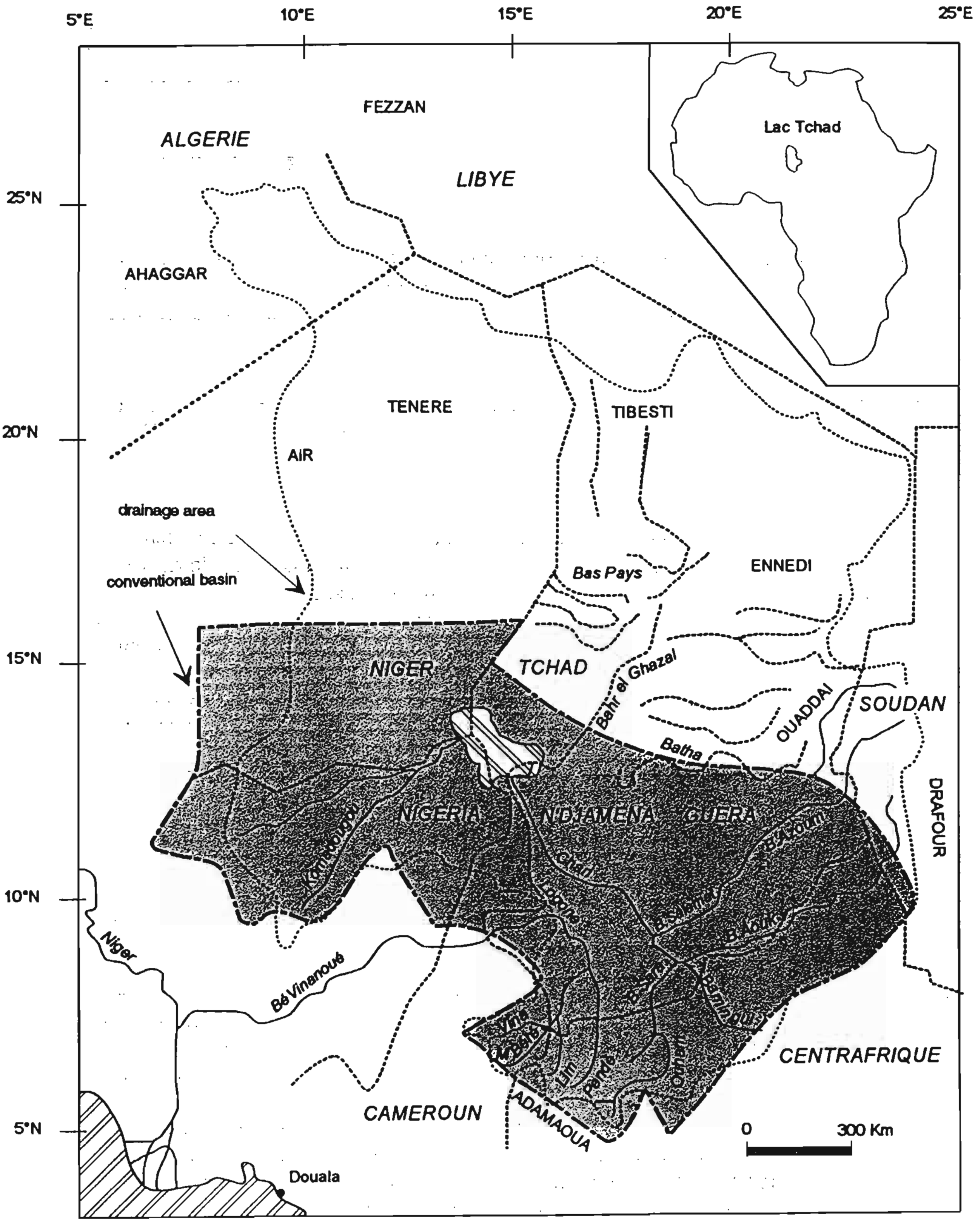
The Lake Chad basin is a fragile milieu because of its Sahelian situation: it is exposed to a strong climatic variability on which man has no hold. He just can try to protect from exceptional situations, statistically rare but with disastrous effects. The rainfall variability mechanically shows as a surface runoff variability, hardly less marked. In the opposite, the groundwaters, though almost entirely dependent of the hydrographic network for their recharge, have a strong inertia towards the climatic events.

The reasonable management of water resources of the Lake Chad basin must combine the specificity of the surface and ground waters. It basically lays on an anonymous and daily work of acquisition and monitoring of elementary data.

The endorheism of the basin and its geographical situation is so that the available water is limited in quantity and it is necessary to manage it to the best. The supply of drinkable water to the strongly increasing population, the watering of their cattle are the main priorities. These demands, low at present because of the smallholding and the standard of living, cannot but grow. As a result it is necessary to analyze with courage and honesty the different important irrigation projects, consuming a lot of water with an hazardous economical profit. This term of the basin water budget is the one on which the most important gains can be expected.

The humid zones of the basin are important as for the animal life as for the hydraulic functioning (flood spreading, recharge of the water table). In most of the cases, they haven't been studied enough to provide an accurate quantization of the hydrologic processes. We must be careful to any intervention on these sensitive sectors before having undertaken adequate investigations, that may require several years of measurement.

The authors really want to thank the persons they met during their assignement (national departments, NGO, UNDP) and particularly the Secretary General of LCBC and his members of staff that made us available the main part of the documentation we needed for this expertise.



DRAINAGE AREA AND CONVENTIONAL BASIN

INTRODUCTION

« Manage the Lake Chad waters for the welfare of the concerned populations » is the objective of the Lake Chad Basin Commission (LCBC). This national organization, one of the oldest in Africa, gathers since 1964 Cameroon, Niger, Nigeria and Chad on the problems of planning and development of an area called « conventional basin » centered on Lake Chad. Since 1994, Central African Republic is a member of LCA and the « conventional basin » was enriched with the upper basins of the Logone-Chari system and the Komadougou Yobe. The « conventional basin » is just a small part of the theoretical hydrographic Lake Chad basin (figure 1). The hydrographic basin, with a surface area of about 2,500,000 km^2, is a desert for half of its surface. It is spread up to Algerian Ahaggar, covers Tenere and the borders of the Aïr in Niger, the Tibesti and Ennedi in Chad. Its hydrological active part only covers 700,000 km^2, with 600,000 km^2 for the Chari river basin, and concerns, apart Nigeria, Cameroon and Chad, the Central African Republic and the province of Darfour in Sudan.

Several synthesis studies were carried out on the Chari-Logone hydrosystem and recent publications made it clearer the evolution of the hydrological regimes. These works permitted an assessment of the Lake Chad hydrological inflow, helping to quantify water resources, major preoccupation of the developers in charge of its optimal exploitation. But these inflows incoming into Lake Chad also create an important resource whose availability depends on a rational management, leaning itself on a good knowledge of the Lake hydrological regime. For 25 years, considerable human and material means were mobilized, especially by Orstom, in hydroclimatological researches. Meanwhile - just talking of environmental sciences- other teams specialized in hydrobiology, hydrogeology, sedimentology, geochemistry, botany, remote sensing and geography made an important multidisciplinary contribution to the knowledge of the lake. All of them had to refer to the variability of the hydroclimatic parameters studied. A lot brought the elements to a better comprehension of the hydrosystem running. The troubled periods in the region interrupted for a time the major part of these researches, even if a minimum of observations could be maintained by the Chadian hydrological department, the national meteorology and the Agrhymed cell of N'Djamena, or by interpretation of available satellite imagery.

The diagnostic study on the Lake Chad waters and basin behavior leans on consulting various documents and the national services of Chad and LCBC. The main works used for this diagnostic are the following ones :

— Le bassin du fleuve Chari, monographie hydrologique Orstom n°2, 1974.

— Hydrologie du lac Tchad, monographie hydrologique Orstom n°12, 1996.

— Sub Saharan Africa hydrological assessment, West African countries. Country reports of Nigeria, Chad, Niger and Cameroon ; World Bank, PNUD... 1992.

— Modèle mathématique du comportement hydrologique du lac Tchad et des fleuves qui l'alimentent par Mott-Mac Donald international, 1994.

— Rapport de la mission d'actualisation des données de base socio-économiques et d'environnement. Paoletti et Lemoalle, PNUD/DADSG/LCBC RAF/88/029 ; 1991.

— Definition of the development strategies of the water resources of the lake Chad basin, G.R. King, PNUD/DADSG/LCBC RAF/88/029, 1993.

— Cartes hydrogéologiques de la République du Tchad. Document BRGM n°209 ; 1992.

Complete references of these works, as well as other publications and reports used are given in annex.

FIRST PART : DIAGNOSTIC STUDY

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1. GENERALITIES

We kept in this chapter the main points referring to the Lake Chad physical milieu, its environment and water resources, and specially their present evolution. In support of this diagnostic, we give in annex some developments of scientific order.

1) GENERALITIES ON LAKE CHAD AND ITS EVOLUTION SINCE THE RECENT QUATERNARY

1.1. Generalities

For many authors, Lake Chad could be what remains from a « Paleochad sea that had a considerable extension, the Chad Low Lands were flooded and the sea could spread up to the limits of the Nile basin. » The fossil hydrography of Aïr, Tibesti and Ennedi shows that at that period there were major streams (fig. 1.1) but the most recent paleoclimatical studies deny the extension of this « sea ».

Nowadays, the lake still takes up a fair-sized surface area, approximately between 10,000 and 25,000 km² depending on the importance of the Chari floods.

One of the most striking characteristics of Lake Chad is its average shallow end that could let it be considered as a tremendous pool rather than a genuine lake. Thus we know around the world some identical cases to a more or less advanced step of fossilization, such as the Great Salt Lake of Utah, Lake Eyre in Australia that can dry up more or less completely after a long rainfall shortage, this is a little the case of Lake Chad, but, unlike what happens usually for such lakes, the salinity of its waters remains low.

The Chari swollen by the Logone is nowadays the main tributary of the Lake, it collects the inflows of the rivers coming from the southern part of the basin. The Komadougou, the El-Beïd and several other rivers coming from Nigeria and Cameroon have a small discharge compared to the Chari.

Lake Chad spreads in an endorheic basin slightly depressed. According to the hydrological phases, it can look like either a genuine little inland sea or a more or less swampy large pool. That is, transforming this into volume, Lake Chad, even in period of high level, is just of little hydrological potentialities compared to the great lakes of the African continent.

Climate varies a lot from the north to the south of the lake. N'Guigmi is close to the desert, except during the rainy season, the dunes are just bare sand. In the south, in the

50ies, the banks of the Chari arriving in the delta, were still covered with a dense forest recalling the Guinean rivers. Unfortunately, under the action of men, this forest has now almost disappeared. A lot of other degradation of the milieu are observed on the basin due to the anthropogenic pressure, especially for what concerns the ligneous cover in all the neighborhood of large towns like N'Djamena, Maïduguri (600,000 inhabitants each) or Maroua and Diffa (100,000 inhabitants) or also areas with a dense pastoral population. But we demonstrated in the zones upstream the water resource that the canopy was not significantly altered by rainfall deficit (Geffard, 1992) and that the parameters of the physical milieu participating to the water budget were not modified.

1.2 The Paleotchad since the end of Pleistocene

Generally speaking, the major climatic trends for Lake Chad show successive maximums between 12,000 and 11,000 years BP, 9,000 and 8,000 years BP, 6,000 and 5,000 years BP and at last 4,000 and 3,000 years BP.

These recent works allow moreover to bring out some important teachings:

— the lacustrian phase of late Pleistocene dated with carbon 14 between 30,000 and 24,000 years BP (Servant, 1973) has still to be confirmed with measurements of Th and U.

— the existence of an Holocene very large lake Chad at the level of 320 m (Schneider, 1967) does not seem so evident for Durand (1984), Fontes and Gasse (1991).The highest level of Lake Chad observed in Niger, dated in 6,000 years BP is at the elevation of 300 m. The hydrological and energy budget modelling calculated from values of paleorainfall cannot report such an increase of the level of a very large lake Chad around 9,000 years BP.

— **an episode generally more humid than today** occurred between 12,000 and 4,000 - 3,000 years BP. It is at the origin of the existence of numerous lakes in the region but this **does not necessarily explain** general interconnections in the most humid phase, leading to observe **a small fresh water Caspian sea** in Chad.

The chapter of paleoclimatic researches is far from being closed, but it is not reasonable to read nowadays references on an inland sea of about 500,000 km² or even more in a recent geological history.

1.3 History of Lake Chad since the last millennium

The stratigraphic and palynologic study of the sediments settled in the Lake Chad bed permitted to Maley (1973) to go back in the time and study the **lacustrian fluctuation since about one millennium**. We can notice :

— an ancient lacustrian phase (transgression t1) finishing between the VIIIth and Xth century ;

— a regression (r1) after the Xth century ;

— a lacustrian phase (t2) centered on the XIVth and XVth centuries ;

— a regression (r2) leading to a partial drying up dated at 460 ± 95 years BP. This drying up occurs approximately in year 1500 ;

— a lacustrian phase (t3) in XVIth and XVIIth centuries ;

— the present regression (r3) with the breaks of humid periods of the 2nd half of the XIXth century and the years 1950-1960 of this century.

Then at end the final adjustment and the establishment of a calendar chronology were carried out using numerous historical data or oral tradition of the regional populations, confirmed by the historians on various genealogies of sultans among which mainly the Kanem's one that is known with a pretty good precision and goes up to the beginning of the last millennium. One example of the importance of these oral traditions is the one that C. Seignobos got from old Fulanis in villages of the south of Lake Chad. Maley dated with a good precision the most important regression of Lake Chad around the middle of the XVth century. And, the very precise and detailed oral traditions collected, describe a long record Lake Chad drying up, the one that Seignobos dated at the same time with known historical data, especially the emergence of the Baguirmi Kingdom in the beginning of the XVIth century. These traditions assert that the Fulanis' ancestors, drove out by drought, installed their villages in the dried out southern part of the lake and this during one generation, i.e. from 20 to 25 years. **The lake came back suddenly and disastrously** and it is mainly this event that shocked the imaginations and was kept in mind (Maley, 1989). **This is indeed a real risk it is necessary to take into account nowadays.** The climatic situation in the middle of the XVth century seems rather identical to the present one, but at that time, the drying up was far longer and more marked. Indices of this drought seem to occur in the sector of the Middle-Niger (Mali, Burkina).

1.4 Present variations of Lake Chad

The interannual levels of the lake are generally included between 279 and 283 m. In 1963, the height 283, record for this century, was reached with a surface of the lake approaching 24,000 km² among which 11,000 for the northern basin and 13,000 in the southern basin. At the end of the 60ies, the size and the volume of the water stretch considerably decreased. In April 1973 the lake was split up in two parts as it was observed in the beginning of the century and got through a chronic deficit with fluctuations going from 280 m (20 km³ in volume, 10,000 km² in surface area), up to less than 2 km³ in a residual water pocket smaller than 2,000 km² in June 1985.

These data are detailed further.

Such "small Chad" episodes are not exceptional, they were observed within this century for short periods, for several decades within the past centuries and long phases of complete drying-up within Quaternary. Nowadays as before, climatic drought is the only cause of it. The present anthropogenic withdrawals are less than 1 km³.year-1 (King, 1993) and represent less that 5 % of the average inflows of dry years. The context is completely different from the Aral sea case, cut by man from its fluvial resources.

2) CLIMATOLOGY

2.1 Climatology of the lake

The climate in the region is due to the path of the intertropical front (ITF), equilibrium between the dry fluxes coming from the north-east (harmattan) and the monsoon fluxeds coming from the golf of Guinea . The ITF, running far south in winter, begins to move northward in spring and reaches the 20^{th} parallel in July and August, then it quickly goes down to the south.

Numerous pieces of information in this paragraph are extracted from Olivry et al (1996).

The mean annual **temperature** is homogeneous on the major part of the lake ; it is about 27.9° C in N'Djamena. The difference between the warmest month, April and the coldest one, January, is of 7° C. The daily fluctuations are at their maximum in February (20° C) and at their minimum in August (under 10° C).

Evaporation is one of the major terms of the hydrological budget. Several methods permit its evaluation, either through direct measurements or by calculation. The estimations can notably differ, for instance in N'Djamena, are installed :

— Colorado pan/1964-1973: 2,571 mm/year ;

— Class A pan/1964-1973: 2,824 mm/year ;

— evapotranspirometer/1964-1973; 1,914 mm/year ;

— Penman: 2,284 mm/year.

At the scale of Lake Chad, evaporation became a physical feature of regional signification. The interannual variations of evaporation on the lake are not important (2,065 mm to 2,255 mm per year, between 1967-68 and 1976-77, table 4.13), because of the microclimate due to the size of the lake Chad. And there is a very good correlation between the 12 interannual mean values (1965 to 1978) of evaporation on the lake (ELAC) and the ones observed on Colorado pan on bare ground (ECOL, station of Bol Matafo) for the same period : ELAC = 0.645*ECOL + 0.318, with n=12, r=0.91) (Pouyaud, 1986).

Annual evaporation on the lake

Hydrological year	Evaporation (mm)
1967-68	2065
1968-69	2150
1969-70	2243
1970-71	2249
1971-72	2183
1972-73	2255
1973-74	2248
1974-75	2069
1975-76	2190
1976-77	2164

There is nowadays no basic modification of the evaporation or evapotranspiration rate on the region, the often mentioned modifications of albedo are not important enough,

when observed, as far as radiative budget is concerned, to lead to an increase of evaporation.

Our study of rainfalls first concerned the regional context, then the lake.

According to the map of L'Hôte and Mahé (1996), the annual mean rainfall, calculated on the period 1951-1989, varies between less than 500 mm in the north and 1,300 mm for the extreme upstream basin, in Central African Republic. A large part of the basin is under semi-arid, even arid, climate.

The different studies carried out on rainfall in Sahel, such as Taupin et al for instance, pointed out the marked variability in space and time : annual rainfall can be twice as much on a distance of 30 km. We must be very careful with observations of an isolated rainfall recorder. The approximate north-south distribution of rainfalls appears only when we can observe cumuls on several years. This heterogeneity decreases when we go south in the areas with more important rainfalls.

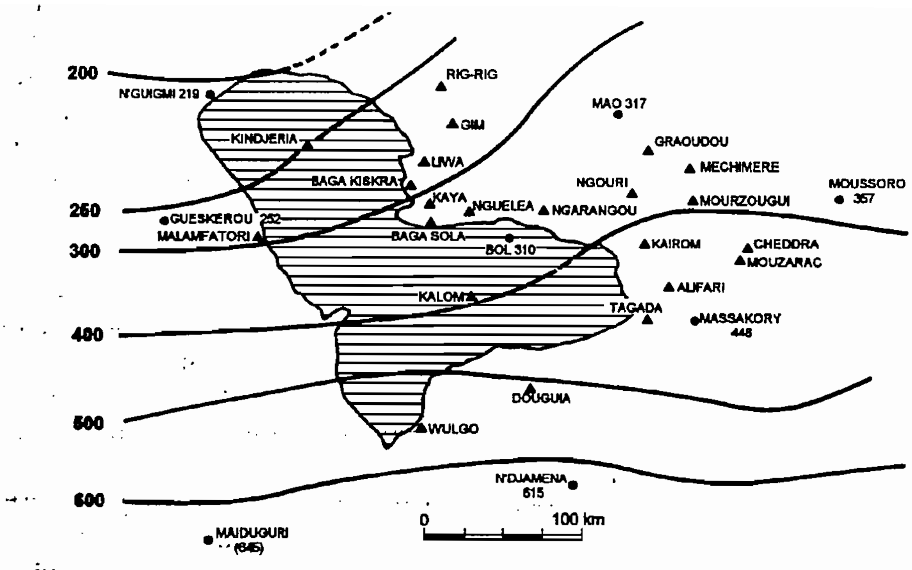
The station of Nguigmi, in the north of the lake, can illustrate the climatic variations for the beginning of the century. We note that the recent past (beginning of the century) already knew particularly dry years, drought of the 70 and 80ies is thus more remarkable by its lasting than its scarce rain. In the opposite, the 50 and 60ies were specially wet.

In the Sahelian area, the decrease of rain for two decades was marked by a reduction of the number of events and not by a decrease of the mean rainfall (Lebel and Le Barbé, 1996). The deficit of the 70 and 80ies, compared to the 50 and 60ies, is more important in the south than in the north and the interannual variability increased.

One of the numerous problems in the comprehension of the meteorological processes is to know what in the available vapor at given moment and place comes from wide scale circulation (Indian and Atlantic ocean) or from the local recycling.

The evolution of the climate is linked as to astronomic parameters, for great oscillations, and to global and local causes. For the time being, though models are developed on atmospheric circulation, it is impossible to make any reliable climatic forecast to the scale of the year or the season and nobody can tell if and how drought of past decades could go on (see infra).

The study of the lake rainfall mainly leans on data recorded at seven official stations located in Chad and Niger. In second range, we used the records of fourteen storage raingauges installed by Orstom in the region of Kanem in the east of the lake and data provided by the storage raingauges installed in 1975 in the Kindjeria and Kalom isles and in Baga Kiskra. We could also use rainfall records of the station of Malamfatori (Nigeria), and of the Haykoulou Mission since 1976 and annual data from the station of Maïduguri (Nigeria) from 1951 to 1989.

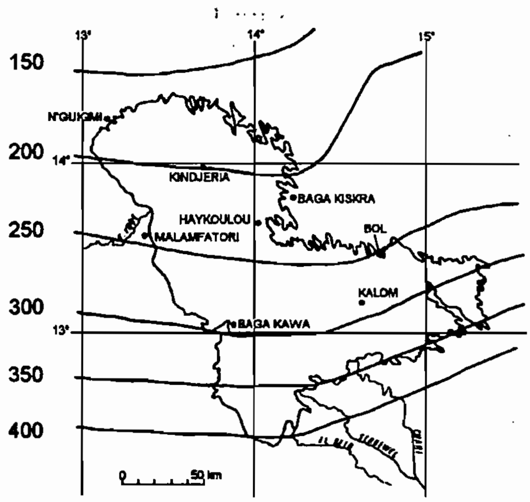


▲ RIG-RIG : PLUVIOMETRE TOTALISATEUR ORSTOM

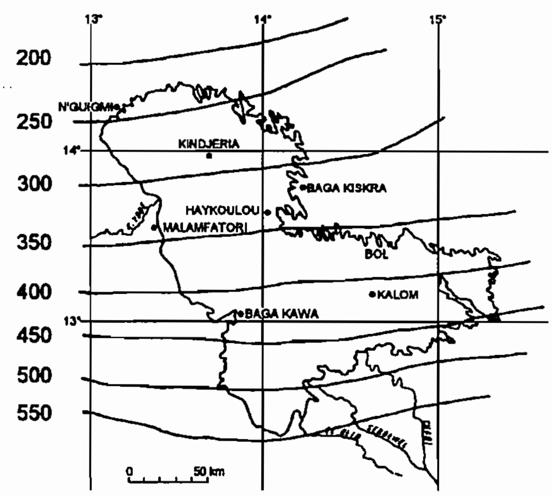
● N'GUIGMI 219 : PLUVIOMETRE OFFICIEL

Interannual isohyets (period 1932-1977).

On the following figures, Mahé (1993) displays the isohyets got from the annual data file observed and reconstituted, on the periods 1971-1989 (b) (in deficit) and 1951-1970 (c) (in excess). A very clear shifting of isohets to the south appears for the last 20 years, the extreme isohyets decreasing from 550-220 mm to 400-150 mm.



Interannual isohyets calculated on the period in deficit 1971-1989 (average: 207 mm)



Interannual isohyets calculated on the period in excess 1951-1970 (average: 320 mm)

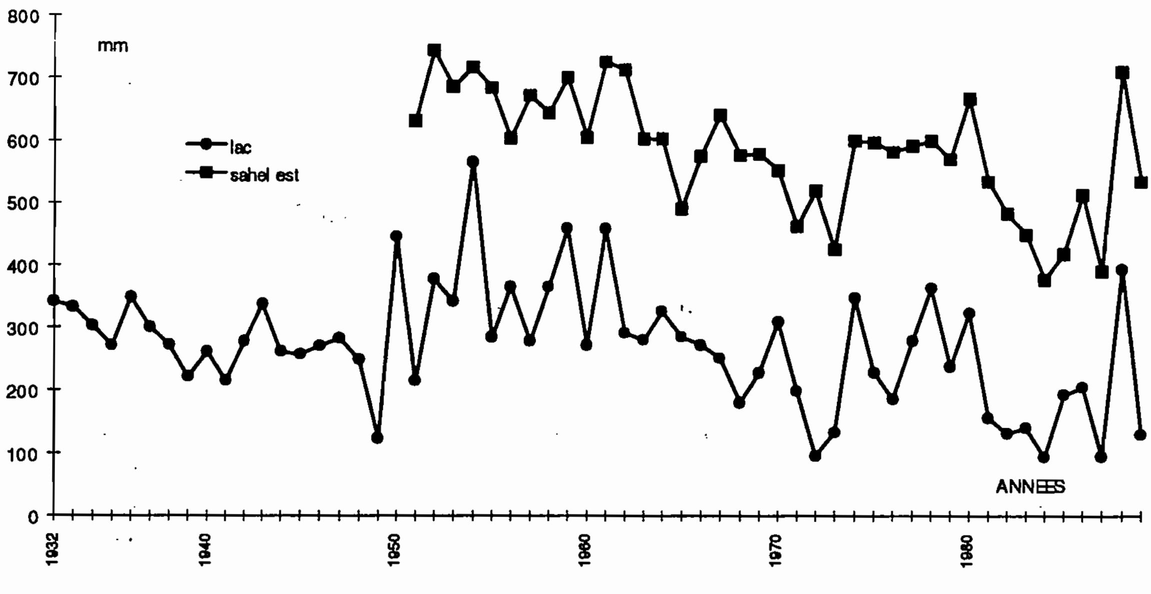
The average annual rainfalls on the lake were calculated by the Thiessen method. The interannual mean is **288 mm**.

The main rainfalls so obtained are roughly approximate, provided the low density of the raingauges and their peripheral situation around the lake. Thus, for the years 1975 to 1977, we got the records of the storage raingauges from the Kalom and Kindjéria isles and from some raingauges on the same bank of the lake.

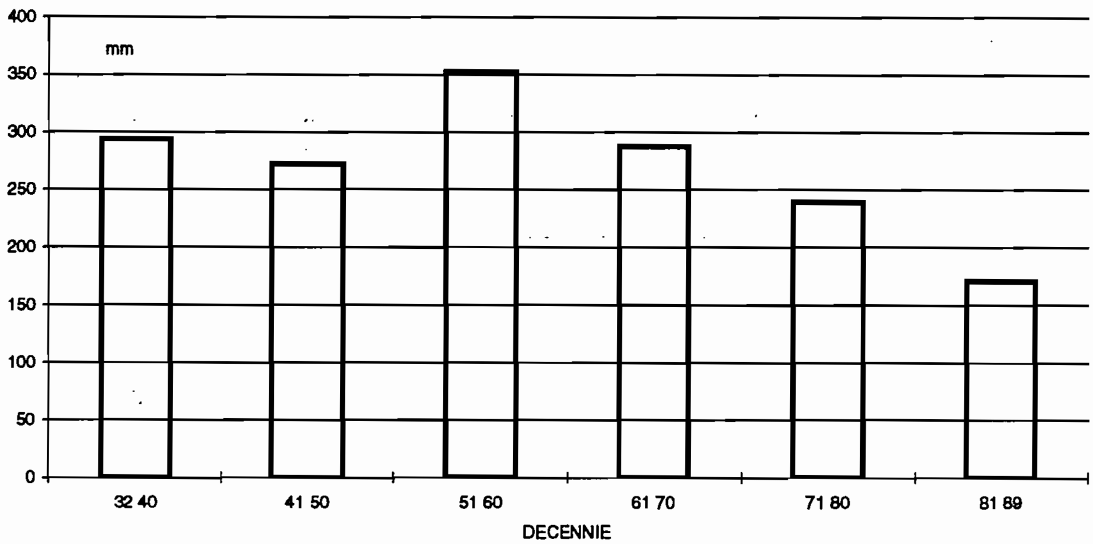
We can notice that from 1937 to 1949, the annual rainfalls were almost always in deficit whereas the period 1950-1961 was, globally, in excess. We notice also the very low values of the years 1972, 1984 and 1987.

Height of the mean annual rainfalls fallen on the lake Chad

YEAR	Average of the rainfalls on the lake (mm)	YEAR	Average of the rainfalls on the lake (mm)
1932	342	1961	458
1933	330	1962	291
1934	303	1963	280
1935	271	1964	326
1936	349	1965	285
1937	301	1966	272
1938	272	1967	251
1939	221	1968	181
1940	262	1969	228
1941	215	1970	309
1942	278	1971	199
1943	338	1972	95
1944	262	1973	133
1945	257	1974	347
1946	271	1975	228
1947	283	1976	186
1948	249	1977	278
1949	123	1978	363
1950	445	1979	237
1951	215	1980	323
1952	378	1981	156
1953	342	1982	131
1954	565	1983	142
1955	284	1984	94
1956	366	1985	193
1957	278	1986	205
1958	365	1987	95
1959	459	1988	394
1960	272	1989	130



Evolution of the mean annual rainfall fallen on the lake since 1932, compared to the average rainfall of the east Sahel from 1950 to 1989.



Mean annual rainfalls fallen on Lake Chad and calculated for the last six decades

2.2. Climatic variations

The climatic variability is a component of the African climate, but we must note that the warming of the oceans of the southern hemisphere during the half 60ies shows that the differences in the anomalies of the oceans sea surface temperature (SST) of the south and the north are in a reverse relation with the rainfall anomalies of Sahel. A good correlation was established between SST and rainfalls on the July-September period and a forecast model of the Meteorological Office of the United Kingdom can make good simulations of the Sahelian rainy season, from the SST of June.

The quicker increase of SST in the south leads to a reduction of the heat transfer and of the monsoon strength in the north. This anomaly was confronted to the increase of greenhouse gas in the atmosphere and thus granted to a global anthropogenic warming.

For a doubled concentration of CO_2 in the atmosphere, to an undetermined horizon, some researchers of the Climatic Research Unit (UK) estimated in a 5 model composite script that the probable increase of temperature could be about 2.5° C., and should increase the rainfall for 45 mm on the regions of the lake, but the rainfall should remain steady on the major inflow areas of the Logone and Chari upper basins. In fact, the temperate zones of the globe could be more affected than the intertropical zones.

In annex, other developments on the subject are given, but we can conclude here that science does not master yet the explanatory phenomena of the climatic variations and that no solution is available to solve the situation of climatic drought. We can add that drought in Sahel is not linked to the local anthropogenic influences, even if those are often responsible for an degradation of environment and the living of the populations of the Sahelian and semi arid regions.

Reason demands that the climatic risks (in a deficit trend) should be taken into account in the long term development projects, these risks being the rule for a lot of incoming years.

Atmospheric circulation and rainfall mechanisms are more and more known. Thus we still are far from being able to seriously forecast the weather at the scale of a season, even by empirical correlation with simple variables (oceans temperature for instance). It is impossible to say if future will be an extension of the present situation or a quick come back to a wealthy rainfall as this was in the 60ies.

For about thirty years, different tests of **artificial rain** were carried out in different countries. There is a general skepticism of scientists towards this method. In Sahel as elsewhere, no one could demonstrate that these experiences have a significant impact on rainfalls (Puech, 1984). The extreme variability in space and time of natural Sahelian rainfalls is naturally so that it is impossible to appreciate scientifically the effects of rain seeding, there is no reference area.

The undertaken tests (Burkina Faso, Niger) always had a limited objective and a ground control insufficient. Even if we imagine that artificial rains had a genuine efficiency, this method is not conceivable at the scale of a large basin like Lake Chad : the gain at a given place is probably at the expense of another area of the basin as noticed when experienced in 1967 at Ouagadougou (Cotte and Lemoine, 1972) with « a rainfall superior to 36 % » in the seeding zone and « a rainfall inferior to 50 % » close to it...

At middle term, it is not possible to hope forecasting or modifying the climate of Lake Chad. The variability, specially the exceptional situation must be considered to appreciate the impact of the different planning already carried out or programmed and to define their management policy and avoid a too strong degradation of the environment.

3) HYDROLOGY

3.1. Generalities

Surface hydrology is the major factor that influence the water resource of the region and its future. We must make the difference between on one hand the tributary inflows in the of the lake and their specific regime, on the other hand the proper running of the lake. Depending the considered periods, the literature provides different values (the means are not established on the same periods) and we will share the terms of the hydrological balance with, on one hand on the whole period (including the first years of the drought and the whole humid period), and, on the other hand the observations of the last two decades of drought.

After some generalities on the fluvial inflows, we will make clear the runningof some diagnostic regions, identified by Kindler (1989), such as the lake itself, the Chari-Logone, the Great Yaere or the Komadougou-Yobe.

In an interannual balance established in 1984, Olivry suggested the following repartition of the balance terms of Lake Chad, for a « middle Chad » at 281.5 m, the superficial inflows are in an average year of 40 km3, among which 37.8 km^3 for the Chari and 2.2 km^3 or the El Beïd and the Komadougou Yobe ; the rainfalls inflow on the lake is about 6 km^3, in steady condition, the losses represent a total of 46 km^3 in which 95 % for evaporation and 3 km^3 for infiltration.

More in details, the upper Chari provides 25.8 km^3 and receives 12 km^3 from the Logone in the 16.8 km^3 measured in Bongor, that supplied the flood plain in right bank for 0.8 km^3 and the Yaere in Cameroon for 3.6 km^3, the difference being connected to other overflows. The Yaere is drained by the El Beïd that returns 12 km^3 to the lake in the Logone inflows and the 0.95 km^3 of the Cameroonian inflows from the Mandara Mounts. The Komadougou Yobe inflows in the northern basin of the lake and the Yedseram's in the southern basin, coming from Nigeria give a total of 1 km^3.

In the recent year context, in deficit, the balance is completely different. The mean Chari inflows on the 1971-1990 period is of 21.8 km^3.year-1, the potential feeding of Yaere does not exceed 0.5 km^3 coming from the Mandara Mounts and 2 $km^3.year^{-1}$ coming from the Logone, its drainage by the El Beïd is just of 0.2 $km^3.year^{-1}$.The inflows in the lake totalize then 22 $km^3.year^{-1}$, that is half of the previous inflows and are globally limited to the feeding of the southern basin.

In his mathematical model, Mott and McDonald International took into account the period 1960-1979 and gives the following results :

Chari at Sahr :	275 $m^3.s^{-1}$
Bahr Sara at Manda :	450
Bahr Keita :	35
Bahr Salamat :	20
Chari at Bousso	735
Chari at Chagoua	730
Logone at Baïbokoum (Cameroon inflows)	285
Logone at Moundou	375
Logone at Laï	485
Logone at Kousseri	350

Chari at N'Djamena 1080 m^3/s, that is 34 km^3/year for this period still marked by the humid period, and with a maximum of mean flood of 3,500 m^3/s and a minimum low flow of 110 m^3/s.

For the 60ies, **the Komadougou Yobe system**, with a surface area of 148,000 km^2, provides 1.5 km^3/year when exiting the upstream part at Gashua and only 0.45 km^3 when arriving in the lake. The same is true for the Yedseram and the Ngadda, controlled at the bridge of Mbuli (9,750 km^2) only bring 3 m^3/s whereas 7.7 m^3/s are measured at Bama upstream (4,750 km^2). The flood plains downstream do not explain everything.

We can reasonably think that the Komadougou Yobe upper basin for a surface area of about 70,000 km² has a specific discharge of about 3 l/s/km², that is an **interannual volume close to 7 km^3 used in multiple works of the Kano and Bauchi provinces and for the major part drawn off to the international waters of Niger-Nigeria of the downstream Yabe (see annex 3)**

3.2. Lake Chad Hydrology

3.2.1. The lake Chad and the Chari river

The lake level study was mainly oriented, in the previous works mentioned by Olivry et al (1996), on the maximums, minimums and the annual amplitude of the level variations. Relationships, could be established between maximum levels of consecutive years, or between successive maximums and minimums and were used to reconstitute missing data and forecast the lake low waters after observing the annual maximum.

The taking into account of recent data shows that these relationships cannot be used for the periods of « small Chad » with spilting up of the north and south basins. The lake levels autocorrelation is for a major part linked to the evolution of the Chari discharges. On the common observation period (1950-1978, 1981 and 1988-1993), we tried to find out which was the best regression between the maximal observed level of the lake at Bol (or fictive level according to the station of Kalom) and the annual values or the moving averages, calculated on 2 or 3 years, maximal floods and annual modules of the Chari river at N'Djamena.

The best relationships were obtained for modules, with correlation coefficients near 0.905 and 0.911 depending on the fact that these were mean modules calculated on 2 or 3 years. We got a good relationship between Hx of the lake and the mean module of the Chari calculated on 3 years. The regression equation is :

$$Hx_i = 0,35\left(\frac{Q_i + Q_{i-1} + Q_{i-2}}{3}\right)$$

with Hx in cm at the staff gauge of Bol and Q in m^3 s^{-1}.

The following table sums up the frequential analysis, done using Jenkinson distributions, of the different hydrological parameters of the Chari taken into account here.

Frequential study of the floods and modules of the Chari at N'Djamena

Parameter in	f %	1	5	10	20	50	80	90	95	99
m^3 s^{-1}	T	100	20	10	5	2	5	10	20	100
Qx		477	1280	1710	2230	3180	4060	4450	4740	5150
Q$\bar{x}$ 2 years		682	1450	1850	2330	3200	3960	4300	4530	4850
Q$\bar{x}$ 3 years		844	1560	1930	2380	3190	3910	4230	4450	4750
Module		113	382	527	706	1050	1370	1530	1650	1820
Mean mod. 2 years		139	407	551	715	1050	1360	1500	1600	1750
Mean mod. 3 years		162	427	568	738	1060	1350	1480	1580	1710

The application of the relationship Hx$_i$ = f (Q Chari) let us suggest for different return periods the maximum level reached by the lake.

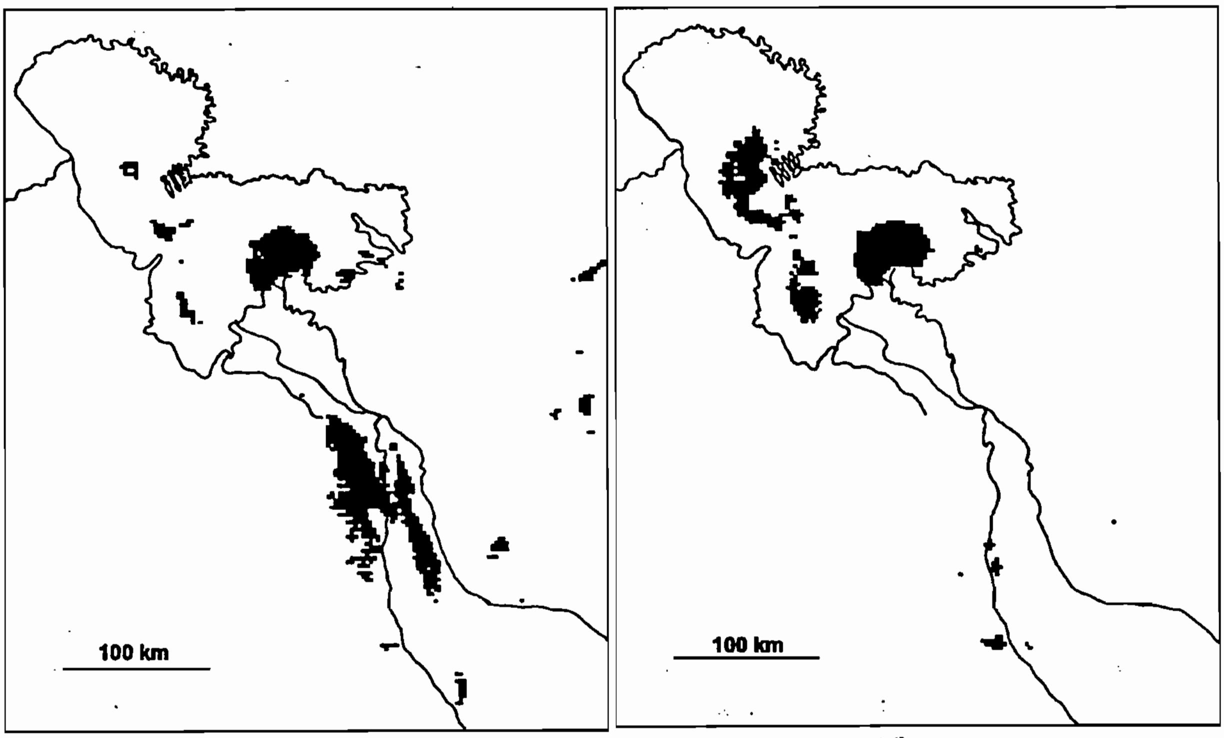
	Dry years				Median	Humid years			
Return period	100	20	10	5	2	5	10	20	100
Level of flood at Bol Hx in cm	57	149	199	258	371	472	518	553	599
Elevation IGN m	278,44	279,36	279,86	280,45	281,58	282,59	283,05	283,40	283,86

These results must be considered with caution for the lowest levels, the authors don't specify in the available works the ranges of uncertainty deduced from the correlation.

3.2.2. The flood of 1994-1995

The abundance of rainfalls in 1994 could let hope a better supply of lake Chad that the one observed after the apparition of the Chari flood. The surfaces in gravitational water detected by Meteosat were replaced in the following figure compared to the section of the normal lake Chad on two images provided by the laboratory UTIS from Dakar of November 9th, 1994 and February 15th, 1995 and processed by Lemoalle.

The image of November 9th shows that the rains and the river floods participated to the supply of flood plains (Yaere) in the south of the Chari-Logone confluence. Within the lake, the southern gravitational water zone of keeps a constant surface area ahead the Chari delta. The rain caused flooding of small surfaces in the low lands of the northern basin. The image of February 15th shows gravitational waters in the south of Baga Kawa. The southern basin is close to its maximum level and overflows in the north basin up to the latitude of Boso. In the lower part of the image, the pool of Maga in Cameroon on left bank of the Logone appears clearly.



November 9th, 1994 February 15th, 1995

1994-95 Flood: Flooding of Yaere in November 1994 and passing of the Great Barrier Reef in February 1995.

3.2.3 The hydrological running of the Small Chad

At a very low level of the southern basin waters (case of the low flow of July 1973) the Chari flood waters successively participate to :

— raising the level of the southern basin ;

— supplying the Bol islands above the white islands threshold;

— supplying the northern basin above or through the Great Barrier Reef.

Concerning the southern basin (gravitational waters, swamps and islands) this cycle can occur every year, the difference between high waters of a year with inflows in deficit (9.4 km^3 in 1987-88 for instance) and a year close to the normal (36.9 km^3 in 1975-76) is of the order of 1 m.

The flooding of the northern basin by the end of January every year (annual maximal extension) was evaluated according to an arbitrary scale from 0 to 3, corresponding approximately to the flooded surfaces :

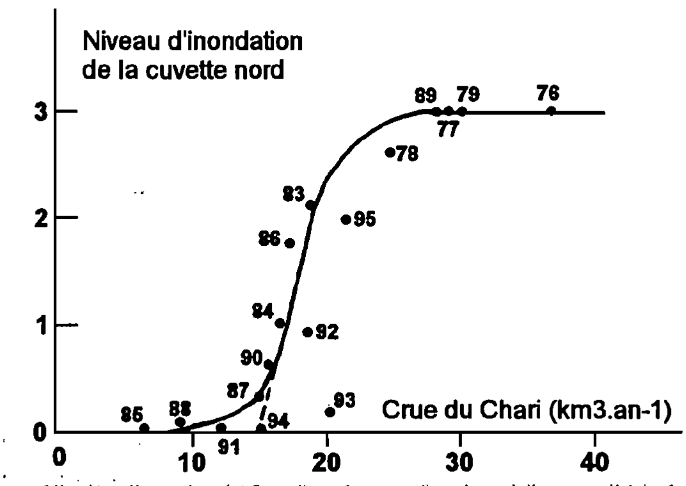
0 = no crossing of the water through the Great Barrier Reef ;
1 = not important flooding of the southern part ;
2 = flooding up to the latitude of Boso ;
3 = noticeably flooding in the north of this limit.

The relationship between the Chari annual module and the importance of the northern basin flooding is represented by a S-curve established with the data from 1975 to 1995 (completed by Lomoalle, 1989) where:

— the module required for a normal annual cycle of the southern basin on its own, without overflow, is of 15 km^3,

— the module permitting a complete flooding the northern basin is of 28 km^3,

— an inflow between 15 and 28 km^3 causes a partial flooding of the northern basin.



Importance of the northern basin flooding (according to arbitrary units) in function of the annual module of the Chari during the period of Small Chad.
The mentioned year corresponds to the northern basin filling (end of January).

Let us recall the threshold effect created by the Great Barrier vegetation. A modification of this vegetation should notably affect the exchanges between the two basins and on their levels. It is what is suggested when we plot the most recent points (1991 to 1995). The northern basin flooding, for the same levels at the chosen staff gauge, requires an extra inflow of the Chari of the order of 5 $km^3.an^{-1}$.

Besides, if we compare the Chari equilibrium inflows for the southern basin in period of Small Chad (15 km^3 for 7,500 km^2) to the whole lake in period of Normal Chad (42 km^3 for around 20,000 km^2), we note that the annual losses per surface unit are roughly 2 m for each considered period. Resized to the total inflows to the lake (and not only to the Chari inflows), these losses represent about 2.3 m per surface unit. The losses by evaporation do not seem to have been modified by the modification of landscapes or the development of the swampy vegetation, in a sensitive manner. In the limit of the approximations, the swamp surfaces have a more or less the same evaporation than the gravitational water.

3.3. The Chari discharges

The filling of Lake Chad is a multi-annual variable, the high or low water levels depend not only on annual inflows of the Chari river but also of the prior filling level of the lake (flood level or low water of the previous year). This partly explains the remaining effect of the present evolution of the lake. This is not sufficient to explain that the Small Chad still continues. There is probably a major persistence effect at the level of the climatic pejoration in the region at the level of the evolution of the Chari present hydrological regimes.

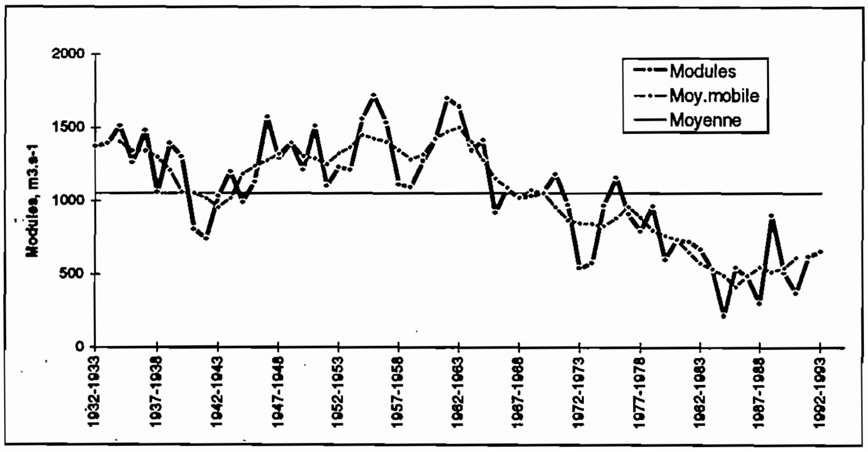
But the series of the mean flood maximums of the Chari, calculated by decades for the reconstitution period (1870-1931) and the period of observation (1932-1994) is clear enough to explain the degradation of the water resources of the river.

Decade	1870	1880	1890	1900	1910	1920	1930	1940	1950	1960	1970	1980	1990 (5 years)
Mean maximum in $m^3 s^{-1}$	5070	4400	4960	3670	3540	3500	3670	3380	3790	4060	2820	1870	1930

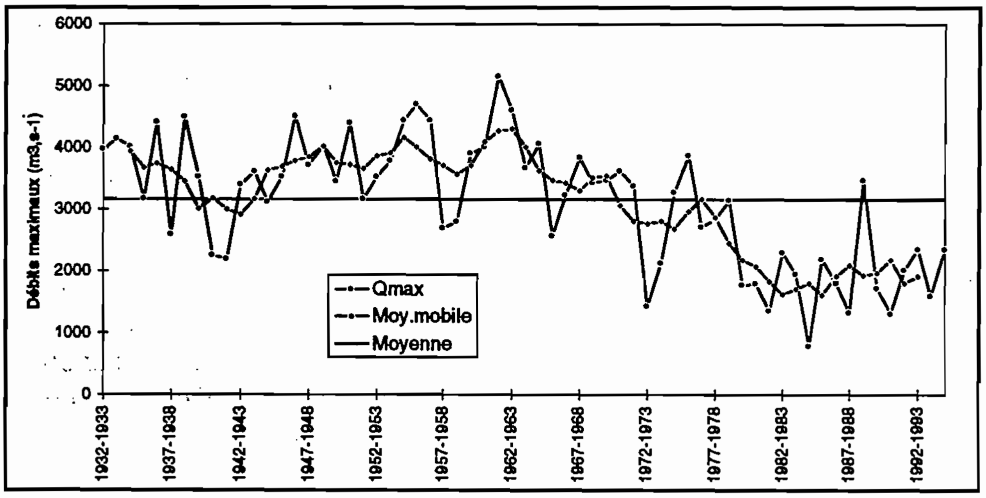
The interannual maximum of flood is 3,660 $m^3 s^{-1}$ on 125 years. The enduring decrease of the Chari hydraulic regime appears more clearly through the last six years for which the interannual inflow is the weakest ever observed, with only 18.4 $km^3 an^{-1}$, that is half of the interannual inflow calculated on the observation period.

The figures below illustrate this evolution of the modules and maximum of flood of the Chari river. The following figure shows some characteristics charts of the Chari at N'Djamena and specially the tremendous hydrological deficit of year 1984-1985 compared to the medium year and to 1961-1962.

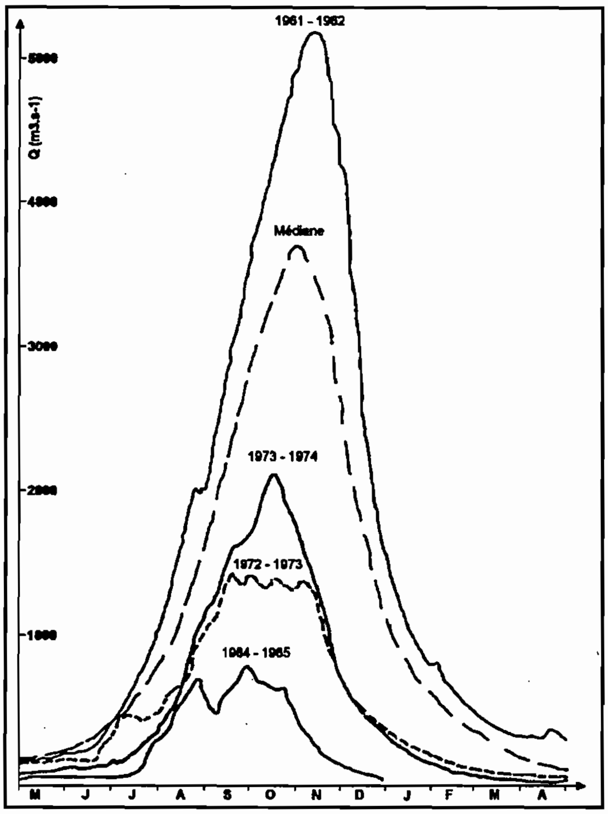
But the case of the Chari is far from being an exception in the region. The phenomenon is general, from Senegal to Chad.



Annual variation of the modules of the Chari at N'Djamena



Variation of the maximal discharges of the Chari at N'Djamena



Flood hydrographs of the Chari at N'Djamena

3.4. The Logone, the Grand Yaere and the El Beïd

The information mentioned here come for the main part from the hydrological monography of the Logone (Billon et al., 1967) and works from Olivry (1986), Naah (1990), Olivry and Naah (1996) and Olivry et al. (1996).

At Laî, the Logone is the confluence of its western arm coming from Cameroon and its eastern arm coming from the Pende. The watershed is 56,700 km² wide, its interannual discharge on the period 1948-1973 is 512 m^3/s ; but on 40 years, with the dry years observed up to 1987, this discharges falls to 464 m^3/s ; the Logone flows in a large sedimentary plain with a gentle slope and its effluents in right bank form the Ba-Illi. In left bank, the Ere effluent joins the Benoue basin via an overflow threshold 4 km wide and under a water depth of 0 to 0.9 m depending on the year (lost volume from 0 to 1 km^3/an, an average 0.3 km^3 that should be underestimated). The Dana threshold is far smaller with runoffs smaller than 10 millions of $m^3.an^{-1}$. At Bongor, the Logone is the border between Cameroon and Chad, its discharge (1948-1973) is 534 m^3/s (488 m^3/s for the 40 years mentioned before) and despite intermediate inflows, it almost does not increase from Lai. From Bongor, the degradation of the hydrographic network is so that the overflows in the flood plains increase and at Logone-Birni, the module is 380 m^3/s (12 km^3/an) on 35 years and 317 m^3/s on 40 years, that is 161 m^3/s less on the last period.

Of course, the gentle slopes and these effluents are at the origin of a slow down in the velocities and a decrease in the flow of the annual flood. The importance of the flood observed in Bongor determines the flooding importance in the Yaere and further the runoff in the El Beïd. The statistical study of the Logone flood maximums at Bongor determines the medium value at 1,990 m^3/s, value that must probably be revised downwards but that is important in the occurrence of the Yaere and the El Beïd hydrological running.

When the discharge at Bongor exceeds 700 m^3/s, important effluents begin to be observed and the Logomatia is filled, the effluents flow north, if the maximum of Bongor is less than 1,100 m^3/s, the flooding extension remains limited to the plain of the Logomatia and to some overflows in the west.

Over 1,200 m^3/s at Bongor, the flood tide floods the whole Yaere. The extension of the flooding in the Yaere varies from 0 to 6,000 km² with an average extension of 3,400 km².

If the discharge is more important than 1,500 m^3/s, the flood tide reaches the El Beïd. The importance of the Logone flood in discharge and duration is perfectly correlated to the El Beïd hydraulic regime (for discharges over 1,500 m^3/s). The El Beïd flood reaches its maximum in mid-December but for the last two decades, there was a lot of years without runoff. The average runoff is 1.23 km^3 (1954-1973) and during the same period, the medium flood maximum was estimated at 180 m^3/s. Before the flood caused by the Logone, we can observe a pre-flood in August, corresponding to the Mandara Mount mayos inflows that only represent 10 to 15 % of the main flood volume. Of course this pre-flood did not occur during the dryer years and the participation of the Mandara inflows to the flood plains of the Yaere is all the most reduced nowadays that the Tsanaga and Boula mayos participate to the filling of the lake Maga (Semry II) and that the north-east mayos rarely pass over the sandy bar of Limani (previously bank of lake Chad), either the discharges are too small or small pools were build in the mountain. This has consequences on the wooded part of the Wanza park. To finish with, the works on the Semry (Maga dam and the embankment of Pouss at Tékélé) affects the water supply of the southern Yaere.

On the last ten kilometers of its downstream course, the El Beïd is a small border river (Nigeria-Cameroon) and its inflows can be precious for the riverside populations and for the supply of the small south-west basin of lake Chad.

3.5 The Chari and Logone minimum flows

Their study is important because the low flow determines the lower limits of the availability in surface waters by the end of the dry season.

The absolute medium low flow of the Chari in N'Djamena was estimated to 126 m^3/s and the dry ten-year value to 88 m^3/s. The absolute low flows of 1973 and 1974 were 47.7 and 38.6 m^3/s and since then, for the worse years, these discharges fell down to 20-25 m^3/s.

Concerning the Logone at Bongor, the absolute medium low flow was estimated to 40 m^3/s and the ten-year dry low flow to 24 m^3/s. In 1984, 1985, 1986 and 1987, the absolute low flow was less than 10 m^3/s.

There was indeed a break in the low waters regime. The new behavior of these very low flows is linked to "memory effect" of climatic drought due, according to Olivry (1987, 1992 and 1993), to a dwindling of the groundwater reserve contribution of the upper basin water tables in the base flow. The increase of the river depletion coefficients gives the reduction of these water table extension. These are enduring consequences of drought it is necessary take into account in mathematical models.

This phenomenon is described more in details in annex.

The modifications of the measurement sections (sandbank, channels moved) at the hydrometrical stations require frequent gaugings in low waters if we want to have a good knowledge of low flows. The hydrological assessment (Water Assessment 1992) pointed out the importance of the relative errors in the calculation of low water discharges with obsolete rating curves.

At last, it is necessary to make sure that the management rules defined by the Moundou agreement, between Cameroon and Chad are respected in matter of irrigated perimeters during the low flow period. There might also be some pumping draw off in the Logone, these increase the deficit of low flows (only for Semry I, Semry II dependent of the Maga pool).

3.6. Water quality

Studies were carried out on the Chari and the Logone on one hand, with a follow-up of the suspended and dissolved loads arriving in lake Chad, and on the other hand on the lake where the turbidity and the salinity spatial evolution were measured.

The solid load incoming the lake comes for is major part form the Chari. The mean monthly concentrations of suspended loads are far more important in the Logone provided they can exceed 500 $mg.l^{-1}$ in July whereas they rarely reach 150 $mg.l^{-1}$ at Chagoua in August. The annual mean values are 54 $mg.l^{-1}$ in the Chari at Chagoua and 123 $mg.l^{-1}$ in the Logone at Kousseri. After the confluence, the annual mean concentration of the Chari at N'Djamena is 76 $mg.l^{-1}$. The comparison of the annual concentration at N'Djamena between wet (73 $mg.l^{-1}$) and dry (97 $mg.l^{-1}$) years shows that the variability of the load transportation is inferior to the variability of the river hydraulic regime. The mean sediment load of the El Beïd is less than 23 $mg.l^{-1}$.

The mean annual inflows in dissolved salts to the lake were estimated in the range 2.6 - 2.8 millions of tons (Carmouse 1972 and 1976, Gac, 1980). The dissolved load varies from 50 to 82 $mg.l^{-1}$ depending on the season and is in average 67 $mg.l^{-1}$. The ion concentration varies from 80 to 1,100 $mg.l^{-1}$ from the Chari delta to the extreme north of the lake. In period of drastic reduction of the water stretch due to the drought, the concentrations considerably raise and this as much as the saline regulation phenomena only occurs on the borders of the « Medium Chad » lake and just a little on its residual basins, this was pointed out by Roche (1973).

Considering the lake as a unique and homogenous milieu, Carmouse (1976) proposed a simplified model of the mean annual dynamic equilibrium of each of its elements on the basis of the following characteristics :

— regime of the fluviatile inflows,

— regime of the seepage and losses by sedimentation,

— hydrochemical condition of the lacustrian storage,

— rate of annual turnover of the storage.

If we compare the different hydrochemical equilibrium, we immediately note that every component of the salination has its own regulation mode. So, only mentioning the extreme regimes, those of dissolved sodium and silica, we remark that the annual turnover of the stock of sodium is 5.3 %, and silica 28.7 %, that is that sodium coming from the rivers stays in average 19 years in the lake before leaking in, whereas dissolved silica only stays 3.5 years because of the importance of chemical sedimentation it participates to. As a consequence, the lake is mainly a transit place for sodium. The regime of the fluviatile inflows and seepage maintain a relatively high storage in sodium. In the opposite, , the lake is mainly a place of chemical sedimentation for dissolved silica. The regime of fluviatile inflows and losses by biochemical way, and at a lower degree, by infiltration, maintain a storage of silica relatively small. The other elements have an intermediate regulation mode.

As far as we know, no comparable study on the water quality in the recent observation years of the small Chad was carried out. The available studies permit thus a comprehension of the hydrochemical functioning of lake Chad that probably did not endure major alterations in the southern basin.

4. HYDROGEOLOGY

4.1 The processes at issue

The lake Chad basin has been the object of a lot of hydrogeological studies for the last thirty years. The geological history and its implications on the groundwater circulation is described in very numerous documents, among which some synthesize very well the present knowledge ; they are mentioned below. Thus, a lot of others are of little interest as far as they often only mention, sometimes awkwardly or incorrectly, the basic works.

Concerning the geological and hydrogeological description of the whole basin, The scientific reference remains the report of Schroeter and Gear for FAO in 1973. In 1987, Solages synthesize pretty well the inventory and the perspectives. Despite some approximations, the update/modelling of Eberschweiler in 1993 is rich in recent pieces of information.

For a study focused on a particular region, we can mention other documents whose different volumes of hydrological assessment of west Africa (Mott Mc Donald et al, 1992), of unequal quality according to the countries and that generally only make partial inventory of the infrastructure in hydrology and hydrogeology. For Cameroon, we must go back to Biscaldi (1968), completed in 1970. For Niger, the synthesis of UNDP (1991) uses the data collected after Greigert (1979) and gives the previous bibliography references to consult. For Nigeria, Barber (1965) or Scet (1979) are the major references, a few other exist therefore.

For the whole Chad, Schneider's works(among which the sum of 1992) are authoritative editions, and more in details, on the Chari-Baguirmi, the modelling of Bonnet and Meurville must to be consulted.

Let us recall briefly the major hydrogeological facts. In the lake Chad basin, the groundwaters of regional importance are mainly represented by two aquifer systems:

— the phreatic water table present in the quaternary sandy or sandy clay, rarely clayed quaternary sediments. These lacustrian fluviatile or eluvial deposits form the upper part of the « Chad formations », they represent a very large horizontal and vertical variety of faciès. Depending on the places, the table lays at a depth varying from some meters to about fifty meters. We can consider it exists on the whole basin. It is generally with low mineral content but the basin extension and the geological variety, specially the continental nature of the deposits, explains that the table has rather variable characteristics : the electric conductivity varies between 50 and 5,000 $\mu S.cm^{-1}$; it is over 1,000 close to the lake. It is abundantly pumped by a lot of wells (traditional or cemented) and by drillings (drinking water supply or irrigation) ;

— the Pliocene table, confined and often artesian, formerly called medium table of the « Chad formation », only located in the central part of the basin. Generally deep (often between 250 and 400 m), it is much exploited in Nigeria. A lot of drillings, digged in the 60ies are often in bad condition, and let important volumes get away for nothing. This table has a smaller geographical extension than the phreatic water table. Its water is a lot more ancient and more mineralized (from 700 to 4,000 $\mu S.cm^{-1}$).

In the populated part of lake Chad, the late-Pliocene clays divide the two aquifers that generally lay from 100 to 250 m deep. They show a monotonous lacustrian sedimentation, rarely cut by thin sandbank. No significant hydrological interchanges is thus possible in natural conditions. In the Tenere zone, this clayed shield could get thinner, the two table piezometry getting closer could be a sign of this phenomenon but the available geological section are too rare and too schematic in this region to be sure of that.

Except these two large aquifers, there could be deeper other confined levels whose extension and capacities are not well known (*Continental Terminal, Continental Hamadien et Intercalaire*). These could probably be very mineralized fossil waters that could at a last resort, be of interest only to some very limited uses. These horizons could have a comparable hydrological load to the Pliocene one, but the exchanges with this latter table are probably null or very limited.

Small not sedimentary zones exist in the south of the basin. They generally have water resources a lot more limited and more difficult to exploit.

The water contained in the major two aquifers represent huge volumes : Shroeter and Gear (1973) gave a « pessimistic » number of 150 km^3 for quaternary table water in the whole basin ; UNDP (1991) gave a superior estimation for the only Nigerian sector of the basin. But a great part of this storage lays in the north of the basin where the needs are almost nonexistent due to the particularly sparse density of the potential consumers (men and cattle).

At different places of the basin, specially close to the lake, there are closed piezometric depressions in the phreatic water table. This form, frequent in the whole Sahel, shows underground flows converging to the depression center and cannot be explained but by a negative [infiltration-evaporation] term and by very poor hydrodynamic characteristics. The most marked have a piezometric surface about 40 m deeper in the center than to the edges.

In Sahelian area, direct recharge (diffuse percolation of rain through the unsaturated area) is generally low. It is also the case in the whole lake Chad basin where the phreatic water table recharge is mainly due to infiltration from the hydrographic network, beneath the rivers, in the flood areas and around the lake when it is full. Among the numerous available signs of these mechanisms, we must mention :

- the piezometry is generally important below the rivers and decreases as we get away from the rivers ;
- the time coincidence of the high levels in rivers and in the water table next to the river ;
- the poor salinity of the water table close to the rivers ;
- the decrease of the water table next to the lake since the drying-up of the northern basin ;
- the low fluctuation of the water table for thirty years whereas the rainfalls varied a lot.

The surface waters and the water table are linked and any surface management will have a certain impact on the quaternary table. On the other hand, the Pliocene artesian water table is independent of the present hydrological conditions (except if exploited of course).

4.2 Quality of the available data

There is at present a piezometric follow-up on a limited number of works in Niger and in Chad. The frequency of the measurement is insufficient to determine the annual variability and eliminate the interference caused by the pumping. In most of the cases, its is not possible to rely to the pumping tests that were undertaken on the wells and drillings to really appreciate the hydrological characteristics of the aquifers and thus to their production capacities. Indeed, the building mode of the works often leads to important load losses and the pumping tests were rarely carried out in satisfying conditions.

The information concerning the wells and drillings are archived in data base in Cameroon, Niger and Chad. The control on their quality before archive is far from being systematic.

There is not much attention paid to the problems of water quality. Chemical analysis are rare and not always reliable. In natural milieu, mineralization has to be studied as for the supply of human consumption (respect to the drinking standards) as for potential agricultural uses (ability to irrigation). Pollution caused by large towns (specially N'Djamena and Maïduguri) must be carefully surveyed.

There is at present no reliable data allowing to know the percentage of the population able to get safely water in reasonable access conditions (in term of distance).

The numeric modelling of underground flow using hydrogeological models is still limited (preliminary modelling in Niger, modelling of the Chari and the whole basin) but represents a very good basis of reflexion.

The main two water tables of the basin, quaternary phreatic and Pliocene confined, have huge storage of a generally good quality water, available in any season on the whole basin. The slow rate of their recharge is so that they are not much sensitive to the short term climatic fluctuations (some years or decades).

4.3. Lake-phreatic water table relations

On the basis of isotope studies carried out in the 70ies (Faure *et al*, 1970, Chouret *et al*, 1977, Roche, 1980), we could note some remarkable properties of the phreatic water table extremely complex system at the lake outskirts:

- the groundwaters generally lay at a level lower than the free lacustrian waters that represent a high point of the system. The aquifer despite does not contain large quantities of lacustrian waters.
- the pressure transfers, that were pointed out by the groundwater studies, generally do not correspond to important liquid material transports. Waters do not moving much ;
- the different parts of the system appeared at that time in equilibrium (permanent regime) that was not noticeably affected by the drought years ;
- the variations of the saline facies are to be linked to the movements of the solutions upward in dry season, downward the phreatic surface in monsoon season ;
- the piezometric depressions waters are recent and more salted than in the rest of the aquifer, but this only concerns the upper part of the table ;
- the salt migration is characterized by a follow-up of aeolian transport that are followed by an unequivocal evolution characterized by an increase of global salinity and a loss in alcaline soils.

These interpretation were based on observations and samplings on the immediate of the Chadian outskirt shore of the lake. They are interesting but must be confronted to hydrodynamic observations, and their validity must be checked in other areas of the lake outskirt. The succession of domes and piezometric depressions very marked on small distances involve, in a purely hydrodynamic point of view, poor values of permeability, as isotopes suggest it. Thus, other assertions deserve being reexamined. So, the analysis of piezometric fluctuations between 1975 and 1990 in the Nigerian south-east seems to indicate that the vanishing of the lake caused a drop of the phreatic water table, which is in contradiction with some isotopic conclusions. This proves in fact that in presence of a table with a slow responsiveness, a punctual observation cannot be significant except if replaced in an history and a larger hydrogeological context.

A lot of fundamental studies are still to be carried out before pretending to know well and to quantify the mechanisms of the phreatic table recharge in the lake Chad basin. One of the components of this knowledge is a long term hydrodynamic and hydrochemical follow-up, the duration and the day-to-day aspect are not compatible with the ambitions of most of the projects undertaken in the region.

4.4. Risks of overexploiting the groundwater resources

It would be wise to moderate the optimism that could raise when reading the estimations of the available storage in the different water tables of the basin. For instance in eastern Niger, the storage estimated by UNDP (1991) could exceed a hundred of milliard (billiard) of cubic meters for a consumption inferior to 20 million cubic meters per year. We must recall that the major part of this storage, almost fossil, is in the north of the basin where the water demand is insignificant and that huge available quantity does not obviously mean easy exploitation.

In the phreatic water table, a lot of enclosed piezometric depressions are as many indicators of very poor permeability and absence of present recharge. These areas can be completely off balance by increases, even limited, of draw off whereas they are probably less sensitive to the climatic variations that occurred for one century. The rest of the phreatic table collects a weak infiltration ; the hydrodynamic characteristics are generally more important but still relatively poor.

These physical parameters allow a limited and diffuse exploitation as it is done with the villagers or pastoral hydrological intakes. But, as soon as the pumping get closer and more important (large towns, large irrigated perimeters), the risk of local overexploitation increases.

In the zones where the water table is at medium or important depth (over 20 m), a modification of the piezometry (by variation of pumping or infiltration) will not have much direct influence on environment because the exchanges with the surface are not important and slow. But where the table is close to the surface, a variation of its level can have an impact rapidly visible : a lowering of the water table leads to a decrease of moisture in the soil, as a result there can be poorer yields or disappearance of some plant or animal species ; a rising up can cause salt precipitation in the soil by increase of evaporation.

At the scale of a region or of the whole basin, the only way to quantify the evolution of the water table is to use a numeric model representing the underground flow. Another way is to simulate the different natural (fluctuations of the hydrographic network) or anthropogenic (draw off) constraints. Without this indispensable tool (cf. for more details, see paragraph 6.2 further) only basic and obvious indications can be given.

The Pliocene water table contains very ancient waters that trickles out naturally very slowly to the Low Land of Chad. The present piezometric situation is artificially caused by the multiplication of pumping and not impeded artesian runoff, specially in Nigeria. Its evolution will depend thus completely on the management conditions the authorities of the different countries will decide. It can be simulated by numeric modelling thanks to an autonomous model taking advantage of the hydrologic disconnection of the two tables on the major part of the basin.

The waste of the Pliocene water table can occur two manners, one, visible by artesian runoff without drilling control, and another one, discrete through corroded tubbing by direct supply of the phreatic water table.

The Pliocene water table is generally very deep. Its overexploitation will not thus have any direct immediate impact on the basin environment, except for instance the drying-up of some artificial ponds supplied by the overflowing of the artesian drillings. The decrease of the hydraulic load because of the Nigerian overexploitation will lead at term to a relative economy of the resource by decrease of the squandered artesian discharges, thus less waste, and by an increase of the exploitation costs, that will financially limit the pumping.

5. WATER DEMAND AND ECONOMICAL ACTIVITIES

The literature is pretty abundant to relate this demand, the estimations vary a lot and the used calculation basis are imprecise. For instance, Falkenmark (1989) evaluates the demand of the Republic of Chad at 160 Mm^3 with 75 % for irrigation and cattle; Alanaye Djogromel (1992) mentions needs for this country at 220 Mm^3 in which only 50 Mm^3 for the irrigated sector... Several studies ordered by RAF/88 settle these needs in details for the conventional basin.

The demand of the populations were calculated on the demographic data of the conventional basin before 1994 for a total of 8.8 million of inhabitants distributed as follows:

— Chad:	3,200,000	h. with 75,4 % of rural population;
— Niger:	200,000	h. with 77,6 % of rural population;
— Cameroon:	2,400,000	h. with 65 % of rural population;
— Nigeria:	3,000,000	h. (% of rural population not known)

The numbers of livestock in UTC (Unit of tropical cattle), increased from 3,900,000 in 1980 to 7,850,000 in 1992. There were 4,700,000 heads of Bovini in 1972 and 6,870,000 in 1992 (+46 %). The global population of the livestock increased of 60 % in 20 years.

For Paoletti and Lemoalle (1991) the needs were estimated as follows:

— population needs (with 15 % of urban population)	168 Mm^3
— cattle needs	60 Mm^3
— irrigated agriculture needs (reduced to 30,000 ha)	768 Mm^3
— that is a total of	988 Mm^3,

value that could have reached 2.4 km^3 if the fitted out 110,000 ha had been exploited.

A projection by 2020, with the demographic increase and 30 % of urban population, gives estimations of human demand from 500 to 640 Mm^3, depending on the consideration or not of an consumption increase per capita of 30 %, the cattle needs should be 77 Mm^3 and irrigation of 220,000 ha would require 4.6 km^3, i.e. a total of 5.2 to 5.4 km^3.

In 1993, G.R. King *et al* published a study well documented on the surfaces of the existing perimeters and their real exploitation in 1992, calculating the needs for the agricultural cycles of the rainy and dry season (rice, gardening, wheat, corn ...) :

Region	Consumption 1992	existing perimeter needs
Logone and Chari	240	460
K. Yobe	134	380
Lac Tchad	86	1930
Total	460	2770 Mm^3

Adding men and cattle, the total needs are at present and up to year 2000 around the amount of 3 km^3 for an optimal exploitation of the existing situation, with 90 % for the projects of the large irrigated perimeters.

These needs must be linked with the expenditures of the different types of activities. We have in decreasing order and per average year (King, 1993) :

- Fishing	26,3 milliards of CFA francs		
- Recession crops	15,5	"	(without Nigeria)
- Cattle breeding	8,6	"	
- Small irrigation	6,3	"	
- Large project irrigation	5,5	"	

The large irrigated perimeters, potentially consuming 90 % of the needs, concern less than 10 % of the produced wealth. This report can be an element for establishing an hierarchy in the development priorities, in the same way, we must point out the enormous cost of the planned large works; in the opposite we must know the real weight of these works in the quest of alimentary self-sufficiency of the region.

The distribution of the large perimeters (Paolettin *et al*, 1991), given in annex, can be summed up as follows :

Region	Chad	Cameroon	Nigeria	Niger	Total (in ha)
Chari-Logone	15,800	13,300			29,100
K. Yobé			13,550	3,700*	17,250
Lake Chad	1,050		87,600		88,650
Total	16,850	13,300	101,150	3,700*	135,000

** with small irrigated perimeters.*

We note that lake Chad is the source of 2/3 of these perimeters and they are mainly located in Nigeria, with a water demand approaching 2 km^3/year.

We also notice in Paoletti (1991) that the small irrigated perimeters total up 12,000 ha (with 7,000 (?) in the valley of the Tsanaga Mayo in Cameroon), that is about 10 % of the large perimeters for a more important produced wealth, gardening making more money (pepper, onions, gumbo, etc.).

We noted that less than 1/5 of the water demand was fulfilled in 1992 ; but less than 5 % of needs were fulfilled from the lake ; despite 20 k^{m^3} inflows in 1991 and 1992, that are not the weakest on the period, the intakes remaining far from the lake water surface.

In the state of weak hydraulic regime of lake Chad, questions raise :

Should the exploitation of large existing or in project perimeters be optimized, insuring the water resources from the lake southern basin, **while lengthening the intake channels**, as planned, **with the risk of reducing the southern basin and the biosphere storage** it is, **helping the filling of the southern basin by embankment works of the Logone and the Chari**, removing the water from the flood plains and **sacrificing the Yaere and its natural storage of animal life, its promises of renewed fish resources or its grazing lands precious** for the numerous herd of the region ?

6. THE TOOLS FOR AN ENVIRONMENT FOLLOW-UP AND THE WATER RESOURCE MANAGEMENT

6.1. The measurement networks

The rainfall station network is managed by the different national or local meteorological services of the LCBC member States. It is globally operational, specially the synoptical stations, but the data are rarely processed, except for the publication of agro-meteorological reports, they allow the estimation of the agricultural campaign evolution. Its density can be considered as being adequate, but controls on the measure quality and the running equipment should more frequent. The stations are too scarce to observe Lake Chad and some island zones should be equipped with automatic recorders or storage raingauges, as this was done about twenty years ago, this to make clear the fallen water depth.

The **climatological stations** are scarcer whereas they are essential in the follow-up of climatic parameters and in particular the parameters for the best approach of the evapotranspiration evaluation. There again, it is necessary to ensure the good quality of the results and to criticize them before publishing year books.

The LCBC's duty should be to centralize in a data base the pieces of information given by the states.

The station surface water follow-up of the **hydrological network** raises a lot of problems.

- in Niger, the network has only few stations on the downstream Komadougou Yobe and the validity of the records can seriously be questioned (see annex 4) ;
- in Nigeria, the network could not be assessed because of lack of information, it would be surprising that there should exist a perennial follow-up elsewhere than in the management of the works of the Komadougou Yobe upper basin ;
- in Cameroon, the whole hydrological network was stopped for about 8 years, because of lack of functioning supplies. Some punctual pieces of information are collected for some specific studies, financed by sponsors, but few of them concern the lake Chad basin ; there are confirmed teams of hydrologists (researchers and engineers) and it could be rather simple to redynamize enthusiasm to an hydrological brigade in the north of the country ;

— in Central African Republic, the hydrological stations of the Chari-Logone upper basins have been abandoned for practically 20 years, the national hydrological service having a lot of difficulties in keeping up a minimum of stations on the Ubangui basin ;

— only the republic of Chad preserved a network reduced to about forty stations in a rehabilitation project and operates the main stations of the Logone and the Chari, and the lake at the station of Bol when the water rises up to there. An automatic station project with remote monitoring via Meteosat on four main stations could be financed by France, in support with the present network and in the framework of HYCOS (WHYCOS), piloted by WMO. But the problem of station calibration raises with the frequent shifting of low waters ; the functioning budgets to go in the field are missing.

The experience shows that the governments are not willing to support the management costs of hydrological networks, that the civil servants of these departments, not well or lately paid, are not inclined to involve themselves in this type of woks without profit and appropriate functioning means. The different experiences of hydrological network rehabilitation, with the help of the international (UNDM-WMO, through AGRYMET for the CILSS countries...) or bilateral (French cooperation and Orstom) assistance do not survive long after the end of the projects ; even if the employees get a rewarding technical training abroad, this training is not often enhanced in the day-to-day management of hydrological departments.

It's the reason why, **the solution of the a minimum network management of environment permanent observation is chosen**, this is being achieved in Chad.

We noted that the Chadian hydrological department is in touch with a good competence in the process of hydrological information and the management of the data banks, it manages by its own its flood warning system and, if adequate functioning means were delivered, the absolutely indispensable field campaigns could be resumed.

But **it is probably LCBC's duty to create its own hydrological cell, while federating the hydrological activities of the different states, for what concerns lake Chad and its basin**, while receiving on temporary assignment some engineers of these States with competence's identified by independent assessors, to insure the management of observatories that would have been retained and the data bank spreading. In gratifying the university research of the State members to the scientific and technical processing of the data, LCBC will bring a plus in the awareness of the local elite to the problems of water and environment.

To manage a resource, it is necessary to know it. As long as the action of man is limited to a minor withdrawal, there is no need to have sophisticated evaluation tools. But as soon as it is necessary to design, to develop a region without the risk that the infrastructure becomes useless by an unexpected degradation of environment, it is advisable to understand and quantify the processes at issue. Multiple national or international projects were not well managed or lead to costly failures only by a lack of knowledge of **hydrogeology** elementary notions : it is not enough to have funds to finance a well or a drilling to pretend mastering the water table.

In matter of groundwaters, where the latent period of the aquifers sometimes overpasses the decade, there is a need first to possess reliable observation networks, running on long periods. The provided data must be efficiently archived and finely analyzed. If needed, this information is used as input of mathematical models that reproduce the present behavior of the natural milieu and anticipate its evolution in front of different natural or anthropogenic constraints.

Even if these recommendations seem to be out of the immediate business of a GEF program, they must imperatively be undertaken. Their organization could be taken in charge by other internal organizations or two-part cooperation.

A control network for the phreatic water table piezometry has to be set up or, when it already exists, must be supported. This requires to select representative works of the aquifer, in ideal, works only planned for observation or else not much disturbed by pumping. The measurement time step must be determined according to the dynamic of the processes to study (for instance increase of the visit frequency in rainy season or during floods for points close to the hydrological network). The observations are more frequent during the first years in order to characterize more accurately every site, the measurements could be less frequent after, according to the first series. Close to the hydrological network, the double or triple measurements, lined up perpendicularly to the axis to recharge, are indispensable to appreciate the geometry of the piezometric domes. Such a network has sense only if it is permanent in a long term.

At present, a phreatic water table piezometric follow-up is carried out in eastern Niger thanks to Swiss funds ; we do not know the real composition and the frequency of the measurements. According to our passed experience, this network only concerned the southern part of the Diffa area ; the measurements are done but not analyzed.

In Chad, there are sparse piezometric data prior to 1970. As from 1986, a national network was reconstituted ; it counted 66 piezometers visited twice a year (Mott McDonald *et al*, 1992). Because of lack of means, it tends to disappear.

In Cameroon and Nigeria, nothing exists.

We can notice that, on the major part of lake Chad basin, observation networks of the phreatic water table are nonexistent or insufficient. The insufficient number of measurements in time and space do not permit either to understand the processes or to describe the evolution in a long term, such as the impact of the anthropogenic pressure increase or the climatic variability effect. A whole work of criticism has to be carried out before archiving the information in hydrogeological data base, this requires an hydrogeological competence it is not possible to find in the departments in charge of the piezometric follow-up.

Concerning the Pliocene water table, there is survey for the time being. Its present regime is much more influenced by draw off than by the natural conditions. The frequency of the future network measurements can thus be less frequent than for the phreatic water table. On the other hand, where artesian outflow still exists, it is necessary to check that tubbings are in good operating conditions and to have adapted pressure measurement equipment.

This requires to have 4WD field vehicles in very good condition, functional equipment (piezometric probe, conductivimeter, pHmeter, GPS) and motivated staff.

It is obvious that, in the basin, a lot of obstacles exist for the constitution and the maintenance of a piezometric network : cyclic insecurity that is the rule in several regions and the financial destitute are not the least.

Added to the routine follow-up of the water quality, apprehended through the conductivity during the piezometric campaign, it would be useful to plan chemical analysis (major ions) carried out in reliable laboratories to check the potentiality of the consumed waters. In the whole basin, a lot of wells and drillings are polluted especially by human and animal ejecta. In rural zone, this contamination can be fought simply by awareness and education of the populations and access limitations to the immediate approach of the works. In large towns, the chemical and bacteriological risk is more serious ; a detailed follow-up and protection measurements must be more severe and thus more expensive.

6.2. The data bases

The collected data must be controlled and processed as they are acquired, archived in data bases and published. In matter of hydrology, data bases are already managed in Cameroon, Niger and Chad, with an identical structure for the data bases in Cameroon and Chad (with Orstom programs : Hydrom and Pluviom). There should not be too much problems to insure the coherence of these three bases. Concerning Nigeria, it is necessary to check the existence of a computer aided process ; if it does not exist, it must be created at the soonest copied on operational organization in the other countries of the basin.

In matter of hydrogeology, data bases exist in Niger and Chad. They do not run with identical programs, but information can be exchanged between the two systems without major difficulty ; the Chadian's is of more modern conception and aspect.

It is necessary to recall that building a data base does not only consists in transferring paper documents to a numeric support, but implies a severe data criticism that cannot be the job of a key entry operator, but must be carried out by an awared hydrologist or hydrogeologist. The deficiencies of the existing bases show that such a work is still to be done, in part at least. It is not sure that at the present time, all the national departments have effective competence to carry out this criticism task. In such a situation, we could consider the following distribution : the collection of information is done by the national departments that feed their data bases ; the measurements are transmitted to a specialist that gathers, processes the data of the whole basin and gives back the analysis to the former providers.

6.3. The numeric models

Among the available computer tools on the Chad basin, we must mention the **mathematical models, used in hydrology**. LCBC have, particularly since 1994, a mathematical model of hydrological behavior of lake Chad and the rivers that feed it, model called HYDROCHAD and developed by Mott McDonald International. This model includes an hydrological production model of rainfall-discharge to the basin upstream inputs and an hydrological loss model of the runoffs in the hydrological network and the flood plains. It is not operational yet at the LCBC and some approximations will probably limit its use, but it is indeed a precious tool for global simulations. Another model of more simple conception was developed by Orstom to help the **flood forecast of the Chari in N'Djamena** on 10, 15 and 20 days. These two models are described in annex 4.

Numeric modelling of groundwater runoffs permit a better understanding of the water table functioning, to be in order to simulate the impact of the possible climatic or anthropogenic modifications. For the time being, the phreatic water table is the main object of the numeric modelling. The Pliocene water table can also be modeled, but because of a less important exploitation (in number of intakes as in pumped volumes), this project is not a priority in the structured mastery of lake Chad basin groundwater resources. Two arguments plead in favor of separated models :

— the hydrologic independence of the two aquifers on the quasi-totality of the basin ;

— a more heavy definition and manipulation of a two-layer model, not indispensable compared to two autonomous models that better respect the specificity of extension and functioning of the two water tables.

On the other hand, it is necessary to develop quickly a genuine numeric modelling of the runoffs in the whole phreatic water table with enough quality and accuracy to make of it a tool of operational management. This requires a regular exchange process between field data acquisition and modelling : the incoming data allowing to improve the model and the model pointing out sensitive zones that require complements of investigation. The numeric modelling is all the most easy to carry out that the requisite data can easily be accessed and handled thanks to an archive in efficient data bases.

As far as we know, there are three modelling that concern the basin :

— the modelling of the phreatic water table in eastern Niger in 1991 within the framework of UNDP DCTD NER86001 project ;

— the pre-modelling of the phreatic and Pliocene water tables on the whole basin (Eberschweiler, 1993) ;

— the modelling of the phreatic water table of the Chari-Baguirmi (Bonnet and Meurville, 1995).

The modelling of Niger will have to be improved in completing and updating the available data. It was carried out only in permanent flow, this seems reasonable provided the slow evolution of piezometry and draw-off observed in the sector. A modelling in transitory regime could be useful if we want to detail the relationships between the Komadougou and the water table, for instance appreciate the impact of the river flood decrease. The good reproduction of the piezometry and the quantization of the water balance different terms, confirming the proposed estimations, leads us to think that the model is operational.

Modelling the whole basin includes in fact two independent models : one for the phreatic water table, and one for the Pliocene water table, this because we estimate that the two aquifers are independent almost everywhere. This means a very useful and important work. It is obviously not the definite tool that will permit to test all the climatic or management scenario. Some uncertainties weigh on the used data, some simplifications can be argued (such as the choice of a wall of the water table, horizontal, uniform on the whole area) and the calibration conditions are not always explicit. These are despite the first fundamental steps to the intelligent management of the groundwater resources at the scale of the basin.

The modelling of the Chari-Baguirmi is, as the others, very dependent of the available data quality. It is carried out well and the report is didactic. It reconstitutes pretty well the piezometry and permits to evaluate the water table evolution for the next years, specially in the region of N'Djamena.

These already undertaken modelling illustrate perfectly what is to be designed as a tool for hydrological modelling.

— a model of the whole basin representing the basic processes and appreciating the regional trends in a long term. The general model because of its size cannot solve the occasional problems. The main important two aquifers of the basin (phreatic water table, Pliocene water table) must be modeled ;

— local models to answer more specific questions (impact of a dam, important increase of the demand in towns, development of irrigated perimeters). They lean on the results of the general model, but their size and the requisite data for their trouble-shooting are adapted to the asked question.

We must pay much attention to the conditions imposed by the model and its accuracy in representing the natural processes. Even if a model never can represent the milieu in its variety, the simplification imposed in the model mustn't distort too much the reality. And, after testing different simulations, it is necessary to check the compatibility of the results with the initial hypothesis.

Modelling groundwater runoffs is an heavy task that requires to be left to an expert having established competencies in hydrogeology, to understand and intelligently simplify the present mechanisms, and in numeric modelling to be in order to master the tool and upgrade it. For the time, such a profile is exceptional in the lake Chad basin (perhaps one person at the DHA of N'Djamena whose experience should be completed).

The « natural » place where the model should be developed seems to be the LCBC. The regional models could on the other hand be developed and maintained either within the application zone or gathered at the level of the basin. As far as it is impossible to find the required competencies to achieve the models and run them in every concerned state, the second hypothesis seems the more realistic one.

Let's thus recall once more that the reliability of a numeric modelling directly depends on the quality of the basic data. The hydrogeological processes interfering in the basin must first be identified and measured (it is not quite sure that identical mechanisms operate in the border of Sahara and in limit of the forest of Central African Republic) ; this requires a huge field work done by confirmed hydrogeologits. Are these competencies available around the whole basin ?

6.4. Satellite imagery

Remote sensing is already a choice tool for researchers in the study of lake Chad and its basin ; a lot of laboratories all around the world are interested in the evolution of this humid zone and it should be possible to better formalize, within the framework of LCBC, the acquisition of SPOT images and their process, choosing a regular follow-up and a reference zone that could be the lake southern basin. The means and competencies in remote sensing and image processing seem to be important (at least at LCBC and CNAR in N'Djamena, Agrhymet in Niamey) and could allow for instance an accurate temporal follow-up of the flooded areas, the cultures, etc.

SECOND PART : SCENARIOS, EVENTUAL RISKS AND RECOMMENDATIONS

1. GENERALITIES

The most recent data (Olivry *et al*, 1996) and the analyses done on the « ill rivers of Africa » (see annex 3) let us consider the evolution of the lake Chad hydrosystem at three levels :

The **first level** is the « **lake memory** ». If several years in deficit were necessary to reach a quasi drying-up, only a few mean years of the Chari inflows or two consecutive exceptional years could be enough, in term of balance, to restore to the lake the aspect it had up to 1970. A 52 km^3 flood in the Chari (already observed) is necessary to observe a unique lake at the level of « normal » Chad, with the maximum in January ; two important successive floods are necessary to have a unique lake permanent all year long (level over 280.8 m in January), and such a recharge already occurred twice for the beginning of the century. The « lake memory » is short enough not to confine it hopelessly to its advanced stage of drying-up.

The second level is **the persistence or not of the climate degradation** in the region ; the main motor of the lake possible evolution is the climatic evolution of the next decades. The increase in the rainfalls of the last most recent years does not mean that the trend changed, it can also mean that pessimism is not de rigueur.

The third level is the « **river memory** ». We said (see annex 3) that the fluvial resource impoverishment was due to the climatic crises the fluvial basins endure and of the cumulated effect of the rainfall deficit on the upper basin aquifer storage that interfer in the base runoffs, this leads to a long-lasting decrease of the resource.

It is the union of the last two levels that are determining for the hydrological future of the Chari and the lake Chad. Several scenarios are possible :

1°/ Continuation or aggravation of the drought : the processes put in evidence are exaggerated, the rivers will rapidly stop being perennial in dry season ; the trend would be Sahelian or semi-desert hydrological regimes and in a long term fossil hydrological networks of Sahara. But nothing in the scenarios of global warming-up and the greenhouse effect goes along with such climatic modifications in the region ;

2°/ Incoming of a long humid period, similar in duration to the present period in deficit : a progressive come-back to the previous low waters can be expected, with again an abundance of resources after ten or fifteen years of recovery (modules and floods) ;

3°/ Occasional come-back of excess rainfalls, alternating with dry episodes ; the duration of these dry episodes will determine the stabilization of the hydrological degradation level with a durable impoverishment of the dry season resources and more globally of the modules and floods, as they were observed during the last years.

Leaving aside the consequences of the most pessimistic scenario, we must underline that **the occurrence of a medium situation leads to perpetuate the degradation of the hydrological regime** of the rivers in the region and that, in the most optimistic situation, the effects of the present drought will still continue during long years.

It seems thus reasonable to consider that the integrated actions of management of the lake Chad basin water resources must lean on the hypothesis of a random resource level around the average level of the last 25 years.

This means that we must count on **Chari mean inflows of about 20 km^3**, on a poor filling of the southern basin, a very hazardous getting over the Great Barrier Reef (with a limited and short feeding of the northern basin of the lake), a null to medium flood of the Grand Yaere, null or modest runoffs of the El Beïd and almost null on the reaches downstream the Yedseram and the Komadougou Yobe.

The statistic evaluation of the risk of failure in the resource must be done on the hydrological series got since 1970.

In this connection — and even if the available meteorological series in many points for the beginning of the century and the various researches dealing with the Sahelian climate permit to determine its fundamental characteristics allowing, though the very important variability, the evaluation of the risk of rare event occurrence — the climatological studies must be updated, in terms of statistics, on the present period and start by assuming that there was a climatic rupture around 1970.

These new series mustn't put aside the occurrence of « strong » events with unlikely return frequencies. The notion of disastrous event risks as the very high floods of the Chari must be established on a predetermination based on all the available series, so that they are not underestimated.

In the present climatic conditions, it seems obvious that the anthropogenic pressure has serious consequences on environment of the populations of the lake and the low plains. The degradations were already listed, whether it can be fish stock overexploitation in the fish refuge zones or of the disappearance of a lot of tree species in wide areas around town (wood for heating), or in zones where the piezometric level decreased too much to insure their existence, excessive number of cattle on smaller grazing lands, the diminution of the animal life and the disappearance of some species, or of overexploitation of groundwater storage or low water discharges.

Even if this anthropogenic pressure is not responsible for the climatic evolution in the region, it is nowadays not proved that the increase of the global greenhouse effect, probably of anthropogenic origin, has any relationship with drought in Sahel.

On the upper basins, different studies using remote sensing showed there were no significant modification of the plant cover able to increase the relief erosion or to modify at the level of receiving surfaces the parameters of the water cycle. The population density is scarce and these regions far from towns that could overexploit the ligneous resources.

2. THE ALTERNATIVES

Are there any possible alternatives to decrease the climate pejoration in Sahel ?

We must first put aside a certain number of ideas that regularly come back in the literature :

- **— the idea of a green belt** that could stop the desert was the object of recommendations in Nairobi in 1977. Dunes can be fixed in sensitive zones with planting appropriate species, but it is not a green belt that will stop the climate aridity ; moreover, planting trees at such a scale means to draw off intensively the not refilled groundwaters : phreatic, their level will decrease so that the plants will not reach it ; Pliocen, they risk not to feed anymore the oasis of the Low Lands in eastern Chad. If as supposed microclimates come out with the creation this green belt, they would be limited to the scale of town and village parks.
- **— the idea of modifying evaporation** could be considered while modifying the practices of agriculture on the cultivated areas (mulching the furrows with casual plants, frequent harrowing of the crusted soils to help infiltration, economy of irrigation waters), but certainly not the building of quickset hedges that would absorb more than the searing Harmatan ;
- **— the idea of artificial or generated rains**, already mentioned in the rather deceiving experiences in West Africa, these are not empowered to solve the problems of insufficient rainfalls on such a wide basin.

Are there alternatives to better master the available surface water resource ?

These alternatives obviously depend the use expected from the resource. The major preoccupation of the governments seems to be to favor the supply of large irrigated perimeters (Bol polders, South Chad Irrigation Project) this through increasing as far as possible the lake Chad filling or the low water discharges of the rivers.

It is possible for instance to **recollect the volumes that evaporate** in the Chari and Logone flood plains, this **while cutting the overflows by a complete embankment** of these rivers (see annex 4). The gain for the lake does not correspond to the evaporation balance of these plains, balance including the rainfalls they receive, but the gain is not negligible as we saw for the Logone. This complementary inflow to the lake contributes first to increase its evaporating surface and takes off water to economically important zones such as the Great Yaere or the El Beïd valley.

The building of large reservoirs upstream on the Pende and the North-Vina was also considered, this to regulate the floods and thus to reduce the overflows in the plains, but mainly to return a storage of about 7.8 km^3 during the dry season. But these artificial lakes add to the general balance an extra loss by evaporation, we come back to the previous case for the plains downstream.

It is also possible to **close the Ere and Dana thresholds** and eliminate the losses that feed the Mayo Kebi, tributary of the Benoue and the Lere, Fianga and other lakes, but this Chadian part of the Mayo Kebi basin, densely populated (the *Bec de Canard*), is part of the conventional lake Chad basin.

Manage the hydrological shortage is not easy and must take into account a certain number of constraints that are mentioned further for the different diagnosed regions affected by eventual designs.

Are there alternatives for a better management of groundwaters ?

Preserve humid zones is one.

In lake Chad basin, humid zones (lake, Yaere, main bed of the rivers) just take up a small surface area. They are despite very important for the exchanges between the hydrological network and the phreatic water table on one hand and for the existence of biological variety on the other hand.

The flood spreading zones are essential for the water table recharge, as the shape of the piezometric curves show it. But we have limited pieces of information on the way infiltration operates in these zones. And, as far as we know, no hydrogeological study ever quantified the recharge from the Yaeres, their real part can just be grasped by analogy with the parts of the basin where these phenomena are better observed.

Before deciding any design, it will be necessary to carry out hydrogeological studies. Before this is done, it is better to consider these milieus as essential and fragile. For instance, the embankment of the Chari and the Logone would increase the lake inflow (in which one part would evaporate) but it would also lower the water table and cause serious risks for the supply in N'Djamena. And it is not sure that the gain in surface runoff would compensate the loss in groundwaters.

Optimize the aquifer exploitation.

The water supply of the lake Chad basin is mainly ensured by the surface runoffs coming from the south. The climatic evolution cannot be forecasted for the incoming years or decades, so it is necessary to consider the present situation as a durable fact. The increase of the population implies an increase of the water demand directly by the supply of drinking water and indirectly for the production of food. The available stock in the basin (surface and underground) was disturbed by the repeated droughts. It is a limited resource it is necessary to manage at the best. Except an hypothetical water transfer coming from another hydrological basin, the strategies must be developed on several axis :

- avoid wastes. In agriculture, for instance, the irrigated crops could be replaced by production of species consuming less water, and more adapted to the climatic conditions. On the other hand, the casing strung of old artesian drillings (tapping the Pliocene) should be repaired and equipped with valves and this could save a lot of water. All this should be done with the education of the population and their administrations and the awareness of their responsibilities ;
- optimize the present natural resource management. This requires reliable and heavy-duty tools.

In the irrigated perimeters, the present cultures must be replaced by agricultural productions more coherent with their environment. During the last decades, common sense was lacking in the management of natural resources, and genuine scientific studies show that the lake Chad basin is an especially fragile milieu. It is better to realize the mistakes in management before its is too late. This questioning of large irrigation projects seems to be accepted now, at least in principle (cf. steering plan of LCBC 1992).

The hydrogeological data analysis shows that the groundwater resources, even in huge quantities, are fragile. As far as it is not possible to count on a short term climatic improvement, the only way to face a considerable increase of water consumption in lake Chad basin could be to manage a water transfer from another basin.

3. THE CONSTRAINTS

3.1 The international waters

From the north to the south, we have successively :

The downstream Komadougou Yobe, border on about 150 km between Niger and Nigeria. At this step of its course, the resources are not sufficient enough to recharge the water table (that is common to the two countries). The works in the upstream basin and the ratio in the Niger/Nigeria populations is so unbalanced that it seems highly improbable to **plan on a reasonable minimum guarantee downstream tailwater**.

The El Beïd, border on about 50 km between Nigeria and Cameroon. It drains the Cameroon's Grand Yaere and is mainly supplied by the Logone. Its discharge depends on the level the Logone flood reaches. The Maga pool in Cameroon (Semry II) often was considered as responsible for the decrease of the El Beïd discharge, but the intake on the Logone is not more than 1 % of the runoff and occurs during the flood. The chance to store one part of the inflows coming from the Mandara Mounts must be kept in mind, these are nowadays not more than 0.4 km^3. Two possibilities can be first the sharing of the resources between the riverside countries and second the filling of the small south west basin when it is isolated from the large southern basin.

The downstream Chari between N'Djamena and the delta, natural border between Cameroon and Chad. It is the main inflow in the lake. Intakes are limited and the sharing of its waters is not a problem. Note that the Serbewel, Chari effluent downstream Kousseri, completely flows in Cameroon.

The Logone, from Bongor, is the natural border between Cameroon and Chad. The large irrigated perimeters are still limited in regards with the available resources, this all the most because they are not all functional and their supply only draw up a small part of the Logone waters, except in low waters when minimum discharges must be guaranteed downstream and large irrigated culture is forbidden.

The lake waters, when they only fill the southern basin, and according to the borders established on the lake Chad, are shared between Cameroon for a small part and Chad for their main part. The use of these waters is a question that will raise. This use could be limited in volumes if an environmental sanctuary has to be preserved. This is a way to preserve the animal life and the flora, the future of the lake resources depends on this preservation.

3.2. The socioeconomic context

These aspects were already mentioned in chapter 5 of the first part. Our aim is not to anticipate the analyses that are done by specialists in socioeconomy, we only want to bring out what, to our opinion, are the priorities for an integrated management of the basin water resources. These reservations expressed, our classification is the following one :

- **human needs satisfaction** (surface and ground waters). To provide water for the population water consumption is not a real problem, and the funds to improve this supply in rural environment as well as in urban infrastructure prove this. There could be a priority in some cases at the expense of agriculture (near large towns such as in Kano) ;

— **bolster and conservation of fishing.** This activity concerns 50,000 fishers and five time as much in marketing fishes (Chadian, Cameroonian, Nigerian), with complex commercial trading between the three countries (Niger being offside for present). The regions concerned by this diagnostic are the Logone and Chari flood plains, among which the Grand Yaere (breeding ponds and nurseries) and of course the lake. There is a clear relationship established between fish production and the Chari maximum. And this activity does not damage the water resource ;

— **bolster and conservation of cattle breeding**, and the fallback zones in dry season specially the Grand Yaere. This conservation could be done by keeping the fodder resources linked to the flooding and the Logone flood importance. This concerns herds coming from the four riverside countries of the lake. Attention must be paid not to overcrowd the grazing lands ;

— **development of traditional recession cultures.** These are of course linked to the importance and the duration of the flood along the river reaches and in the low lands ;

— **limited development of the irrigated culture.** i.e. to privilege the small farming irrigation compared to large industrial irrigated perimeters, and to vary the cultivated areas and the culture type according to the availability at the time.

Two diagnostic regions clearly emerge from this enumeration at the economical and environmental levels : the lake only for its southern basin and the Grand Yaere. The important parameter for the hydrological part are the Logone and the Chari floods. This is not new, but implies that **the flood must be preserved in its natural state, without any management that could modify the hydrosystem.**

The problem that remains is of importance, because, the possibility to observe an interesting flood is dubious. If the hydrosystem is not modified, it is necessary to plan to get external yields.

4. THE SOLUTION OF WATER TRANSFERS

4.1. The transfers in Nigeria

In Nigeria, the project is to transfer water from the Hawal river (tributary of the Golgola, itself tributary of the Benoue) to the Ngadda and Yedseram rivers on one hand and on the other hand from the upper Gongola (via the dam of Dindima) to the Komadougou Gana (Komadougou Yobe tributary).

Concerning the transfer of the Hawal river, the inflows could be 0.82 km^3 and a mean discharge of 20 m^3/s. We have no precision concerning the transfer to the Komadougou Yobe. Provided the associated irrigation projects, the inflows to lake Chad could be considered as negligible. These irrigation projects should remain a national affairs in Nigeria , except if these inflows compensate on the Yobe one part of the discharges used on its upper basin and supply the international waters, shared with Niger.

4.2. The TRANSAQUA project

It may be a giant project, this « idea for Sahel » imagined by Bonifica (1991), Italian research consultancy, but worth being developed. The project intend to transfer to the Chad basin **100 km^3** a year, i.e. a mean discharge of 3,200 m^3/s form the **Zaire basin**, that would indeed loose only 8 % of its interannual module. This transfer would pass through a 2,400 km long canal, with 1,600 km in Zaire. This canal would cross the upper basin of tributaries in Zaire and Central African Republic, up to the water divide Zaire-Chad, where it would catch an important part of the resources (basin surface area crossed by the canal : 220,000 km^2, elevation at the canal beginning : 900-950 m ; ship canal 100 m wide and 25 m deep, etc.). The water flowing in the Chari upper basin could provide in various hydropower works from 30 to 35 billion of kilowatts and would supply irrigation of 7 million hectares, among which one part in the Chad Low Lands.

Appealing by its monumental aspect, the project is less pleasant by the expectable costs of such a execution, that in the coming decades will remain undoubtedly an utopia. It could moreover have **impacts on environment**, these are not listed yet but risk to be serious : impoverishment of Ubangui, organic load of equatorial waters in the Chari waters, renewal of fluvial erosion in the Chari bed and eventual filling of the southern basin of the lake, introduction of new fish species that risk to destroy the equilibrium of the existing fish resource, etc.

4.3. Water transfer from the Ubangui to the Chari

Coming after TRANSAQUA, this project seems more realistic ; it is nonetheless very important and will suppose heavy investments. The idea is to transfer from 300 to 500 m^3/s from Ubangui, upstream Bangui, thanks to a dam on the river, then a canal 70 km long, and a pumping on a 250 m long slope to reach the divide line and then naturally flow via the Fafa river, tributary of the Ouham and the Chari, with electricity production to allow pumping. The transfer volume could be according to the chosen range from 9.6 to 16 km^3/year.

This project, on proposals of the Nigerian Electric Power Authority (NEPA) and studied by Mott-McDonald Int., plans to link the Zaire to the Ubangui by a 170 km long canal, than to connect the Chari to the Logone by another canal, in order to supply the Mayo Kebi (then the Benoue).

A prefeasibility project should be retained on this project with objectives concerning the Chad basin and not only the production of electricity (management of the Gauthiot falls on the Kebi for instance). The aim is not only to fetch the resources in the Zaire (with the supplementary cost it implies), the project should make clear the use that will be done of the water and then the schedule of the draw-off in the Ubangui that must take into account in dry season the opportunities of low water sustain, this to lengthen the navigability on the Congo-Zaire. The Ubangui water resources also decreased with the deficit in rainfalls (see Orstom studies) and for the last ten years, the mean discharges of March and April are under 500 m^3/s. On the other hand, the discharges from July to December are over 2,500 m^3/s.

In the preceding paragraphs (especially paragraph 3.2) we pointed out that what was important in the water resource management, in keeping with durable development and environment, was **the sustain of the Logone and Chari annual flood**. The project allows this, favorable conjunction with the Ubangui discharges, if the option of the

Chari-Logone canal is kept, insuring a complementary supply to these rivers, to the Grand Yaere, the El Beïd and the lake.

5. RECOMMENDATIONS

5.1. Physical milieu follow-up networks and environment observatories

We already noted recommendations in chapter 6 in matter of **meteorological, hydrometrical and piezometric networks**. Numerous projects defined the standards and costs of such networks ; such references can be found in the Water Assessment of the LCBC countries (1992), they could be a base for the redefinition of objectives more adequate than the ones planned within this expertise in the framework of GEF. These networks, this follow-up are indispensable for a more accurate approach of the functioning and modelling of the Chad system. The developed data bases will be widely spread.

At the global environment level, lake Chad is a unique and original entity we need to know to protect it. In this aim, it is very important to plan a lacustrian environment observatory within the southern basin at the Kalom Island, where an automatic recorder was observed during a long period by Orstom and DREM. It is necessary to install a station on piles, observing complete climatological, hydrological and hydrochemical measurements (another solution could be a floating station installed on something like a ferry, for instance the wreck of the Kousseri-N'Djamena ferry that could be refloated). This station needs a guard (changing of the guard every 15 days), connected to LCBC by radio and equipped with remote monitoring sensors for scientific information.

5.2. Environmental follow-up of humid zones

With the lake, the Yaere, the fluvial valleys (Chari, Logone, El Beïd and Komadougou Yobe) should be observed, in term of ecology, biodiversities and integration of human activities in the milieu. An inventory of the degradation must be lead and solutions found for a better conservation of humid zones (animal life and flora).

UICN is specialized in this field and acts in the region ; its actions should be federated with LCBC projects dealing with nature protection (parks, forest or animal reservations) within the framework of actions supported by GEF.

In these actions, we recommend the study project of the small pools management impact on the mayos of the Mandara Mounts, on the western part of the Waza park, already identified in the development plan of LCBC.

We also recommend the creation of an **ecological protected zone within the southern basin** of the lake, where the observatory we previously mentioned should have a central position.

5.3. Other recommendations

A **flood warning system** was installed in N'Djamena for the Chari floods. It is operational but could be improved by the design of a backup model, in case the upstream reference stations fail. This system could be extended downstream on to the lake and could be coupled with a geographical inquiry locating the new inhabitants in the low lands of the minor beds and in the areas around the lake that could be flooded in case of important floods. A 10 day forecast like the existing one, could be relayed by local radios in vernacular languages and would help avoiding losses in human lives and also losses of herds isolated on islet-banks before being drowned.

The prefeasibility and impact study of Ubangui-Chad water transfer should be a priority of LCBC. The time limits of starting up such a project, of finding funds don't let us hope a quick achievement, all the more that the works should last several years.

In the shortage context that risks to continue, a fair negotiated water sharing must be organized under the auspices of LCBC that will have to calm down bit by bit every consumer concerns on the use done of the resource by others, arbitration helped by appropriated independent inquiries.

In matter of water quality, with the monitoring of urban or industrial pollution (thinking to the oil exploitation in the south of Chad) and water table supplying the populations, there is no incoming problem of agricultural pollution, fertilizers and pesticides being used underneath the standards.

5.4. Institutional measures

Experience proves that the present organization (national administrations + LCBC) does not function properly. But, the two levels, national and basin, are important and it would be unrealistic to eliminate one of them. The bad circulation of information is one example the misunderstanding, a lot of documents are not transmitted by the national departments to the LCBC and, conversely the administrations don't seem to know much about the major studies carried out by LCBC.

Whereas groundwaters often are the only permanent resource, the weakness of real hydrogeological competence is a major handicap for the durable management of environment in the lake Chad basin. And, the multiple difficulties connected to a very difficult economical context have a quick negative impact on the motivation of the implied personnel.

In the different national administrations, the training of technicians and field executives being often limited, this situation does not let them master the complexity of the natural milieus. As long as this situation remains, the best should be to gather the established competence within teams not too numerous to be efficient. This is one of the reason why it is necessary to maintain a basin organism like a « renewed » LCBC. The other reason is that the impacts of important management projects must be assessed at the basin level, if possible by a structure independent of political pressures.

The routine control of the natural resources and the management of small works are obviously left to the national level.

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ANNEXE A : TERMES DE RÉFÉRENCE DE LA MISSION

ONU (DADSG) **Mai 1996**

FOND MONDIAL DE L'ENVIRONNEMENT - PNUD

GESTION INTEGREE du BASSIN DU LAC TCHAD (Assistance "B")

RAF / 95 / G48

TERMES DE REFERENCES DES CONSULTATIONS

EN GESTION INTEGREE DES RESSOURCES EN EAU

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TITRE : *Specialistes Ressources en eau au Sahel :*
1 Hydrologue et 1 Hydrogeologue

DUREE : *2 Semaines chacun*

LIEUX : *1 Semaine N'Djamena (Tchad) Hydrologue du 18 au 26 Juin 1996*
Hydrogeologue du 21 au 29 Juin
et 1 Semaine de redaction a domicile.

OBJECTIFS :

1) Apporter un diagnostic d'experts sur le comportement des eaux du lac Tchad et de son bassin (ressources en eau, mais aussi utilisations amonts et impacts sur la qualite des eaux) et

2) orienter l'assistance preparatoire au futur programme FEM pour

- la prise en compte des contraintes connues liees a la maitrise des ressources en eau internationales, de leur variabilite et des risques identifiables,

- donner des recommandations de sous-programmes complementaires, realistes et prioritaires, afin de pouvoir observer l'evolution de l'hydro-systeme international des points de vue quantitatifs et qualitatifs, et pour pouvoir, si possible, ameliorer l'efficience de son utilisation et de sa protection (gestion conjointe des eaux de crue et des eaux souterraines..., mesures preventives contre les risques possibles pour les populations et les eco-systemes tels qu'ils sont actuellement identifiables par la mission sur le court et le long terme ...)

TACHES A EFFECTUER :

Sous la supervision du siege des Nations-Unies (DADSG), et en coordination etroite avec le consultant en developpement integre de bassin et avec la CBLT, les deux consultants auront conjointement a realiser les taches suivantes :

1) Prise de connaissance et analyse des etudes principales existantes, bases de donnees et modeles, sur les ressources en eau dans la perspective de valoriser les acquis, et identifier les lacunes, pour pouvoir orienter les questions prioritaires a faire ressortir par l'assistance preparatoire. L'evolution passee et recente du niveau du Lac Tchad, ainsi que des etiages des principales rivieres perennes et des niveaux piezometriques seront decrites et expliquees, de maniere concises avec des figures illustratives.

(Les principaux documents se trouvent dans les institutions scientifiques specialisees, et a la CBLT).

2) Dans un deuxieme temps les scenarios possibles d'evolution du Lac Tchad et des eaux internationales seront decrits. Un avis d'expert sera donne sur l'importance relative des risques (economiques, sociaux ou environnementaux) associes a chaque cause possible : secheresse pluviometrique prolongee, crues violentes "oubliees", modification durable du climat, modification du couvert vegetal des hauts-bassins, sur-exploitation des reserves souterraines ou des eaux d'etiage, diminution des plaines d'inondation et des zones d'infiltration, developpement incontrole de reservoirs sur les rivieres... Cet avis des deux experts conduira a classer les causes de risques potentiels par ordre d'importance probable.

Les alternatives envisageables pour mieux maitriser les ressources en eau, et leur variabilite, seront ensuite rapidement explorees avec leurs avantages et inconvenients connus (transferts inter-bassins, controle des crues et des infiltrations, diminution des evaporations, connaissances prouvees sur les pluies artificielles...) en couvrant tout l'eventail des possibilites imaginables. Les connaissances disponibles sur chaque alternative seront presentees et decrites. Celles meritant des investigations complementaires seront identifiees.

D'autre part les alternatives d'adaptation / prevention aux conditions du milieu et a leurs risques seront examinees. Pour ces alternatives les moyens pouvant etre mis en oeuvre, et juges prioritaires, pour mieux exploiter la ressource disponible et limiter les risques liees au caractere imprevisible de la variabilite climatique (suivi piezometrique, annonce de crues...) seront decrits. Les risques previsibles (sur-exploitations, conflits d'allocations des eaux trans-frontieres, pollutions par les villes , les industries, les activites agricoles ou par les accidents ...) feront l'objet de recommandations d'actions preventives, et/ou de sous-programmes integres.

RAPPORTS

Les deux consultants presenteront un rapport commun dont le plan aura ete propose au DADSG. Ce rapport d'orientation pour les missions ulterieures de l'assistance preparatoire sera concis et pratique. Les principales conclusions de la mission commune de terrain feront l'objet d'un aide memoire qui sera laisse sur place au consultant en developpement integre et participatif de bassin.

Le rapport provisoire sera envoye au DADSG, au maximum 3 semaines apres le retour de la mission de terrain.

L'edition finale prenant en compte les remarques de la CBLT et du DADSG sur la version provisoire sera editee en 8 exemplaires en Francais et 6 exemplaires en Anglais et envoyee au DADSG pour diffusion aux agences du FEM, dans un delai inferieur a deux semaines apres reception des remarques.

ANNEXE B : LISTE DES PERSONNES RENCONTRÉES

Bonvillain, Centre National d'Appui à la Recherche (Tchad)
Chéné, conseiller technique ONU-DADSG, chef du projet
Darde, coopérant technique à la DREM (R. du Tchad)
Diguera Baba, Dpt. Aménagements, projets - Unité Ressources naturelles- CBLT
R.P. Faure, Secadev N'Djaména
Gence, représentant de la FAO au Tchad
de Grammont, Direction de l'Hydraulique et de l'Assainissement (Tchad)
Harrisson, consultant en développement participatif
Jauro Abubakar Bobboi, Secrétaire Exécutif de la CBLT
Mahamad Saleh Adam, chef de programme Environnement, Agriculture PNUD
Nelgar, responsable adjoint service hydrologique DREM Tchad
Sadio, expert FAO à Diffa puis N'Djaména
Sédick Ahmed, hydrologue à la CBLT
Walbadet Appolos, hydrologue DREM Tchad
Secrétaire exécutif adjoint de la CBLT
Chef de la Documentation CBLT
M. le Ministre de l'Elevage du Tchad
M. le Ministre du Plan du Tchad
M. le Ministre du Développement rural du Tchad
M. le Ministre des Transports du Tchad
M. le Représentant du PNUD à N'Djaména
M. le Représentant Adjoint du PNUD à N'Djaména

ANNEXE 1

Hauteurs des précipitations et variations climatiques

1. Généralités

La notion de variation climatique nécessite de spécifier à quelle échelle temporelle celle-ci se réfère. La paléoclimatologie a été abordée dans la première partie de cet ouvrage ; nous venons dans ce qui précède de caractériser les variations saisonnières du climat du lac Tchad. Il s'agit ici d'aborder les fluctuations du climat à l'échelle de temps du monde contemporain et des quelques générations concernées.

Il n'y a pas une cause unique aux variations climatiques sur une échelle temporelle quelconque. Au-delà de la portée des prévisions météorologiques établies selon des méthodes déterministes, la dynamique interne de l'atmosphère perd de son importance et les caractéristiques extérieures à l'atmosphère commencent à prédominer jusqu'à ce que, à l'approche des périodes portant sur les ères géologiques, ce soient les forces extérieures au système Terre-Atmosphère qui prennent de l'importance (Mahé, 1993).

Ainsi, pour les périodes portant sur des saisons et des années, les variations climatiques sont étroitement liées aux interactions externes entre l'atmosphère et la surface sous-jacente des océans et des terres émergées. Pour les variations portant sur des périodes très longues, nous devons étudier des facteurs qui sont davantage du domaine de l'astronomie, les caractéristiques de l'orbite terrestre et la production de rayonnement solaire, par exemple.

Les données climatologiques qui servent de produits d'entrée à l'analyse hydrologique sont elles-mêmes les produits finaux d'un processus bien défini, que l'énergie solaire régit en dernier ressort, mais que viennent modifier, à l'échelon mondial et local, des phénomènes dont l'action de forçage s'exerce sur des périodes de durée très variable. Certains ont un caractère périodique, d'autres sont le produit d'interactions intervenant entre l'atmosphère, l'océan, la biosphère, la cryosphère et la lithosphère, et à l'intérieur de chacun de ces milieux. D'autres encore, au nombre desquels on peut ranger l'activité météorique et volcanique, se manifestent de façon plus sporadique et peuvent être assimilés à l'injection de "chocs statistiques" dans le système. Dans un certain sens, les émissions de gaz agissant sur le rayonnement peuvent être classées dans cette catégorie. Ainsi il est impossible de considérer les séries de données climatologiques et hydrologiques comme des valeurs constantes (Mahé, 1993).

"Il est incontestable que les climats évoluent, la thèse traditionnelle d'un statisme du climat n'est désormais plus défendable" (O.M.M., 1988, 1989).

Selon White (1986), il semble certain que l'augmentation des gaz absorbant l'infrarouge (gaz à effet de serre) provoquent un réchauffement du globe. On a estimé que si la teneur en CO_2 de l'atmosphère était doublée, cela aurait pour conséquence une élévation moyenne de deux à trois degrés Celsius de la température du globe, avec des réchauffements plus importants pour les hautes latitudes que pour la zone équatoriale.

D'après l'O.M.M. (1986), les précipitations pourraient augmenter dans les régions tropicales humides, et les sécheresses estivales devenir plus fréquentes sur les continents situés aux latitudes moyennes dans l'hémisphère nord. L'augmentation de température devrait être plus importante aux pôles qu'à l'équateur, ce qui devrait ralentir les échanges méridiens d'énergie.

2. La normale et l'événement anormal

Les lois de distribution statistique des événements permettent de définir des pourcentages d'apparition d'une normale. Il est d'usage courant de se référer à la normale pour décrire la qualité d'un événement. On parle ainsi d'anomalie positive ou négative. Mais cette conception donne aux occurrences rares une apparence anormale, qui ne se justifie pas puisqu'il est normal qu'elles apparaissent avec un certain pourcentage de probabilité même faible.

Pour la description de l'évolution climatique, la définition d'une échelle de temps est primordiale pour replacer les événements dans un contexte probable d'apparition. Ainsi la notion d'anormalité varie en fonction du nombre d'événements utilisés pour établir la loi de distribution.

Pour l'Afrique soumise au flux de mousson, les banques de données de divers paramètres climatologiques ne portent le plus souvent que sur des périodes d'observation variant de 10 à 40 ans. Les modèles de circulation atmosphérique se basent sur ces données pour la reconstitution des événements. Deux problèmes se posent alors :

I. Y a-t-il une importante variation climatique durant les années qui servent à établir la climatologie ? Pour l'O.M.M. (1988) l'évolution climatique -sous-entendu à l'échelle humaine- est une réalité. La distribution des événements postérieurs à l'établissement d'une climatologie peut de ce fait s'écarter de la normale.

II. Existe-t-il des paramètres non pris en compte pour le calcul de la climatologie et dont les variations pourraient la faire sensiblement varier ? Un événement non prévu dans la climatologie et qui se produit néanmoins va constituer statistiquement une situation anormale (et non plus une déviation probable par rapport à la normale).

L'importance de l'apparition d'événements "anormaux" par rapport à la climatologie augmente au fur et à mesure que le climat évolue.

3. Cas de la Région du lac Tchad

Les précipitations annuelles sur le lac évoluent interannuellement suivant une tendance régionale. Les deux séries présentent les mêmes caractéristiques : précipitations les plus fortes durant les années 50 puis tendance décroissante des totaux annuels jusqu'à la décennie 80 où les totaux annuels sont remarquablement bas tous les ans. Depuis 1967 les totaux annuels n'ont dépassé la moyenne 1932-1989 que 6 fois sur 23 ans. Si l'on se réfère aux normales O.M.M. successives et qu'on les compare à la répartition des pluies annuelles des années qui ont suivi, on observe nettement l'évolution du climat régional en constant déphasage par rapport aux normales :

Période de calcul de la normale p	Normale O.M.M. (mm)		NB. d'années suivant la normale jusqu'en 1989 ns	Nombre d'années supérieures à la normale considérée nx	Rapport nx/ns
1932-1960	p_1	300	29	7	0,24
1941-1970	p_2	304	19	3	0,16
1951-1980	p_3	293	9	1	0,11

Cette évolution se retrouve au niveau de la région.

On a représenté ci-après le nombre de stations pluviométriques ayant enregistré leur totaux annuels les plus forts et les plus faibles. Au cours de chacune des 4 dernières décennies, dans la région Sahel est (59 stations), plus de la moitié des minimums se produisent entre 1981 et 1989, dont 25 entre 1983 et 1984 et 11 entre 1972 et 1973.

Décennie	1951-1960	1961-1970	1971-1980	1981-1989	Total stations
Maximum	35	12	9	3	59
Minimum	2	2	19	36	59

Sur les précipitations moyennes calculées par décennie sur le lac, on observe que de 1981 à 1989 la moyenne est plus de deux fois plus faible que celle de la période 1951-1960 (171 et 352 mm).

En 1988, les précipitations ont été abondantes sur le lac, mais également dans toute la région (figure 5.7) et sont comparables à la hauteur de la pluviométrie des années 50 ; 2 postes ont même enregistré leur maximum sur la série 1951-1989 cette année-là. On a pu observer par satellite le remplissage du lac ; pour la première fois depuis de nombreuses années l'eau passait la Grande Barrière en direction de la cuvette nord (Citeau *et al.* 1988a).

L'évolution des précipitations au Sahel, a été particulièrement importante au cours des 40 dernières années. Les effets du déficit pluviométrique ont été amplifiés au niveau du lac Tchad par une diminution drastique des surfaces inondées.

La très grande variabilité des totaux annuels de pluies est la caractéristique essentielle des pluies dans la région du lac ; même si les pluies peuvent être régulières et abondantes pendant quelques années, par exemple entre 1932 et 1951, des événements exceptionnels peuvent survenir : 1949, 1950. Il est clair également que des modifications à moyen terme (quelques décennies) du régime pluviométrique ont lieu, dont on n'a pas encore trouvé l'origine fondamentale dans la circulation atmosphérique du globe et qui sont impossibles à prévoir, aussi bien pour leur date d'apparition que pour leur durée.

Depuis le début des années 1990, un certain retour à des précipitations plus abondantes paraît devoir s'affirmer globalement dans toute l'Afrique soudano-sahélienne ; certaines années restent très nettement déficitaires, mais on ne peut pas ne pas mentionner les espérances que l'année 1994 largement excédentaire a suscitées dans l'ensemble de la région. Ainsi N'Djaména a reçu, en 1994, 800 mm de pluie, tandis qu'on a relevé 415 mm à Bol et 403 mm à Matafo.

ANNEXE 2

Le contexte déficitaire régional

1. L'évolution récente des précipitations et des écoulements

En Afrique tropicale sèche les déficits pluviométriques, marqués par une première phase aiguë dans les années 1972 et 1973, n'ont jamais cessé, même s'ils ont varié en extension et en intensité suivant les années. Une recrudescence notable de la sécheresse s'est manifestée en 1983 et 1984 et les déficits restent la règle générale jusqu'à la période actuelle. Ceux-ci se sont exacerbés au niveau des écoulements des grands fleuves. L'ampleur géographique du phénomène et sa durée, sans équivalence connue dans les chroniques hydroclimatiques (Sircoulon, 1987, 1989), ont conduit certains auteurs à parler de rupture climatique (Carbonnel & Hubert 1985).

Dans les régions soudano-sahéliennes, les hauteurs annuelles de précipitation montrent une tendance à la baisse particulièrement accusée dès 1968 avec des valeurs presque toujours inférieures aux médianes. Certains indices régionaux (Lamb, 1985, Nicholson *et al*, 1988) montrent cette dégradation constante depuis vingt ans. Une amélioration récente a été observée mais reste encore très relative.

Jusqu'à une période récente, on a pensé que la variabilité de l'écoulement annuel constituait, par l'intégration spatiale du régime des précipitations qu'il suppose sur l'ensemble d'un bassin versant, un paramètre de choix dans l'étude des fluctuations climatiques (Olivry 1983, 1987). De fait, les déficits pluviométriques se sont largement répercutés, et généralement amplifiés, dans l'écoulement des bassins fluviaux au point que dans la période la plus récente les paramètres hydrologiques ne sont plus en phase avec la variation pluviométrique annuelle (figure 9.16).

Dans la période récente on a relevé qu'en dépit de certains sursauts d'une relative abondance, l'hydraulicité des fleuves de la région n'a cessé de se dégrader. Cette tendance persistante à la baisse doit être soulignée car elle montre une dégradation durable du système hydrologique malgré un retour assez sensible à de meilleures conditions de précipitations.

Le régime hydrologique des fleuves d'Afrique intertropicale est directement influencé par celui des précipitations mais subit aussi, avec un effet retard, l'incidence du cumul de déficits pluviométriques répétés.

Les apports des fleuves de l'Afrique sèche du Sénégal au Chari totalisent en moyenne 275 km^3 an^{-1}. L'appauvrissement de la ressource en eau est pour la décennie 1981-90 de 85 km^3 an^{-1} (Olivry *et al*, 1993 ; Mahé, 1993).

2. La maladie des basses eaux et l'hypertarissement

Le régime naturel des basses eaux sur le Chari à N'Djaména, comme sur les autres fleuves soudano-sahéliens, est très gravement affecté par la sécheresse actuelle. Les étiages absolus des deux dernières décennies sont systématiquement les plus faibles de la série. L'évolution de la phase de tarissement constitue le processus majeur responsable de l'appauvrissement des basses eaux.

Après transfert à la station d'observation des écoulements rapides (ruissellements), on observe à partir d'un certain stade de la décrue de l'hydrogramme annuel, une décroissance régulière des débits ou phase de tarissement. Celle-ci correspond à la période où la vidange des nappes souterraines constitue la seule contribution à l'écoulement des cours d'eau de la région.

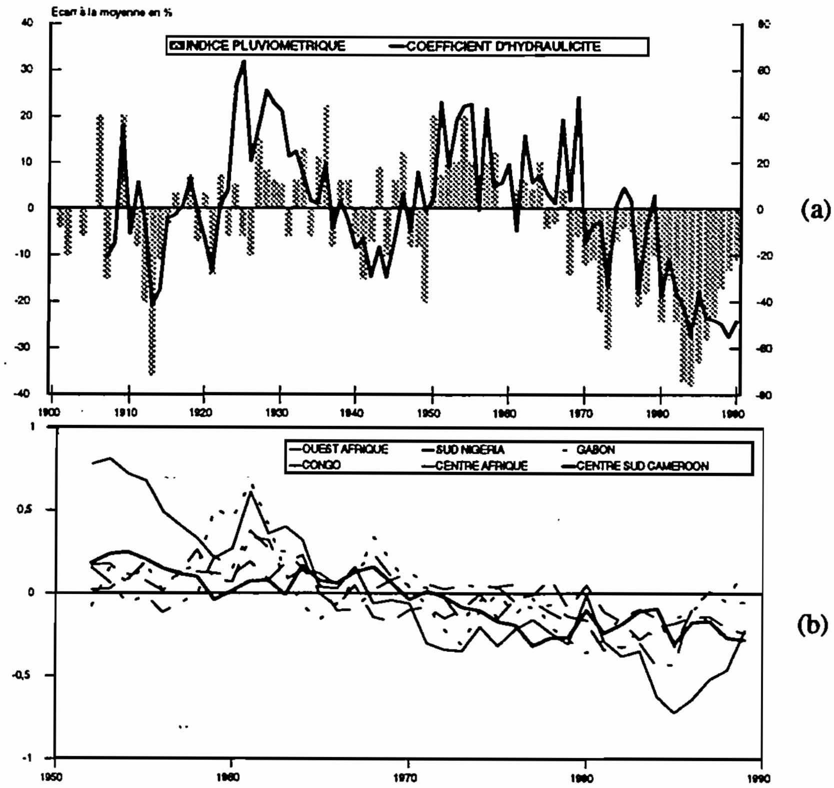


Figure 9.16

Variations hydroclimatiques.

a : pluviométrie et hydraulicité de l'Afrique tropicale sèche de 1900 à 1990

b: évolution de l'écart réduit des précipitations en Afrique humide depuis 1950.

Pour les cours d'eau tropicaux, cette décroissance des débits suit une loi exponentielle classique :

avec Qi et Qo, débits aux instants ti et to exprimés en jours et α, coefficient de tarissement dépendant des caractéristiques physiques et géométriques de l'aquifère qui a la dimension de l'inverse d'un temps.

Le tarissement principal, par les volumes qu'il implique et sa représentativité de l'ensemble des aquifères du bassin, constitue une caractéristique importante du régime hydrologique des fleuves soudano-sahéliens. L'étude des coefficients de tarissement montre jusqu'aux années 1972-73 une relative régularité des valeurs.

Les choses changent du tout au tout au cours des années les plus récentes ; on observe alors un véritable bond des valeurs de α.

Ainsi sur le fleuve Chari , les données montrent une première période de 40 ans avec un coefficient de tarissement moyen nettement inférieur à 0,02 j^{-1} et depuis 1975 des valeurs en augmentation qui tendent vers 0,03 j^{-1}.

On peut multiplier les exemples dans la région soudano-sahélienne (Sénégal, Niger). On retiendra que le temps nécessaire pour que le débit de tarissement des cours d'eau soudano-sahéliens diminue dans le rapport de 10 à 1 est passé *grosso modo* de 4 mois à 2 mois (Olivry, 1993a).

Cette faiblesse quasi générale des étiages traduit un amenuisement croissant des réserves souterraines des bassins fluviaux résultant du cumul des déficits pluviométriques.

La similitude des tarissements observés en milieu intertropical dans les chroniques de débit antérieures à la période de sécheresse (les valeurs du coefficient α évoluent entre de 0,015 à 0,025 j^{-1}, en moyenne 0,02 j^{-1}), qu'il s'agisse de grands cours d'eau drainant des bassins de taille très variable ou de petites rivières aux bassins versants très limités, pour autant que les précipitations annuelles dépassent 1000 - 1100 mm, montrent que l'alimentation des basses eaux des rivières apparaît comme principalement due au cumul des vidanges de petites nappes de versant assez semblables et caractéristiques de la géomorphologie générale de l'Afrique intertropicale.

L'augmentation considérable du coefficient de tarissement dans la période sèche correspond essentiellement à une réduction de l'extension des aquifères et donc de la largeur des nappes de versant.

La baisse importante du niveau piézométrique est une constante des observations hydrogéologiques des régions soudano-sahéliennes. L'augmentation considérable de l'épaisseur de la tranche aérée du sol au-dessus de la surface piézométrique ne permet pas une réalimentation facile des nappes. Les eaux infiltrées connaissent un long cheminement interstitiel qui n'aboutit pas toujours à la nappe. La zone non saturée peut piéger l'ensemble de la lame d'eau infiltrée de l'année. Celle-ci pourra être reprise par évaporation ou rester en partie en attente d'apports complémentaires des années suivantes. Ceux-ci, s'ils sont assez abondants, et donc que l'on observe de bonnes précipitations, finiront, (effets pistons successifs), par aboutir à une recharge de la nappe.

C'est dans la partie amont de la nappe de versant que l'épaisseur de la zone aérée est la plus grande et donc que les problèmes de réalimentation sont les plus cruciaux. La sécheresse en privant l'aquifère amont des apports de l'infiltration a conduit à une réduction de l'extension de la nappe de versant soit par épuisement des réserves de l'amont, soit par coupure des liaisons entre les aquifères des parties aval et amont

La recharge éventuelle de l'aquifère amont reste dépendante d'un fonctionnement hydrogéologique pluriannuel et, dans la période actuelle, on observe bien un effet mémoire de la sécheresse inscrit dans l'évolution des réserves souterraines.

Le retour à des débits plus soutenus en saison sèche suppose d'abord la reconstitution des aquifères. Celle-ci ne peut-être immédiate et cela s'est bien vu dans la faible incidence d'une meilleure pluviométrie sur le tarissement. Du fait même des aquifères, les réactions sont plus lentes dans la restitution des basses eaux ; elles nécessitent un temps de réponse de plusieurs années et ne sont effectives qu'avec le cumul de variations climatiques de même sens.

A la sécheresse climatique se surimpose avec un décalage pluriannuel une sécheresse spécifique aux cours d'eau qu'on pourrait appeler « sécheresse phréatique ». Les lois de l'hydrogéologie sont telles que, dans de bonnes conditions de pluviosité, l'amélioration du régime de basse eaux pourrait demander un temps comparable à celui qui a conduit à son actuelle dégradation.

3. Evolution de la puissance des maximums de crue annuels

Le déficit d'alimentation des fleuves par les nappes souterraines, apparent en saison sèche, est bien entendu sous-jacent en période de crue et ceci explique aussi la faible hydraulicité et les modestes maximums de crue que l'on continue d'observer malgré une certaine reprise de la pluviosité. Au cours des deux dernières décennies, l'affaiblissement de la puissance des crues n'a fait que s'accentuer.

La comparaison des hydrogrammes de crue des différents fleuves étudiés montre dans la période actuelle deux types de situation :

- un hydrogramme tronqué sans maximum nettement affirmé correspondant à une saison des pluies normale en durée mais très déficitaire au coeur de la saison.
- un hydrogramme réduit en durée correspondant à une saison des pluies tardive ou écourtée.

Dans les deux cas, le volume de la crue et le maximum sont faibles.

La persistance de faibles maximums annuels malgré un certain retour à de meilleures conditions de pluviosité constitue un fait d'observation pour l'ensemble de la sous-région (Olivry, 1993 b).

On constate notamment que, pour des saisons des pluies équivalentes, le maximum de crue de la période actuelle reste nettement plus faible que dans le passé.

Or des études récentes du ruissellement sur petits bassins représentatifs ont permis d'observer des conditions générales de genèse des crues sans modification significative par rapport aux observations effectuées une trentaine d'années auparavant (Joignerez et Olivry, 1992). A l'échelle de grands bassins, dans de mêmes conditions pluviométriques, la contribution à l'hydrogramme de crue des écoulements rapides (ruissellement et écoulement hypodermique) devrait être identique. La persistance de l'amoindrissement de la puissance des crues doit donc être recherchée dans une contribution réduite des apports d'origine souterraine.

Ceci nous ramène aux observations effectuées sur le tarissement principal de ces grands fleuves. La part de cet écoulement de base est difficile à chiffrer sur les grands bassins ; elle est probablement plus importante qu'on ne l'imaginait, mais a considérablement diminué dans la période actuelle.

Le régime déficitaire des précipitations de la période actuelle est bien évidemment responsable de la baisse de puissance des crues. Il a d'abord un effet immédiat, avec des crues réduites en puissance et (ou) en durée, suivant la saison des pluies. Il a ensuite un effet mémoire avec le cumul de déficits des années antérieures et les apports réduits des nappes phréatiques. On doit donc s'attendre à une certaine persistance des faibles maximums de crue, même dans l'éventualité d'un retour à une séquence humide.

ANNEXE 3

La Komadougou Yobé

1. Hydrologie de surface :

Le bassin de la Komadougou est particulier pour plusieurs raisons :
- c'est le seul cours d'eau aboutissant à la cuvette nord du lac,
- dans la partie aval, la rivière ne reçoit aucun affluent et les débits diminuent au fur et à mesure que la rivière s'avance vers son débouché dans le lac Tchad : en année "moyenne" le débit annuel est de 1,3 km^3 à Gashua et seulement 0,3 à l'arrivée au lac alors que dans la partie amont on a estimé à 7 $km^3.an^{-1}$ la contribution de l'ensemble des tributaires aux ressources en eau de surface.

En régime naturel, l'écoulement n'est dû qu'aux précipitations tombant sur la partie amont (états de Kano et Bauchi au Nigéria) et aux ponctions représentées par l'évaporation et l'infiltration vers la nappe phréatique. Les observations du début des années 80 montraient que la Komadougou Gana disparaissait plusieurs dizaines de kilomètres avant sa confluence théorique avec la Komadougou Yobé. Plusieurs autres affluents étaient dans le même cas.

Depuis quelques années, plusieurs barrages réalisés au Nigéria (dont celui de Tiga dans l'état de Kano) ont diminué les écoulements dans la rivière en durée et en volume total. La rivière servant de frontière entre le Niger et le Nigéria dans sa partie aval, les ponctions des aménagements amont peuvent être source de conflit.

Les mesures hydrométriques sur la Komadougou réalisées pour Iwaco en 1984 montraient des décalages avec les courbes hauteur-débit antérieures. Même si les conditions de réalisation des mesures de 1984 semblent imparfaites, cela incite à la prudence dans la manipulation des débits supposés. Cette précaution peut être également illustrée par les chiffres de la station de Bagara, près de Diffa : avant 1984 le débit moyen variait entre 1,5 et 2,2 millions de m^3 par jour alors qu'il dépasserait 3,2 après 1987 ; la cause semble être un déplacement de l'échelle limnimétrique sans recalage des nouvelles hauteurs lues, d'où une surestimation des débits récents.

Il conviendrait donc de relancer une campagne significative de jaugeage sur la Komadougou Yobé si l'on veut disposer de chiffres fiables.

2. Hydrogéologie :

La nappe phréatique est alimentée par la Komadougou Yobé et, autrefois, par les rives de la cuvette nord du lac Tchad. Au nord et au sud de la rivière se rencontrent deux dépressions piézométriques fermées profondes d'une quarantaine de mètres. La quantification de la recharge de la nappe par la rivière avait été estimée de manière rapide par Iwaco (1985) à 21 millions de m^3 par an (mais 37 millions ailleurs dans le même texte !). Basée sur plusieurs méthodes d'estimation présentée dans la synthèse du PNUD (1991), la modélisation numérique des écoulements souterrains a retenu un chiffre de 25 millions de m^3 par an. En attendant de nouvelles mesures de terrain, il ne faut considérer ces chiffres que comme des ordres de grandeur.

L'eau souterraine est de qualité variable, mais généralement bonne. Elle est peu minéralisée à proximité de la rivière et très chargée en bordure du lac. Elle est utilisée principalement pour l'abreuvement des troupeaux et l'irrigation et, dans une moindre mesure du fait de la faiblesse démographique, pour l'alimentation humaine.

3. Environnement :

La surface couverte par la crue annuelle est variable : dans la plupart des cas, l'eau recouvre simplement les anciens méandres alors que la région de Hadejia-Jamaare au Nigéria est beaucoup plus vaste. Ces zones inondables recèlent encore une très grande richesse biologique, même si les espèces sont moins nombreuses qu'au début du siècle lorsque Foureau décrivait la région. Cette diversité est directement liée à l'eau.

Les rives de la Komadougou sont aussi particulièrement utiles pour l'agriculture et la pêche. En particulier on peut citer la production de piments et oignons, particulièrement appréciés, facilement exportés et générateurs de revenus non négligeables.

4. Avenir du bassin :

Comme il n'est pas possible de modifier les pluies tombant sur la partie haute du bassin versant et que les prélèvements divers se sont multipliés depuis quelques années tout le long de son cours, il est clair que la partie aval de la Komadougou Yobé (notamment là où elle trace la frontière entre le Niger et le Nigeria) subit une dégradation sensible de la crue annuelle.

Parmi les impacts prévisibles ou déjà observés (Hallis et al., 1993), on peut citer une diminution sensible des surfaces inondées et une moindre recharge de la nappe phréatique. Pour l'agriculture cela implique une diminution des cultures de décrue et un recours plus important à la nappe phréatique, donc des coûts plus élevés. La nappe sera à la fois moins réalimentée et plus pompée ; son niveau devrait donc baisser rapidement et durablement.

La baisse de la rivière et de la nappe fera également disparaître de très nombreuses espèces, animales comme végétales dont la vie dépend directement du retour annuel de la crue. Il n'est pas certain que les périmètres irrigués dans la partie amont du bassin versant, à la rentabilité hypothétique, justifie une telle catastrophe environnementale. La prise de conscience, apparue depuis quelques années, que les grands périmètres irrigués sont extrêmement gourmands en eau et en subvention et qu'ils ne contribuent que très peu à l'auto-suffisance alimentaire des populations devrait inciter à plus de prudence dans la gestion du bassin-versant de la Komadougou Yobé.

Comme il n'est pas possible d'effacer les aménagements déjà réalisés, il convient d'en limiter les impacts négatifs. Le remède proposé par certains est le transfert d'eau depuis une rivière du bassin du Niger vers la Komadougou. Avant de se lancer dans de tels travaux, il conviendra de réaliser une véritable étude de faisabilité technique : il n'est pas impossible que les fortes pertes constatées dans le lit de la Komadougou Yobé comme dans celui de la Komadougou Gana se produisent également dans le canal et que l'apport réel à la rivière dans sa partie aval ne soit de toutes façons très faible.

ANNEXE 4

Modèles utilisés en hydrologie au Tchad

1. Modèle mathématique HYDRO-CHAD

Réalisé par Mott - Mac Donald (MMD) 1994, le modèle mathématique du comportement hydrologique du Lac Tchad et des fleuves qui l'alimentent est un modèle physique qui a demandé un énorme travail d'analyse des données disponibles sur le bassin du Lac Tchad (hydroclimatologie, limnimétrie, etc...). Il est construit sur la base d'un modèle hydrologique précisant les entrées en débit (ou hauteurs d'eau) des principaux tributaires du Lac Tchad et d'un modèle hydraulique reproduisant les transferts d'eau dans les biefs principaux, d'une part, dans les plaines d'inondation et le lac, d'autre part.

1.1 MODELE HYDROLOGIQUE

Le modèle hydrologique est une adaptation du modèle de transformation Pluie-Débit CATCH WK_3 (à 6 paramètres) traitant des **données mensuelles**. Adapté au bassin du Lac Tchad sous le nom de LCBCMOD avec deux options, l'une calquée sur CATCH, l'autre avec seulement 4 paramètres (capacité maximum de rétention d'humidité du sol, proportions d'écoulement vers les aquifères, taux de tarissement des eaux souterraines, temps de montée de l'hydrogramme unitaire), il comprend :

. Le calcul de la pluie moyenne mensuelle du bassin considéré (maillage d'un 1/10 degré carré et pondération suivant le réseau pluviométrique en service).

. La formulation des relations pluie-débit et l'application de coefficient de retardement de l'écoulement mensuel.

. La prise en compte d'un hydrogramme unitaire triangulaire dont le temps de montée est 1/3 du temps de base.

Le modèle principal prend en compte les entrées du Logone à Laï, du Chari à Sahr et du Barh Sara à Manda (un module complémentaire a été prévu pour la Komadougou Yobé à Gashua et la Komadougou Gana à Kari).
On passe des données mensuelles à des **débits journaliers** (interpolation linéaire entre valeurs centrées au milieu du mois) et leurs hauteurs d'eau correspondantes pour définition des entrées du modèle hydraulique.

1.2 MODELE HYDRAULIQUE

Le modèle hydraulique comprend un modèle principal de transfert dans les biefs du Chari et du Logone (plus la Komadougou Yobé), avec un noeud tous les 20 kms à partir de N'Djaména, plus les noeuds des stations hydrométriques et un modèle des plaines d'inondation avec cellules de rétention (54 en tout), pour lesquelles sont introduits les paramètres précipitations et évaporations journalières. Les cellules de rétention concernent les ensembles :

. Ba Illi du Nord
. Padjouk
. Pertes Mayo Kebi
. El Beid
. Bahr Erguig
. Loumia
. Serbewel
. Lac Tchad et Bahr el Ghazal

L'utilisation des équations de S[t] Venant nécessite qu'en chaque noeud soient déterminées les caractéristiques géométriques des sections des seuils, un coefficient de rugosité (Manning) unique ayant été retenu.

Les sections naturelles mesurées aux stations hydrométriques n'ont été utilisées que pour le calage hauteur-débit. Cette approche mathématique des seuils -qui s'éloigne du modèle physique- a été critiquée par Clarke (1993).
Pour le Lac Tchad, on a en plus un paramètre infiltration (0,55 mm/jour pour la cuvette nord et 1,15 mm/jour pour la cuvette sud) qui est directement inspiré des travaux d'Isiorho et Matisoff, localisés au sud-ouest du Lac.
L'ensemble du modèle HYDRO-CHAD a été obtenu à partir des données de 1960 à 1979.

1.3 SIMULATIONS DE CALAGE

Dans son rapport final, MMD présente les simulations de vérifications des hauteurs d'eau faites sur les années 1963-1964, 1988-1989 et 1990-1991 et sur l'année 1975-1976. MMD indique que les performances sont bonnes pour les années sèches et humides, à l'exception des maximums du Chari à Chagoua et N'Djamena pour 1988-1989 avec 1 m sous la valeur observée de 293,4 m et 60 cm sous celle de 1963-1964 (293,6 m observé). MMD impute cette différence à des apports des Bahr Salamat et Keita, non intégrés au modèle, qui auraient pu être élevés ces années-là. En volume annuel, cela supposerait 6 km^3 pour 1988-1989, soit 50 % de plus que la valeur interannuelle, peu probable cette année-là ; la seule vérification des différences des débits maximums observé et simulé aurait permis de rejeter cette explication.
Avec Clarke, on peut regretter que les figures présentées ne portent que sur des hauteurs d'eau et non les hydrogrammes des débits. MMD ne soulève pas le problème du décalage de la phase de décrue entre valeurs simulées nettement plus fortes que les hauteurs observées. Ainsi la phase de tarissement naturel du Logone à Logone-Gana montre entre les cotes 298 et 295,5 m de décembre 1988 à mars 1989, un décalage de 60 cm avec la simulation.
D'autres exemples fournis montrent à Katoa, Bongor, Eré pour 1988-1989 et 1990-1991 le même type de simulation surestimée (sensible aussi en début de crue) et qui représente jusqu'à 1,6 km^3 soit + 20 % des apports.
Il n'y a pas de décalage pour les limnigrammes de 1963-1964.

1.4 CRITIQUES DU MODELE

Clarke, déjà cité, a émis un certain nombre de critiques que nous ne reprendrons pas ici (notamment sur la partie hydraulique du modèle).
En complément, nous indiquerons d'abord, dans la suite des simulations sur les années les plus récentes, que le modèle (établi sur la période 1960-1979) ne prend pas en compte l'évolution des hydrosystèmes vers des phases de tarissement plus rapide depuis la fin des années 1970. Il y a donc un biais dans le calcul des entrées du modèle hydrologique. (voir notre note sur l'hypertarissement des rivières intertropicales lié à la persistance de la sécheresse).
MMD a relevé qu'une infiltration nulle permettait une meilleure estimation du bilan du lac. Les valeurs initiales choisies, citées plus haut, sont largement surestimées (8,8 km^3 soit 19 % des 45 km^3/an d'apports) et ne concernent que des sables localisés entre Baga et Kirenowa qui ne représentent pas la nature des fonds du lac (cartographié par Dupont, 1970).
La relation H eau/Superficie/Volume du lac a été extraite de Carmouze et Dupont (1970), mais aurait dû être actualisée par les travaux de Lemoalle (1979) et Vuillaume (1981).. Ainsi, à la cote 282 m, le lac a un volume total estimé à 63 km^3 quand MMD donne 80,2 km^3. Les surfaces de l'archipel et des ilôts-bancs n'ont pas été déduites. Ceci explique sans doute une partie des différences importantes observées entre les valeurs des bilans hydrologiques de MMD et celles des travaux de Vuillaume (1981).
Les analyses statistiques effectuées par MMD sur les écoulements annuels et les débits maximums annuels du Chari à N'Djamena faites sur 21 ans (période 1972-1992) doivent être utilisées avec beaucoup de prudence. On peut effectivement considérer l'échantillon récent pour l'écoulement annuel, même si cela n'a guère de sens pour des périodes de retour « humides » (de 64 ans pour 1975-1976 avec 36,3 km^3), en considérant une médiane à 20,5 km^3 comme caractéristique des conditions actuelles. Mais c'est beaucoup plus dangereux pour des débits maximums de crue : la crue 75-76 est donnée avec une période de retour de 38 ans, alors qu'elle est à peine supérieure à la moyenne, si on considère l'ensemble de l'échantillon. Pour des raisons de sécurité des populations riveraines, il n'est pas prudent de considérer cet événement comme ayant une fréquence aussi rare.
Sans revenir sur les notions de rupture climatique sur lesquelles on ne peut trancher, et donc sur le choix des échantillons à prendre en compte dans les études statistiques, la règle à utiliser par les projeteurs devrait être la suivante :

. **Ressource en eau** (débit annuel), maximums de crue d'année sèche, étiages : prendre en compte l'échantillon de la période sèche comme s'il y avait eu rupture climatique et actualiser l'échantillon. Déterminer les **défaillances**.
. **Maximums de crue**: prendre l'ensemble de l'échantillon disponible pour ne pas minimiser le **risque de crues catastrophiques**.

1.5 UTILISATION DU MODELE

Plusieurs simulations ont été proposées par MDD, suivant différents scénarios et comparés à l'année 1975-1976 :
- élévation de température moyenne de 3 à 4° avec ses conséquences sur l'évapotranspiration qui augmenterait de 7 à 17 %, baisse des maximums du lac de 0,2 à 0,4 m et pertes dans les plaines d'inondation de 0,4 km^3 supplémentaires, manquant dans les apports au lac.
- construction de digues le long du Logone ; 80 % de pertes en moins dans les plaines d'inondation et gain sur le lac de 6,1 km3, mais plus de Yaéré et d'écoulement dans l'El Beid.
- réservoirs de stockage à Foré sur la Pendé et Koumban sur la Vina-Nord ; avec 7,8 km^3 (2,8 et 5) disponibles de novembre à juillet, élévation du niveau du Logone de 0,5m jusqu'à N'Djaména, pas sensible à l'aval.
- influence du barrage de Maga ; baisse de 0,5m dans les plaines d'inondation du parc de Waza.
Les utilisateurs du modèle à la CBLT nous ont fait une démonstration partielle (coupures de courant électrique à N'Djaména) : évolution du niveau d'un bief du Chari sur une année donnée (suivi des lignes d'eau), calcul de bilans du Lac. Des problèmes sont apparus dans la comparaison d'hydrogrammes simulés et observés, dus d'après la CBLT à la dernière version du modèle qui introduit un module Komadougou Yobé. Toujours d'après les utilisateurs, le modèle admet des bornes inférieures pour les étiages en entrée du modèle hydraulique supérieures aux étiages observés aujourd'hui et le modèle ne tourne pas. Autre inconvénient relevé par les utilisateurs, il s'agit d'un modèle de simulation avec ses 365 entrées journalières de paramètres et non d'un modèle de prévision.
En conclusion, l'outil n'est pas encore vraiment opérationnel à la CBLT au-delà des démonstrations concernant les années-type du document MDD. Il doit pouvoir être amélioré en renonçant au modèle hydrologique qui introduit des biais et en considérant les **entrées réelles des stations hydrologiques** retenues, dont **le suivi doit être une priorité** et qui ne constitue pas en soi de difficultés majeures par rapport au suivi de stations pluviométriques. Le modèle peut être utilisé comme modèle de prévision à partir de septembre après observation des maximums de crue aux entrées, en complétant l'année hydrologique par les données d'années-type antérieures voisines dans la première phase des hydrogrammes. La précision du modèle n'est pas assez grande pour simuler avec fiabilité des aménagements de moyenne importance sur le bassin ; en revanche, il devrait être performant pour simuler les projets de transferts à partir de la RCA de volumes importants (voir par ailleurs).
Dans la perspective d'une actualisation du modèle Hydro-Chad, il est suggéré de reprendre le modèle hydraulique sur la base d'une prise en compte des sections en travers réellement observées pour chacun des noeuds retenus.

2. Modèle de prévision de crues du Chari à N'Djaména

A la demande de la DREM du Tchad, et suite à une urbanisation spontanée des parties basses de la ville de N'Djaména généralement hors d'eau depuis les années sèches, la Coopération française a chargé l'Orstom de réaliser un modèle de prévision des crues permettant d'alerter les populations des risques d'inondation.
Le modèle est un modèle statistique faisant intervenir les données de stations amont et permettant une prévision à 10, 15 et 20 jours. Divers ajustements de relations entre les différentes stations ont permis de retenir 4 stations : Moundou à 500 km à l'amont de N'Djaména sur le Logone et Sahr à 600 km en amont sur le Chari, pour l'essentiel des apports de crue, et, d'autre part, Bongor sur le Logone et Bousso sur le Chari, respectivement à 240 et 340 km de N'Djaména utilisées comme stations intermédiaires et de contrôle et prenant en compte les autres apports et les défluences vers les plaines d'inondation.
Le modèle a été calé en reliant les séries chronologiques de cotes observées à ces stations et à celle de N'Djaména sur les périodes suivies par l'Orstom jusqu'en 1979 et par la DREM de 1981 à 1994.
Un logiciel particulièrement convivial sous WINDOWS appelé « Système d'annonce de crues du Chari à N'Djaména » a été mis à disposition du Service Hydrologique de la DREM en 1995 et est opérationnel. Les

cotes observées aux stations amont sont communiquées chaque jour à la DREM par radio (BLU de la Météo) et permettent une prévision immédiate de la hauteur de crue du Chari à N'Djaména d'une très bonne qualité avec 10 jours d'avance et d'une qualité légèrement dégradée pour 15 et 20 jours. Le système d'alerte à 10 jours (largement suffisant à N'Djaména pour prendre des mesures de sécurité publique) suppose cependant que les données amont parviennent bien au complet au centre de traitement.
Dans la perspective de défaillances d'une ou plusieurs stations, l'Orstom a réalisé un modèle de prévision en « mode dégradé »en introduisant les hauteurs d'eau manquantes suivant des fréquences empiriques de Hazen établies par dates et stations. La mise en œuvre opérationnelle du nouveau logiciel devrait faire l'objet d'un nouveau contrat.
Afin de minimiser le risque de défaillances dans les observations, il a été aussi proposé de doubler le système de collecte des données par un système de stations automatiques avec télétransmission par satellite (Météosat) prévoyant une station de réception à la DREM. Ce système pourrait être financé par la Coopération française et les stations concernées pourraient être incorporées au réseau de stations de référence du réseau africain HYCOS du WHYCOS de l'OMM, projet qui assure une surveillance mondiale de l'environnement à travers le suivi de la composante « eaux de surface » du cycle de l'eau.
Limité dans ses objectifs, ce modèle peut être utilisé, grâce aux relations établies par ailleurs, pour évaluer le remplissage du lac (vs. maximum de N'Djaména).

ANNEXE 5

Commentaires sur les projets 1, 2, 3 et 4 du Plan Directeur de la CBLT (1992)

Projet n°1 :

Le descriptif de ce projet indique qu'il cherche à "initier une action concrète... visant à rendre (le lac) moins vulnérable à la sécheresse". Cet objectif ambitieux est peut-être utopique puisque le niveau du lac dépend principalement de conditions climatiques sur lesquelles l'homme n'a aucune prise. Il peut permettre cependant de dégager les initiatives humaines qui pourraient encore aggraver la situation.

Projet n°2 :

Il s'agit d'étudier en détail la faisabilité du projet pharaonique de détournement d'une partie des eaux du Haut Oubangui vers le bassin du lac Tchad. Au vu des travaux gigantesques requis par une telle entreprise, une courte pré-étude serait peut-être suffisante pour mettre en évidence les difficultés techniques majeures, les coûts et avantages attendus ; elle devrait ajouter une étude d'impact. On peut cependant se demander qui aurait actuellement la capacité de financer un tel projet.

Projet n°3 :

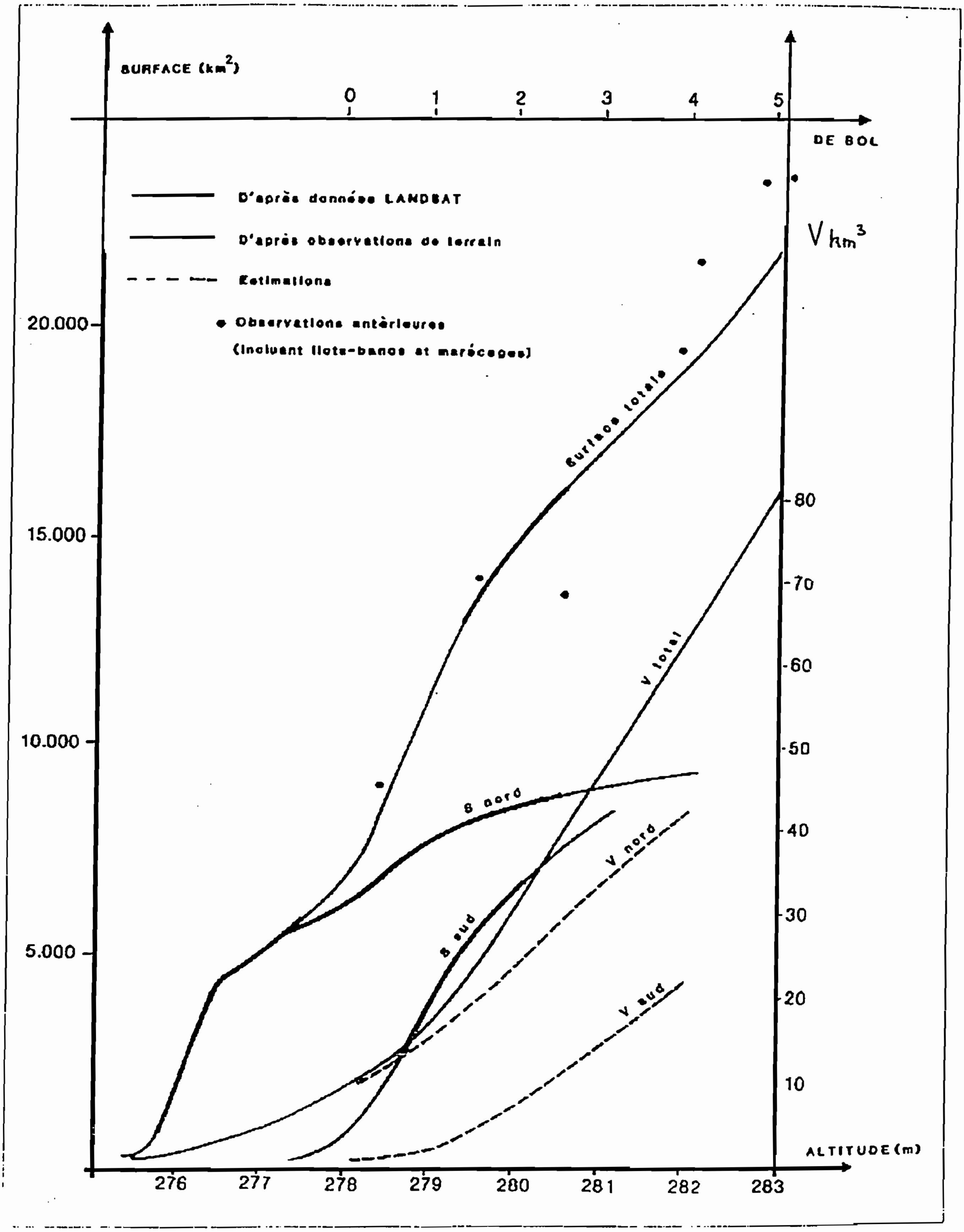
Ce projet vise à une gestion intégrée des eaux du système Chari-Logone. Son succès repose en grande partie sur l'utilisation du modèle hydrologique, dont l'état actuel ne permet pas d'imaginer qu'il soit capable de répondre finement aux questions posées.

Si l'on veut s'intéresser "dans les moindres détails" au rôle des plaines inondables, il faudra réaliser des travaux topographiques conséquents et installer des points d'observation en surface et dans la nappe et accumuler des observations pendant une durée bien plus longue que celle prévue pour le projet (2 ans).

Projet n°4 :

Les points 1, 2 et 3 justifiant la proposition de projet sont des évidences de gestion des eaux qu'il fallait probablement rappeler. Par contre, les problèmes de déforestation ou de mouvement de dunes (points 4, 5 et 6) ne sont pas liés aux ressources en eau.

Il n'est nulle part fait mention des moyens envisagés pour comprendre et prévoir l'impact des différents aménagements du bassin amont : une double modélisation, hydrologique et hydrogéologique, est indispensable.



Correspondance entre surface et volume du lac Tchad