

The variability of Lake Chad : hydrological modelling and ecosystem services

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Abstract

As in most of West and Central Africa, the rainfall regime over the Lake Chad basin has changed around 1970 from a humid to a dry period. This rainfall change is the cause of the changes in Lake Chad area. Lake Chad being a closed lake, its surface area has changed according to the lower water inputs from the watershed. The lake, which covered about 22000 km² in the 1960s, is now divided into different individual seasonal or perennial lake basins.

In the northern basin of the lake, the seasonally inundated area has varied from zero in dry years (as in 1985, 1987) to about 6000 km² (1979, 1989 and 1999-2001). In the southern basin of the lake, the between year variability has markedly decreased. The changes in lake area and in the links between the lake basins have been modelled as a function of the river inputs. Satellite estimates of water area in the northern basin and gauge levels in the southern basin have been used as calibration data. The water volumes incorporated in and lost by the sediments during the annual wet and dry cycle have been taken into account in the model.

The hydrologic changes are the driving forces for the natural resources associated with the lake i.e. fisheries, recession cultivation on the lake floor and green vegetation for livestock. Whereas the yearly cycle of the natural resources has become fairly predictable in the southern basin, vulnerability has much increased in the northern basin.

Field observations and the model are used to discuss the benefits and drawbacks of the present situation compared with the wet period before 1970, and in the hypothesis of climate change. The possible impact of the planned inter-basin transfers from the Congo-Zaire basin is also analyzed.

Keywords : Africa, Lake Chad, model, hydrology, natural resources

Introduction

As most closed lakes, Lake Chad (Figure 1) has a long history of wet and dry periods which span different time scales, from the Quaternary to the last century (Servant & Servant, 1983; Olivry et al., 1996; Lemoalle, 2004; Leblanc et al. 2006). A recent striking manifestation of this variability has been the recession of the lake in 1973-75 as a consequence of the drought in the African Sahel belt. In 1975, the northern basin of Lake Chad, which covered an area of 9000 km² during the 1960s, completely dried up. Since this time, this basin has been only occasionally and partially inundated, with heavy consequences on the ecology of this region and on the livelihood of the local populations.



Figure 1. Situation of Lake Chad in Africa

A first use of Meteosat data has been made to forecast the inundated surface area in the northern basin of the lake some time ago (Lemoalle, 1991).

A new methodology for more precise estimates of the inundated area has since been developed, using Meteosat data (Leblanc, 2002). The results are presented here. They provide a record of the variations in the northern pool of Lake Chad where there has been no gauge readings since 1977. They have been used for the calibration of a simulation model of Lake Chad hydrology, which is presented in this paper together with the consequences of the lake variability on the natural resources of the lake.

The main characteristics of Lake Chad hydrology

Considering the large variability of the water level and associated landscapes, a classification in three main states of the lake was proposed by Tilho (1928), who showed that the lake level variations were directly related to rainfall changes on its basin.

- The Large L. Chad, holds 25,000 km² of open water with a limited coastal sand dune archipelago, a water surface altitude of 283.5 m and occasional slight overflow towards the North-East through the Bahr El Ghazal. This Large Chad state has been approached only for short periods during the last century.

- The Normal (intermediate) Lake Chad is a single body of water covering about 20,000 km², at an intermediate level of 281 to 282 m, an archipelago of some 2,000 dune islands, some limited marshy vegetation on the shores (Figure 2). The shift from Normal to Small Lake Chad occurred in 1973-75.

- The Small Lake Chad, is made up of different separated bodies with a permanent open water pool of about 1,700 km² at a maximum altitude of circa 280 m facing the River Chari delta. The other water bodies are mostly permanent or seasonal marshes ranging from 2,000 to 14,000 km² covering the northern basin of the lake and parts of its southern basin (Figure 2). The lake has been functioning as a Small Chad since 1975.

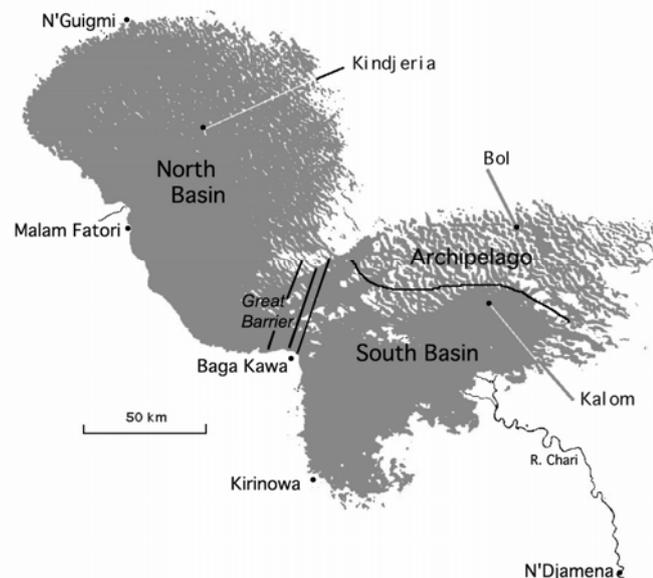


Figure 2. The contours of the « normal » Lake Chad from a Landsat mosaic of January 1973 with the main sills between basins. The gauging stations are indicated, with Bol still being operational.

The mean water budget of the Normal Lake Chad has been studied by a number of authors, from Touchebeuf de Lussigny (1968) to Olivry et al. (1996). During the period 1954-69, the water budget resulted from an equilibrium between :

- river inflow (43.6 km³/year) of which 96% from the River Chari,
- direct rainfall (329 mm/year) and evaporation (2170 mm/year)
- plus some outflow seepage (2.3 km³/year) (Vuillaume, 1981).

For the period 1972-89, the mean River Chari annual input was 22 km³, and the mean rainfall over the lake 207 mm/year.

The Normal Lake Chad may be divided in two main basins, north and south, which are separated by a shallow sill, locally known as the Great Barrier, often covered by aquatic macrophytes. The southern basin is itself divided by a sill between the southern open water and the archipelago (Figure 2).

A state of Small Lake Chad occurs when the water level decreases below the altitude of the main sill : the northern basin receives some water from the main tributary only when the southern basin spills over the Great Barrier (see Figure 3). The annual cycle in the northern pool during a Small Chad period is then highly variable. Since 1976, the inundation of the northern basin has varied from year to year and season to season, depending on the River Chari flood, on the level in the southern basin and on the spillage over the Great Barrier. The input from the small River Yobe (about 0.5 km³/year), feeding directly the northern basin at the border between Nigeria and Niger, is just sufficient to maintain a marsh area around its estuary. The maximum yearly flood extent of the northern pool varied from zero (in 1985, 1987) to more than 6,000 km² (January and February 1976, 1977, 1979, 1989, and from 1999 to 2004). From 1975 to 1998, the basin was almost completely dry for several months each year between October and December (Lemoalle, 1991 ; Leblanc, 2002). From 1999 to 2005, however, some water remained all the year round (Leblanc et al. 2003, and Landsat data). Local populations used the former lake bed as arable land and range land during the draw-down periods, and fisheries were extremely active when the flood occurred.

During the Small Chad period, the annual cycle of the water level in the southern pool has been relatively stable compared with that of the north basin, as shown by the Bol and Kalom gauge readings (DREM) complemented by accurate Topex/Poseidon satellite altimetric data (Birkett, 2000 ; Mercier et al. 2002). Starting from the seasonal low level in July or August in the southern pool, an increase in level by about 1.5 m occurs with the input of the R. Chari flood, until a level of 279.5 to 281 m is reached in December. Overflow may then occur toward the northern basin of the lake through the Great Barrier and toward the eastern archipelago (Figure 3). The altitude of the sills is close to 279.3 m. But they are covered with a dense vegetation acting as a break to the circulation of water (the Great Barrier extends more than 40 km between the two basins). It has been observed that significant transfer of water over the ridges occurs only when the water level in the south pool reaches 280.0 m. The flow is also dependent on the physiological state of the macrophytes and on the occurrence of channels cut through the vegetation to allow for navigation.

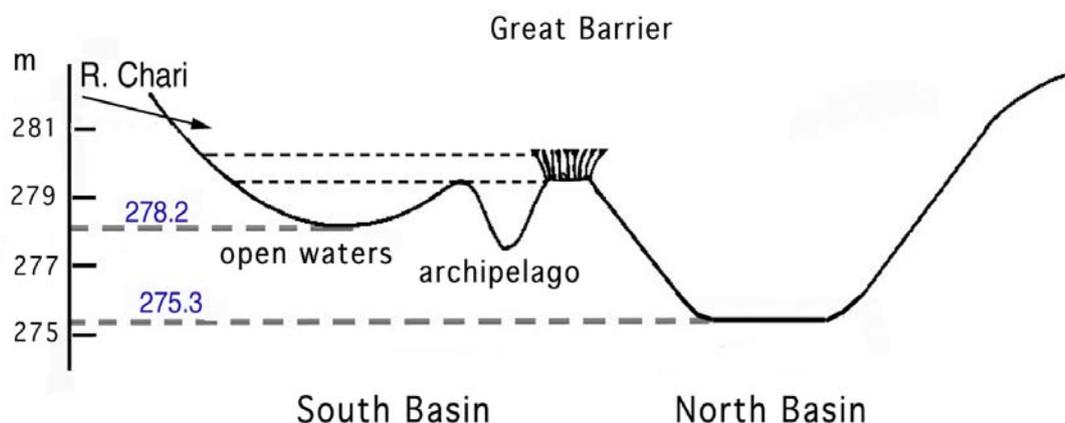


Figure 3. A schematic cross section of lake Chad showing the two main basins, with indications of the altitude of the sills and of the basin floors.

Methods

Estimating the water surface area

We have used a combination of satellite data to reconstruct the fluctuations of the total surface area of Lake Chad.

The period that spans from June 1973 to October 1977 has been studied by Lemoalle (1978) using Landsat MSS data and aeroplane surveys. Later Lemoalle synthesised and updated his work with the use of Meteosat data (Lemoalle, 1991; Lemoalle in Olivry, 1995). This led to the publication of the extent of Lake Chad north pool in January ("maximum annual extent") from 1973 to 1990. Using AVHRR/LAC and Meteosat Tmax archived thermal data we complemented this work with a comprehensive monthly time series of the total surface water area of the lake from 1986 to 2001 (Leblanc, 2002; Leblanc et al., 2003, Leblanc et al., 2007). When available, AVHRR/LAC data were used as they have a higher spatial resolution (1 km) than Meteosat (5 km). These data, however, are not always available. Therefore, they were complemented with Meteosat Tmax 10-days thermal composite data. Due to the Meteosat sensor's high temporal resolution, 10-day and monthly Tmax (Maximal Value Composite) offer the possibility to bypass cloud cover. These Meteosat data have been archived systematically from 1986 to 1987 (April to October) and since 1988.

In semiarid regions, the difficulty of mapping water under aquatic vegetation can be overcome by using thermal satellite data (Leblanc et al., 2003, Leblanc et al., 2007). The rationale of the methodology is that both open water and water covered with aquatic vegetation have a higher thermal inertia than the surrounding bare dry land and non-aquatic vegetation. That is open and covered water warms up less during the day and cools down less at night. Near Lake Chad, a strong discrepancy between diurnal and nocturnal temperature is observed all year long (Olivry, 1996). Rosema (1990) showed that, in the region of Lake Chad, Meteosat thermal data can be used to detect the boundary between the land and the wetlands. Travaglia (1995) also applied this method of thermal inertia to map the extent of water bodies in the Sudd wetlands in Sudan. This region has a similar environment to that of Lake Chad with wetlands covered by dense mats of floating vegetation within which areas of open water occur. The authors report that AVHRR/LAC thermal data (channel 4) can achieve a clear distinction of both open water and water under vegetation from the bare soil and soil with active vegetation (Travaglia et al. 1995).

The hydrological model

A simple model has been set up in order to describe the hydrological functioning of the lake, and especially the inundated surface area of its northern basin during a period when there has been no water level recording (1976-present).

It is a spreadsheet model, with the water volume in each lake basin (south, archipelago and north) used as the state variable computed on a daily time step. In each basin, the change in water volume is the difference between input and losses. Input is the sum of direct rain on the water surface plus surface inflow, either from rivers (River Chari and secondarily the River Yobe) or from overflow spillage over the sills between basins. Losses consist mainly of evaporation.

There is no seepage to the water table, but some water is used to fill a reservoir underlying the lake itself. The functioning of these reservoirs is slightly different in the archipelago and in the north basin (Figures 4 and 5).

The model is a modified and updated version for the Small Chad of the monthly hydrological budget presented by Vuillaume (1981) for the Normal Chad.

The lake is divided into three pools isolated by sills. One sill divides the southern basin into the south pool, directly fed by R. Chari inflows, and the Bol archipelago, which is in fact made of a great number of small pools. The other sill is the Great Barrier (Figure 3). The model inputs are the Chari and Yobe discharges and the rain and evaporation rates. The outputs are volume, area and level of water for each of the three basins and the Bahr El Gazal discharge (Figure 4).

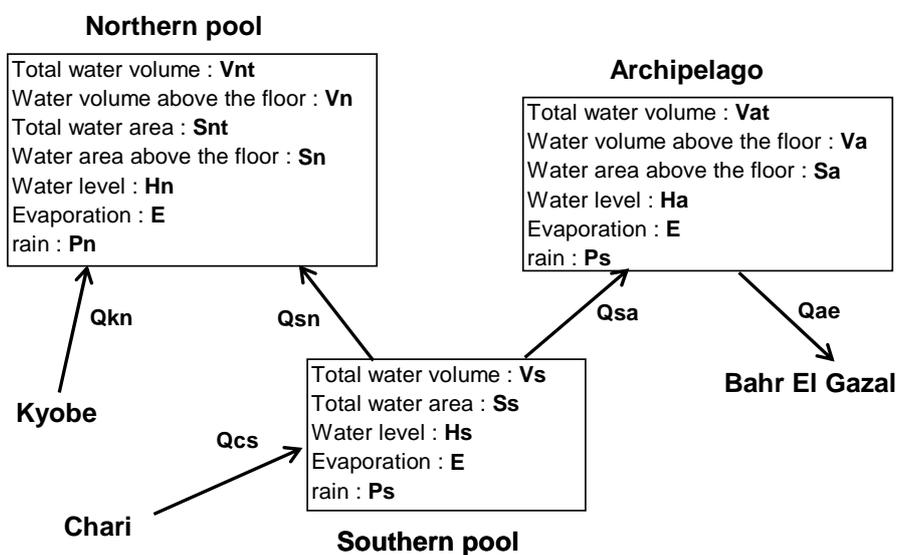


Figure 4. Design of the model

THE WATER VOLUMES

South basin

The volume V_s of the southern basin is straight forward, with the Chari discharge Q_{cs} plus direct rain inputs P_s on surface S_s , minus evaporation E and spillage Q_{sn} and Q_{sa} towards the two other basins.

$$V_s(t+dt) = V_s(t) + (S_s(t) * (P_s(t) - E(t)) + Q_{cs}(t) - Q_{sn}(t) - Q_{sa}(t)) * dt$$

Northern basin

Observations during the seasonal refilling of the northern basin indicated that a large amount of water is used to saturate the upper sediment. This has been modelled as a fictional reservoir of thickness D_n , whose value was calibrated (1.62 m). The water surface is in equilibrium between the lake itself and the sediment (Figure 5). The total water volume V_{nt} varies with the discharges coming from south basin (Q_{sn}) and Kiobe river (Q_{kn}), and with Rain P_n and evaporation applied to the whole wet surface S_{nt} . The proper volume V_n of the lake is calculated from V_{nt} .

$$V_{nt}(t+dt) = \max(0 ; V_{nt}(t) + (S_{nt}(t) * (P_n(t) - E(t)) + Q_{sn}(t) + Q_{kn}(t)) * dt)$$

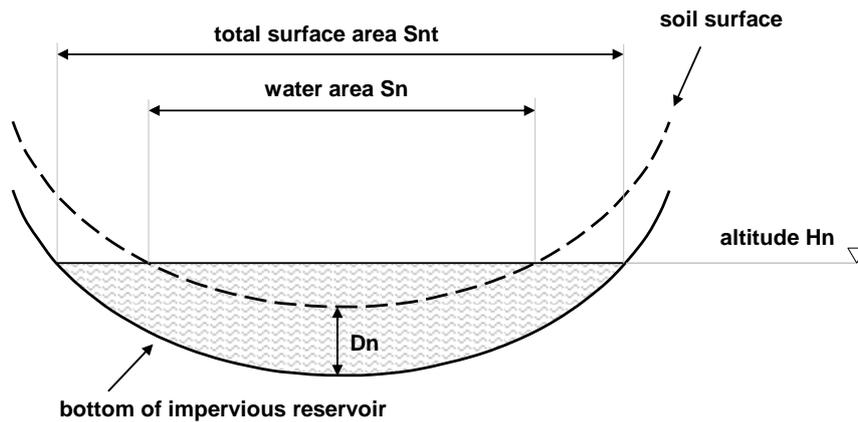


Figure 5: Hydrologic functioning of the northern basin with a double reservoir. The visible reservoir, above the land surface, is the lake proper. The second reservoir is contained by the upper sediment and extends further than the lake shores.

Archipelago

The total volume of water Vat is partitioned between the lake water proper, Va , and some water in the underlying sediment. To simulate the seepage and water contents of some sediments, the sediment has been divided into two parts. The part of the sediment underlying the lake area at level $Ha1$ (calibrated at 278.87 m) is pervious, while the sediment above $Ha1$ is impervious. The total water volume Vat is zero when there is no open water (level $Ha0$), and can be negative when there is only some water in the sediment. The total volume Vat varies with the discharge coming from south basin (Qsa) and lost in the Bahr el Ghazal (Qae), and with rain and evaporation applied to the whole wet surface. This surface is equal to Sa when Ha is above $Ha1$, and to $Sa1$ when Ha is below $Ha1$ (Figure 6):

$$Vat(t+dt) = Vat(t) + (\max(Sa(t), Sa1) * (Pn(t) - E(t)) + Qsa(t) - Qae(t)) * dt$$

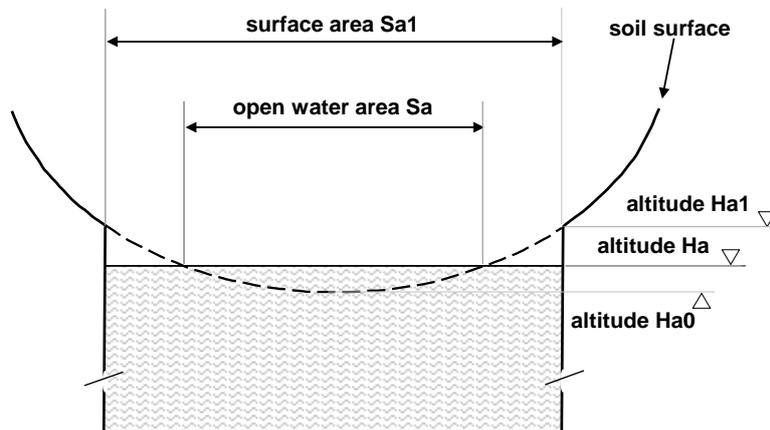


Figure 6 : Hydrologic functioning of the archipelago.

THE FLOWS

Flow from south to north basin Qsn

In the model, the link between the southern and the northern basin Qsn is a channel of length d and width L , with an horizontal bottom at $H0n$. When the flow is directed from south to north, the slope of the water surface is J and the mean depth is Z .

We evaluated Qsn by $Q0$ by applying Manning Strickler formula as follows:

$$\begin{aligned}
Q_0 &= k * L * ((H_s + \max(H_n ; H_{0n})) / 2 - H_{0n})^{N_n} * ((H_s - \max(H_n ; H_{0n})) / d)^{0.5} \\
&= A_n * ((H_s + \max(H_n ; H_{0n})) / 2 - H_{0n})^{N_n} * (H_s - \max(H_n ; H_{0n}))^{0.5} \\
\text{with } A_n &= k * L / d^{0.5}
\end{aligned}$$

The parameters H_{0n} , N_n et A_n have been determined as follows :

- H_{0n} : the altitude of the sill estimated from field observations : 279.30 m
- N_n : as the impact of the vegetation can change as a function of water level, n may be slightly different from the theoretical value of 5/3 and was calibrated to 1.4373.
- A_n : depends on L and d and was determined, as the Strickler coefficient, from optimization procedures ($2171 \text{ hm}^3/\text{jour m}^{-1.9373}$).

When running the model, some oscillations may appear when H_s and H_n have almost the same value. This has been avoided by setting a limit value $Q_{sn_{\max}}$ for Q_{sn} , which leads to equalize the levels H_s and H_n at the end of time step.

The flow Q_{sn} at time t is

$$Q_{sn}(t) = \min(Q_0(H_s(t), H_n(t)), Q_{sn_{\max}}(H_s(t), H_n(t)))$$

Flow from south basin to archipelago Q_{sa}

The flow from the southern basin to the archipelago is calculated in the same manner :

$$Q_o = A_a * ((H_s + \max(H_a ; H_{0a})) / 2 - H_{0a})^{N_a} * (H_s - \max(H_a ; H_{0a}))^{0.5}$$

If $H_s(t) > H_a(t)$:

$$Q_{sa}(t) = \min(Q_o(H_s(t), H_a(t)), Q_{sa_{\max}}(H_s(t), H_a(t)))$$

If $H_s(t) < H_a(t)$:

$$Q_{sa}(t) = \max(-Q_o(H_a(t), H_s(t)), Q_{sa_{\max}}(H_s(t), H_a(t)))$$

The parameters of Q_{sa} have been determined in the same way as Q_{sn} :

$$H_{0a} = 279.30 \text{ m} ; N_a = 2.8491 ; A_a = 1636 \text{ hm}^3/\text{jour m}^{-3.3491}$$

Outflow from the lake Q_{ae}

When the water level of the lake is high, (282,5 m) an overflow may develop into the fossil Bahr El Ghazal, out of the archipelago toward the low Bodele depression in the north-east.

Q_{ae} is the discharge to the Bahr el Ghazal, modelled as a broad crested weir, L_{ae} wide and at altitude H_{ae} . The discharge writes (m^3/s) :

$$\begin{aligned}
Q_{ae} &= 0.385 * L_{ae} * (2 * g)^{0.5} * (H_a - H_{ae})^m \\
&= B_a * (H_a - H_{ae})^m
\end{aligned}$$

$$\text{with } B_a = 0.385 * L_{ae} * (2 * g)^{0.5}$$

The parameters used here are :

- $H_{ae} = 282.0 \text{ m}$ from field observations (Olivry et al. 1996),
- m : usually equal to 3/2, this exponent was calibrated here at 1.730 with the very few data available (November and December 1956),
- B_a : calibrated with the same data, at $21.92 \text{ m}^{1.27}/\text{s}$

THE OBSERVED DATA

The only long term gauge on Lake Chad is situated in the archipelago at Bol. We have used monthly mid-month data from 1988 to 2004. According to field

observations, we have assumed that the maximum annual water level, when above 282 m, is similar in the south basin, Hs, and in the archipelago Ha. The series of the inundated water area in the north basin, Sn, has been obtained as explained above.

The measured mean monthly inflows from the River Chari as measured in N’Djamena for 1983-2004 have been provided by the Direction des Ressources en Eau et de la Météorologie (DREM, Chad). It is assumed that there is no loss nor gain between N’Djamena and the lake.

The distribution of monthly rainfall and evaporation is based on past measurements (Olivry et al. 1996) and has been set as constants, with an annual total rainfall of 150 mm and 300 mm over the northern and southern basin respectively (see Table 1). The mean annual evaporation has been estimated from annual water budgets and from potential evapo-transpiration measurements in Bol from 1964 to 1977 as 2170 mm/y (Vuillaume, 1981; Olivry et al. 1996)(Table1).

Table 1. Monthly distribution of rainfall and evaporation used in the model (mm/month)

Month	J	F	M	A	M	J	J	A	S	O	N	D
Evaporation	136	155	212	229	226	201	175	150	159	199	178	150
North Rain	0	0	0	0	0	0	30	80	40	0	0	0
South Rain	0	0	0	0	0	0	50	150	70	30	0	0

The stage-area relationships have been derived from satellite data and gauge readings when the lake progressively dried up in 1972-76 (Lemoalle, 1978; Olivry et al. 1996), and from series of earlier maps and airborne photographs for the “Normal” Chad period (Touchebeuf de Lussigny, 1969; Carmouze et al., 1983).

Results

Analysis of the satellite imagery

The new method for estimating the inundated area of the northern basin of the lake provided the time series of the inundation of the northern basin from 1986 to 2001, with three main results (Figure 7):

- the data obtained have been used as calibration values for the hydrologic model ;
- the 1990-2000 decade has been progressively more humid in the northern basin (Figure 7),
- the relationship between the river discharge and inundation of the northern basin has been improved and may be used for a simple and better forecasting of the inundation (see below).

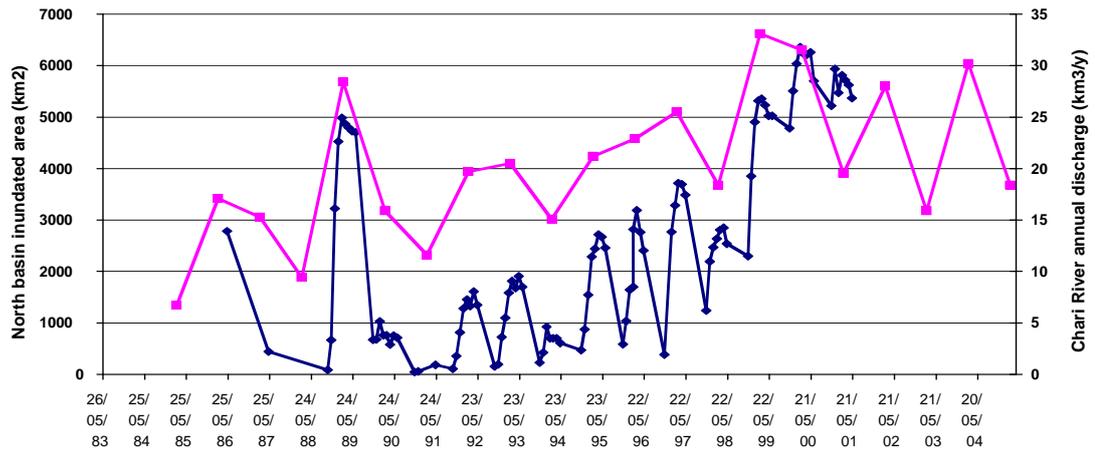


Figure 7. The inundated surface area of the northern basin of the lake as determined from Meteosat and AVHRR/LAC data (blue), and the River Chari annual discharge (red).

The new results significantly improve the semi-quantitative relationship proposed some time ago, relating the Chari annual input with an index of inundation extension based on an analysis of Meteosat data. As the river hydrograph is of a simple tropical form, it was possible to relate the peak flow of the river in N'Djamena at the end of October to the probable extent of inundation in the northern basin in January-February (Lemoalle, 1991). This was used as a warning system for the populations cultivating the exposed sediments in the bottom of the lake, and especially for those of the northern basin.

Satellite data are currently applied to the monitoring of surface water levels. Birkett (2000) and Mercier (2002) have provided pioneer applications to the southern basin of Lake Chad. Unfortunately, there were no satellite altimetric data available for the northern basin of the lake. We have shown here that inundated areas can be used, provided that the stage-area curves are available.

Simulation of Lake Chad hydrology

The water level observed in the southern basin indicated that no outflow from the lake has occurred between 1985 and 2003, and thus the parameters of outflow in the Bahr el Ghazal (m; Ba) have been calibrated with very few and ancient data.

Six main parameters of the model (Nn, An, Na, Aa, Dn and Ha1) were calibrated using Excel solver, in order to adjust the results to the observed values of level in archipelago (Ha) and south pool (Hs) and of surface area of north pool (Sn). The criteria to minimize was the mean of the standard error of these three outputs of the model, calculated on the following period : 15/08/1985 – 31/12/2003. Estimates of the error on the main variables of the model are presented in Table 2. The adjustment obtained is shown on figures 8 and 9.

Table2. Nash coefficient for the calibration over the period 1985-2003.

variable	Hs	max(Ha , Ha0)	Sn	mean
Nash coefficient	0.840	0.798	0.798	0.812

The model has been run to answer the following questions :

- how does the northern basin behave in a period of Small Lake Chad,
- what is the river discharge needed to restore a « normal » Lake Chad,
- what may be the impact of some strong increase in water input to the lake, resulting from transfer from the Congo-Zaire basin ?

The simulation results needed to answer these questions are presented in Figures 8, 9 and 10.

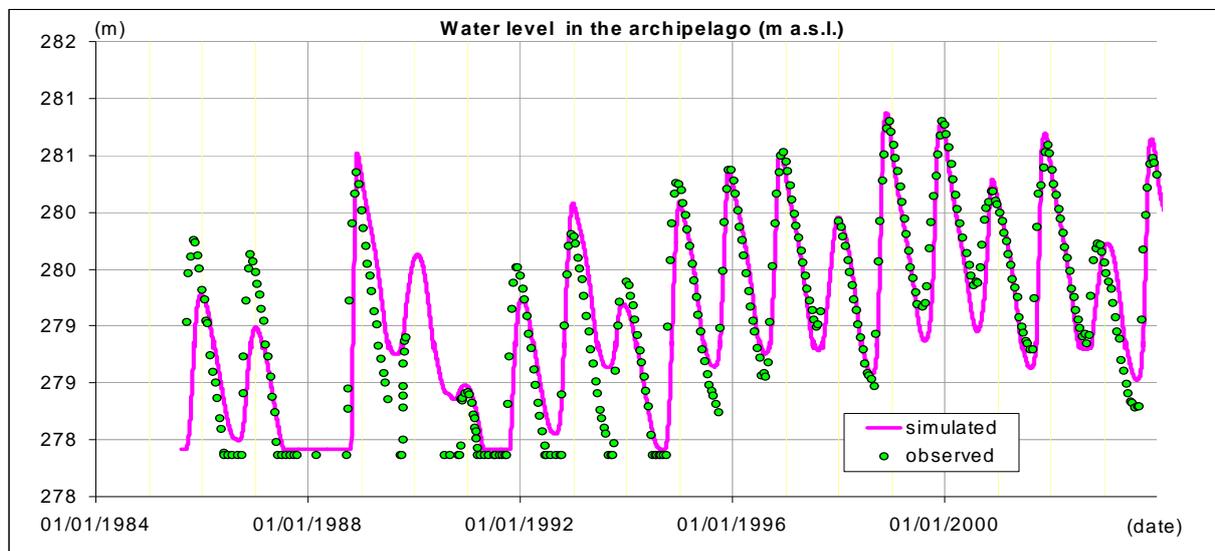


Figure 8. Observed and simulated water level in the archipelago (Bol gauging station). Observed data from DREM, Chad.

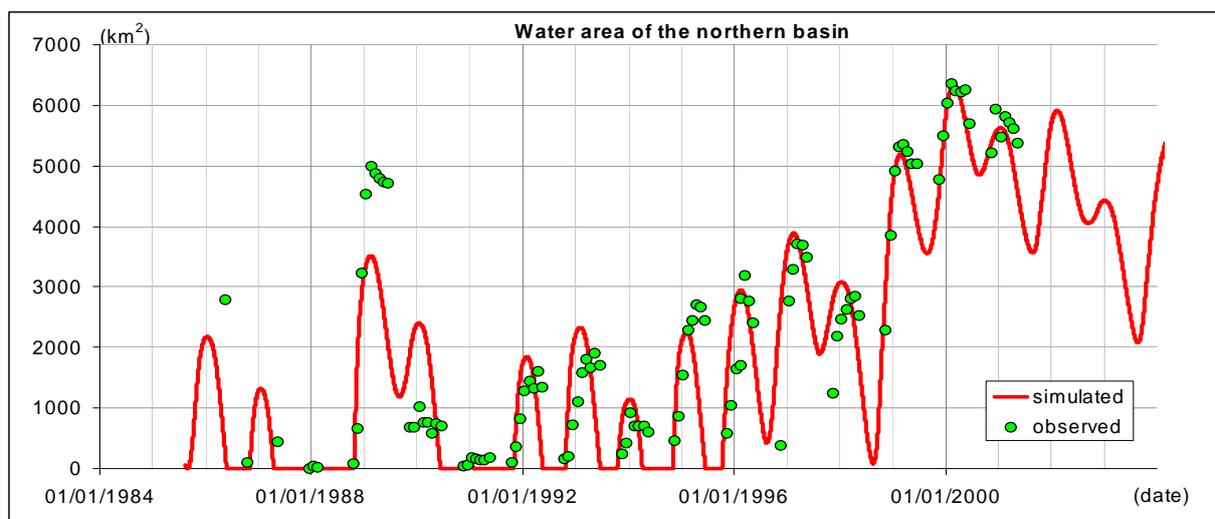


Figure 9. Observed and simulated inundated area of the northern basin. Observed data from our analysis of AVHRR/LAC and Meteosat archives.

Discussion

The reason for the present Small Lake Chad

Historical descriptions of Lake Chad indicate clearly that its level can vary according to natural causes such as rainfall changes over the basin. A long period of above average rainfall from 1950 to 1967 over the West African Sahel was followed by below average rainy seasons after 1970, with harmful droughts in 1972, 1973 and 1984 (L'Hôte et al. 2002). Over the Chari-Logone basin, annual rainfall has decreased by about 150 mm (L'Hôte & Mahé, 1996 ; Climatic Research Unit, 2003). As a result, the annual discharge of the main tributary to the lake has also been lowered (Table 3). This is the main reason for the decrease in Lake Chad level and the shrinking of surface area from a Normal to a Small Lake at the beginning of the 1970s. Water abstraction for irrigation is in proportion of small importance (Lemoalle, 2004).

Table 3. Measured mean annual Chari discharge for the recent period. data from ORSTOM/IRD and DREM Tchad. N'Djamena gauging station.

Period	1960 - 69	1970 - 79	1980 - 89 (-2)	1990 - 99	2000-04
Annual Chari discharge km ³ /y and (m ³ /s)	41 (1300)	31.1 (987)	16.6 (507)	21.6 (684)	22.2 (703)

The possibility to recover

The model indicates that one annual inflow of 38 to 40 km³/year would immediately re-establish a Normal Lake Chad comprising a single body of water. The same annual inflow is further needed to maintain this status of the lake in the ensuing years, as it used to be in the 1950s and 1960s.

It has been observed that a permanent lacustrine water body is maintained in the southern pool of the lake, even for an annual Chari discharge as low as 10 km³/year. The delimitation of a rather small pool around the R. Chari delta by the two main sills allows for this situation as the depth of this pool is sufficient to avoid desiccation during the low inflow season. Such a division into smaller basins when the water level falls significantly is a feature common to other closed lakes (e.g. the Aral Sea,) which is useful in lowering salinity and maintaining lacustrine communities when evaporation over the whole lake would exceed inflows.

The natural resources associated with the Small Lake Chad

The main natural resources associated with Lake Chad are the fish, the natural grasses to feed the livestock and areas of rich land used for recession cultivation. As a result of the hydrologic functioning of the Small Lake Chad, the two main basins (northern basin on the one side, and southern basin plus archipelago on the other side) provide these resources in a very different way.

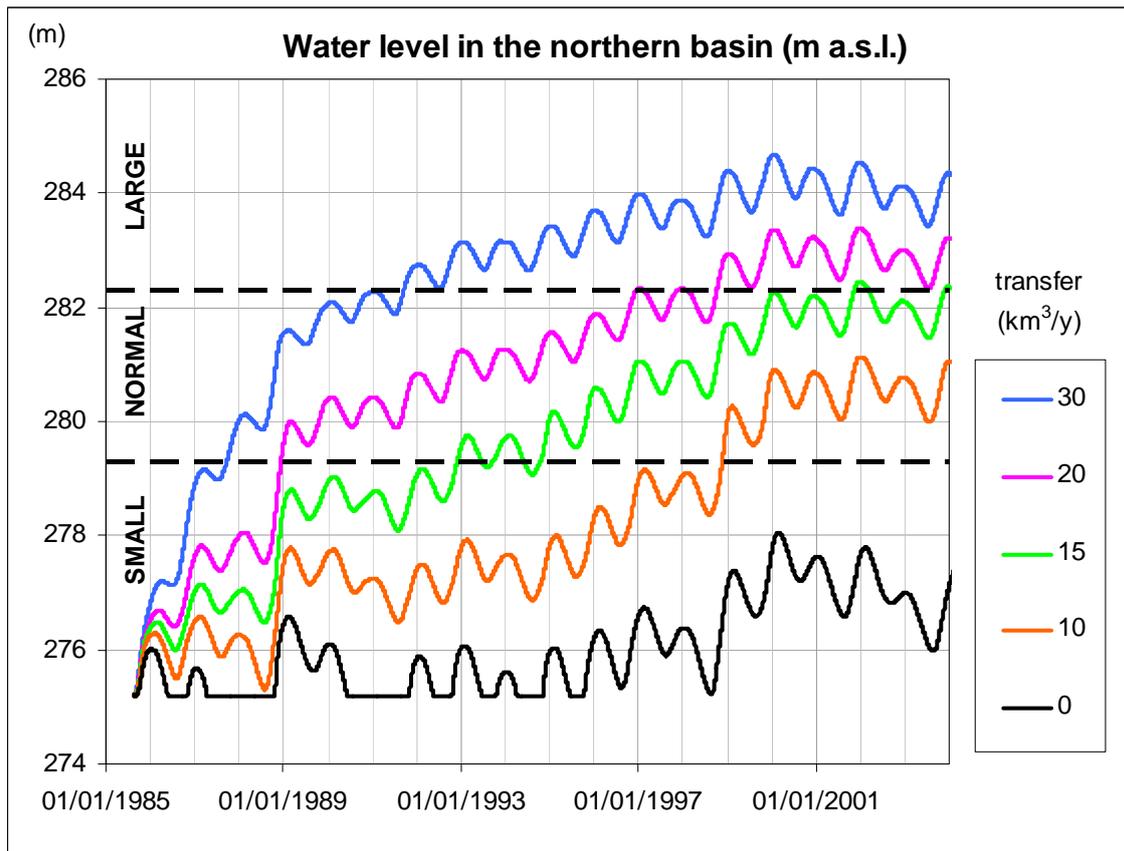


Figure 10. The simulated water level of the northern basin with the natural inflow (transfer zero, bottom curve) and for hypothetical inflows resulting from various transfers from the Congo-Zaire basin (from 10 to 30 km³/y).

In the southern basin, the water is permanent in the center of the basin and in some pools of the archipelago. The water level fluctuates between 278.8 and 281.0 m, with a seasonal amplitude of 1.5 to 2.3 m. This is in the range where the change in area is the most sensitive to the changes in water level with about 2000 km² per m level change. This area is covered by aquatic vegetation when wet, and grazed by the cattle, and can be cultivated for cereals and legumes during the draw down period. The inundated area varies between 1700 and 6000 km², which allows for fisheries both in the open waters and in the marshes (Kolawole, 1988; Lemoalle, 2004).

The northern basin is more or less inundated according to the rainfall over the Chari basin, but it happens that it dries up completely for one or several whole years. On these occasions, there is no fish, no fodder for the cattle and almost no possibility to cultivate. The wells are often not deep enough to reach the groundwater table. The men have to migrate to find their livelihood elsewhere. In years when the inundation covers a good part of the northern basin, the fish migrate in great numbers from the southern basin and are easily caught in the shallow waters, recession cultivation becomes possible and some cattle can feed on the natural vegetation.

In a state of Normal Chad, the amplitude of the seasonal water level fluctuations is usually smaller than 1 m, and in both south and north basin the drawn down zone accessible to cultivation is also much reduced. Larger canoes and better gear are needed to access the open waters of the lake, with no increase in the catch. The natural resources are probably less important than during a good year of small

Chad, but less variable and the people living around the northern basin appreciate having permanent access to water.

Interbasin transfers

The transfer of some water from the Congo-Zaire basin to the Lake Chad basin has been proposed long ago as a mitigation of the semi-arid climate of the African Sahel. The idea has been given new interest with the drought in the Sahel and its impact on Lake Chad (Bonifica, 1988; LCBC, 2000). A call for a feasibility study has been launched in late 2007 to study the feasibility and impact of 40 to 100 km³/year transfers.

The simulation using different additional volumes to the observed low discharges observed from 1985 to 2004 (mean value 22 km³) indicates that a transfer of 15 to 20 km³/year would compensate the present dry climate and allow for a Normal Chad, and a 20 to 30 km³ transfer would lead to possible overflow from the lake to the Bahr el Ghazal in a state of Great Chad (Figure 9). The proposed 40 to 100 km³/y in the original Bonifica project would create overflows that are not within the framework of our model. In any case, a study of the impact along the river valleys of the Chari and Logone rivers, and on cities such as Sahr, Kousseri and N'Djamena is mandatory.

Conclusion

In the present context of low rainfall over the Chari-Logone basin, the hydrologic functioning of Lake Chad is that of a Small Chad, with a northern lake basin partially and irregularly inundated. Some important natural resources are associated in the southern lake basin with this functioning, but their irregularity in the northern basin remains a major concern. We have developed a model that helps to analyse the hydrologic impact on Lake Chad of the proposed interbasin transfers from the Congo-Zaire, but the ecological and socio-economic impact on the natural resources and on the societies living along the water courses and around Lake Chad needs attention.

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