Chapter 13

LAKE CHAD : A CHANGING ENVIRONMENT

Jacques LEMOALLE

Laboratoire Divha, IRD, BP 64501, 34394 Montpellier cedex 5, France (lemoalle@mpl.ird.fr)

1 INTRODUCTION

In closed lakes, an equilibrium water level is reached when the surface area allows for an evaporation that balances the rain and stream flow into the lake. As these inflows are closely associated with rainfall over the basin, such water bodies are highly sensitive to the climate variability, and have been described as amplifier lakes. In natural conditions, they are good indicators of climate changes, but they also react rapidly to man-made changes in their water budget. An analysis of the hydrological and ecological functioning of some closed lakes experiencing modifications to their water budget may provide some pointers to future management strategies for water resources in endoreic basins subject to global climatic change. The recent evolution of Lake Chad is presented here in this context.

J.C.J. Nihoul et al. (eds.), Dying and Dead Seas, 321–339.

Lake Chad lies in an endoreic basin in the centre of Africa on the southern margin of the Sahara (Figure 1). There is no surface outflow. River and rainfall inputs are offset by evaporation losses, some seepage and by volume and area fluctuations according both to seasonal and annual variations of the water budget.
As a result of a decrease in rainfall over the basin, the lake level and area have progressively decreased. In 1973-74, previously shallow areas of the lake bed have emerged and the lake has subsequently split into separate pools. This change in the hydrology and landscape of Lake Chad led to concerns that it might be dry up altogether (the death of the Lake), causing major ecosystem and livelihood changes in the region., with the loss of the natural resources provided by the lake.

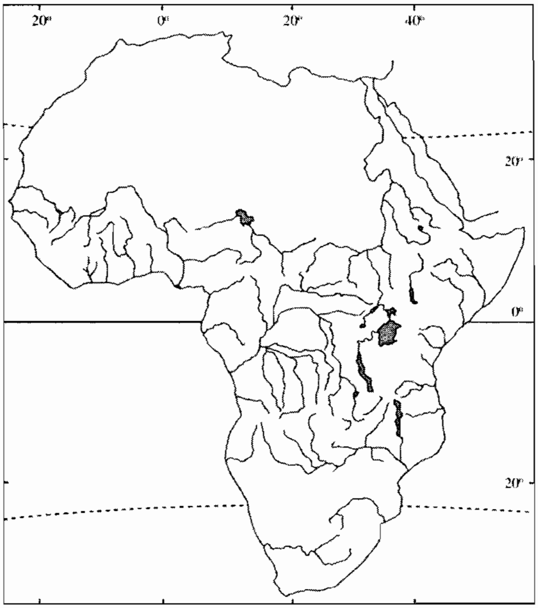

Figure 1. The situation of Lake Chad in Africa, at the southern border of the Sahara.

The purpose of the this chapter is to describe the present functioning of the lake, and to analyse the conditions necessary to enable the Lake once again to achieve a "normal" state. The chapter draws extensively on previously published papers and data summarized in Carmouze, Durand and Lévêque (1983), Lemoalle (1991) and Olivry et al. (1996), with updates from recent satellite and ground data.

2 LAKE CHAD : VARIABILITY AND LANDSCAPES

Lake Chad has a long history of wet and dry periods which span different time scales. During the quaternary, the last lacustrine transgressions, although interspersed with dry shorter episodes, occurred between 12,000 and 6,000 BP (when the water level reached up to 300-310 m asl and the total lake extent achieved was 250,000 km^2) and from 3,200 to 1,800 BP (287-290 m asl) (Servant & Servant, 1983).
Over a shorter time scale, during the last millennium, data from sediment stratigraphy and pollen analyses and other historical analyses indicate a similar succession of high (up to 285 m asl) and low levels, with four to five drought periods between 900 and 1900 AD. A very dry period of 25- to 30- years duration at the end of the 15th century has been well documented (Maley, 1980).

Some European explorers have visited the lake in the 19th century : Denham in 1822, Barth and Overweg in 1851, Rohlfs in 1866, Nachtigal in 1870 and Monteil in 1892. They described L. Chad as a very large water body, but reported from local tradition that it was probably much smaller at some time between 1822 and 1850 (Carmouze et al., 1983). Later military missions indicated that the lake had receded between 1904 and 1915, with large areas of previously open waters emerging as marshes or dry land. Detailed descriptions of this new environment have been provided by Destenave (1903a, b), Freydenberg (1907), Tilho (1910) and Garde (1911).

These important changes initiated the first dispute between scientists on the potential desiccation of the lake. However, a quick recovery in water level led to a hypothesis that the Lake periodically dried up and re-emerged over time. 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 km^2 of open waters 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.
- The Small Lake Chad, is made up of different separated bodies with a permanent open water pool of about 1,700 km^2 at a maximum

altitude of circa 280 m and permanent or seasonal marshes ranging from 2,000 to 14,000 km^2.

- The Normal (intermediate) Lake Chad has an intermediate level of 281 to 282 m, an archipelago of some 2,000 dune islands, some marshy vegetation on the shores and a single body of water covering about 20,000 km^2 (Table 1) .

Table 1. The main characteristics of the different states of Lake Chad

Lake Chad	Small	Normal	Large
Chari discharge (km^3/y)	10 - 35	40	45
Water level (m asl)	279 - 280	281 - 282	283.5
Number of water bodies	several	one	one
Total lake area (km^2)	3,000 – 14,000	18,000-22,000	24,000
North basin area (km^2)	0 – 7,000	9,000	10,000
Landscape	marshes	dune islands	open waters
Vegetation	+++	++	+

The Normal Chad may be divided in two main basins, north and south, which are separated by a narrow and shallow belt, locally known as the Great Barrier, often covered by aquatic macrophytes (Figure 2). On the north-east side of both basins, the lake is bordered by an erg of ancient dunes, the altitude of which progressively decreased along a NE-SW axis. This creates an archipelago of sandy islands, with a decreasing altitude towards the open waters of the two basins. The seasonal variation of the lake level determined the distribution of the riparian vegetation, commonly limited to a narrow band along the steepest shores of the dune islands and close to the lake border, though more extensive towards the open waters, along the south and west shores of the south basin and over the Great Barrier. The summit of some drowned dunes would also be covered by some reeds, including Papyrus, Typha and Phragmites, constituting « bank islands », spots of helophytes apparently developing in open waters. The open water areas were quite extensive, covering about 4,000 to 6,000 km^2 in each basin.

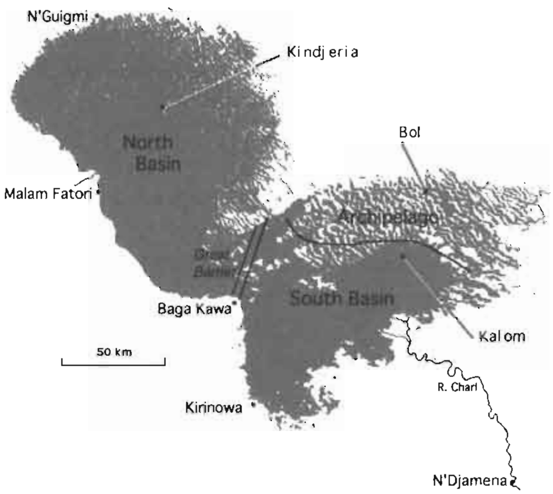

Figure 2. The main regions of the Normal Lake Chad and the situation of the main sills, between the open waters and archipelago in the southern basin and between southern and northern basin (Great Barrier).

3 THE TRANSITION TO A SMALL LAKE CHAD

After a period of Normal Lake since the beginning of water level monitoring in 1953 the lake level progressively decreased as a result of reduced rainfall in the basin. The lake level decreased from 283.27 m on January 1, 1965 to 279.70 m on January 1, 1973, a rate of 0.45 m/y (Figure 3). The aquatic vegetation along the shores of the lake was not able to withstand this decline, and by January 1973 had totally disappeared. At this time, the lake was still made of a single body of water, although very shallow in some regions, especially in the Great Barrier and at the limit between the open waters and the archipelago of the south basin.

In March 1973, the sediment of the shallow regions emerged and the lake was split into smaller pools, either connected with a water input (e.g open water facing the R. Chari delta), or only subject to evaporation losses. The level of these pools therefore behaved differently (Figure 4).

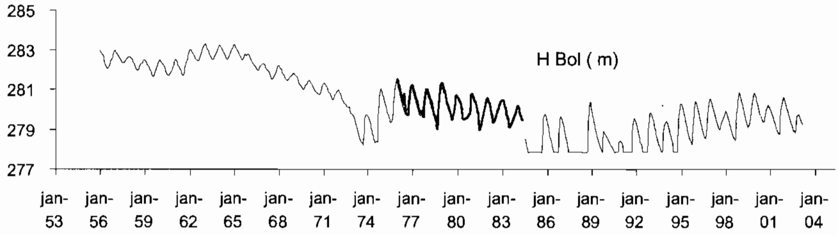

Figure 3. The water level as monitored at the Bol gauge (data from ORSTOM and DREM). Since March 1973, the Lake has split into basins of differing water levels and can not be described by a single water level. The level from March 1979 to May 1984 has been calculated from Kirinowa levels using a correlation between the two stations.

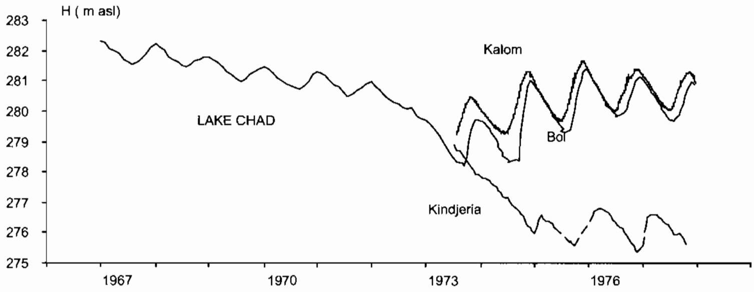

Figure 4. The water level in the three main regions of L. Chad during the transition from Normal to Small lake. The location of the gauges is given in Figure 2.

In the large pool facing the R. Chari delta, and fed by the river discharge, the level decreased only slightly. In the numerous small pools of the eastern archipelago, isolated from any input, evaporation led to marked changes, as in Bol where the decrease was 1.19 m between March 1 and September 15, 1973. Further large areas of the archipelago sediment became exposed to the air. In July of that year, the onset of the rainy season triggered the germination of seeds present in these exposed sediments. A dense vegetation grew up, comprising *Cyperus papyrus*, *Phragmites australis*, *Typha australis* and *Aeschynomemne elaphroxylon* and other smaller plants. When the R. Chari flood arrived in the south basin, these plants remained in place and constituted a large marshy area (Iltis and Lemoalle, 1983). The areas of open water in the south basin at

the end of 1973 were those which had remained inundated during the low level period. This distribution of the vegetated/open water areas has remained almost unchanged since 1974.
After March 1973, the north basin was separated from the south basin by the emergence of the Great Barrier. It received some water from the River Yobe, with only a limited impact around its estuary, but no water from the south basin passed over the Great Barrier until January 1975. During this 22 month duration, the water level in Kindjeria, the centre of the basin, decreased by 3.82 m. After a small spill over from the south basin in January 1975, the level decreased again until June 1975 when the basin completely dried up (Figure 4). At that time, although some rain fell around August 1973 and 1974, vegetation did not develop, probably because the soil salinity, higher than in the south basin, was detrimental to *C. papyrus* and *A. elaphroxylon.* With the exception of the Great Barrier, where the marsh vegetation developed in 1973 as in the south basin, vegetation in the north basin appeared only at the end of 1976, and was a mixture of reeds and shrubs including *Ziziphus* and *Aeschynomene spp.* More permanent humidity in the estuary of the K. Yobe River promoted some marsh vegetation in this area.

Since 1976, the inundation of the north basin has varied from year to year and season to season, depending on the level in the south basin and spillage over the Great Barrier. The maximum yearly flood extent varied from zero (in 1985, 1987 and 1988) to more than 7,000 km2 (January and February 1976, 1977, 1979, 1989, and from 1999 to 2003). From 1975 to 2001, the basin was almost completely dry for a number of months each year between October and December (Lemoalle, 1991). From 1999 to 2002, 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.

In both basins, the new hydrological regime and the development of the fixed and floating vegetation created a new environment with changes in water chemistry as well as in the lacustrine communities ranging from phytoplankton to fish. These have been described for the first years of the Small Lake Chad (see Carmouze et al. 1983).

4 THE WATER FLUXES AND BALANCE

The water level of the lake may be described and analysed only during periods of Large or Normal Lake. In periods of Small Lake, the different level recorders and gauges are only representative of the pool in which they stand; extrapolation of data to the whole lake has sometimes led to misinterpretations of the lake regime.
The Normal Lake level varies with time, seasonally and from year to year, and is mainly a function of the discharge of the River Chari. The river has a tropical regime, with very low discharge during the dry season and a high flood: the mean ratio between the highest and the lowest monthly discharge at N'Djamena was 18.5 during the Normal Lake Chad period. This seasonality of inflows was reflected in seasonal level variations of about 0.7 m in the lake, with peak levels in December or January, and low levels in August. The variation between years (January to January) were generally lower, with a maximum range of 0.6 m.
The water level may also differ at any given time, from place to place. This partly results from the flooding pattern from the R. Chari delta to the extremities of the south and north basins, and because of the wind pattern, with a diurnal and seasonal period which creates wind set-up. The seasonal change in wind direction from northeast (November-May) to southwest (June-October), associated with the migration of the Inter Tropical Convergence Zone (ITCZ), creates a tilting of the water surface of 0.4 m between Bol (northeast) and Kirinowa (southwest) in the south basin (Talling & Lemoalle, 1998).

4.1 Normal Lake Chad

The water budget of Lake Chad has been studied by a number of authors, from Touchebeuf de Lussigny (1968) to Olivry et al. (1996). Mean values for the period 1954-1969 of Normal Lake Chad have been calculated by Vuillaume (1981) (Table 2). During this period, the lake level has varied between a minimum of 281.02 m in July 1954 and a maximum of 283.32 m in February 1963, but the initial and final levels, on May 1, 1954 and May 1, 1969 differ by only 0.03 m.

Table 2. Mean values for 1954-69 of the components of the water budget of Lake Chad. Values expressed as water height (mm/y) over the lake surface area (from Vuillaume, 1981)

	Units	Normal L. Chad
River inputs	mm/y	+1946
Direct rainfall	mm/y	+329
Evaporation	mm/y	- 2170
Net seepage	mm/y	- 102

The major part of the input to the lake is the discharge of the R Chari (82.3 % of total inputs), supplemented by direct rainfall (14 %) and inflow from the other small tributaries, El Beid and K. Yobe (3.6 %). It has been estimated that the losses in the R. Chari discharge between N'Djamena, where the discharge was measured, and the lake, are compensated for by inflows from the other tributaries. The respective mean figures were :

- R. Chari at N'Djamena : 41.7 km^3/y
- El Beid 1.43 km^3/y
- K. Yobe 0.49 km^3/y.

The losses result mainly from evaporation (95.5 %) and seepage out of the lake (4.5 %). The seepage may change in direction, seasonally or from year to year, according to the trend in the change of the water level. This may explain some differences between mean annual seepage rates and instantaneous local observations (Isiorho & Matisoff, 1990).

4.2 Small Lake Chad

The hydrology of the Small Lake results from two main sills separating three pool systems (Figure 2). One sill divides the south 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. 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.

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, larger than during the Normal Chad period, occurs with the input of the R. Chari flood, until a level of 279.5 to 281 m is reached in December. When this level is reached, overflow occurs toward the northern basin of the lake through the Great Barrier and to the eastern archipelago (Figure 5).

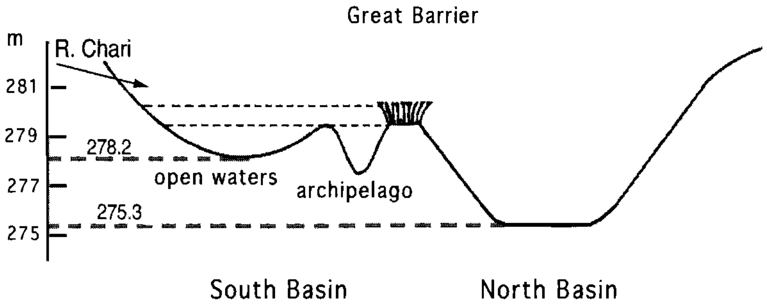

Figure 5. A schematic cross section of lake Chad showing the two main basins, with indications of the altitude of the sills and of the basin floors.

When compared with a Normal Lake Chad period, the Chari discharge maintaining a Small Lake is much lower (Table 3). The rainfall over the lake, calculated from five or more stations around the lake has also decreased since 1972 (Olivry et al. 1996).

Density and health of the vegetation over the Great Barrier, limits the possibility of high seasonal water levels in the southern pool. The annual cycle in the northern pool during a Small Chad period is, on the contrary, highly variable, as described above.

With these lower inputs an equilibrium level may only be achieved through lower losses, especially in their main component, evaporation, caused by a reduction in the lake surface area.

Table 3. The Chari discharge at N'Djamena during Normal and Small Lake Chad periods (data from Orstom and DREM-Tchad), and calculated rainfall over the lake.

	Period	Value	Period	Value
Chari discharge (N'Djamena) (km^3/y)	1950 - 71	39.1	1972 -2000	21.8
Direct rainfall (mm/y)	1950 - 71	320	1972 - 89	207

5 THE CAUSES OF THE PRESENT STATE AND CONDITIONS FOR RECOVERY

Historical descriptions of Lake Chad indicate clearly that its level can vary according to natural causes such as rainfall changes over the basin. Human activity in the basin may be considered as having had no effect on its hydrology at least until 1960. The impact of global climatic change on the basin climate, or the influence of the land use changes within the basin on water runoff, which may be attributed respectively to global or local human activities, remain uncertain and will not be discussed here. The more recent implementation of irrigated schemes and their possible impact on the lake water budget is, however, discussed below.

5.1 Rainfall over the basin and river discharge

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) (Figure 6). Over the Chari-Logone basin, annual rainfall has decreased by about 150 mm, with a North-South displacement of the rainfall gradient of 150 km (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 (Figure 7). 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.

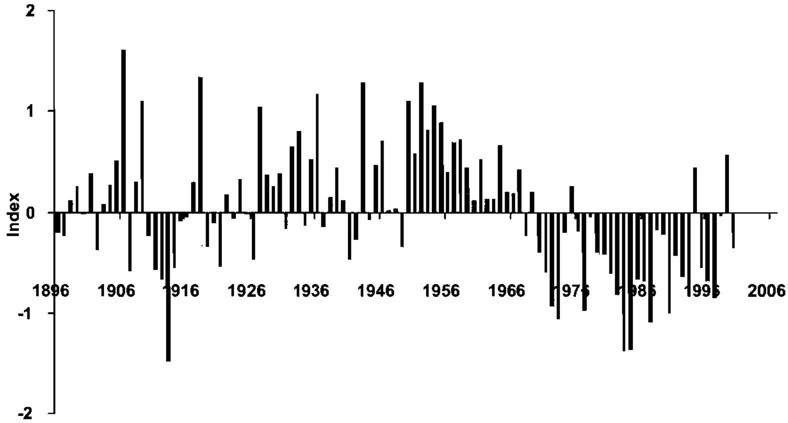

Figure 6. Time series from 1896 to 2000 of a normalized rainfall anomaly index over the West African Sahel (mean value computed for 1921-2000). From L'Hôte et al., 2002.

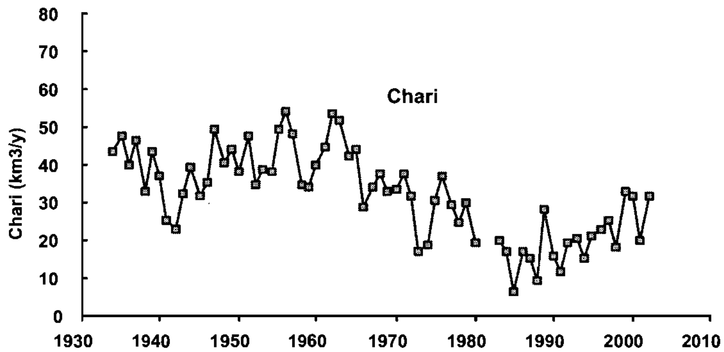

Figure 7. The River Chari annual discharge at N'Djamena. Data from ORSTOM-IRD and DREM (Chad).

If the values presented in Table 3 are applied to a totally closed lake (assumed to have no seepage) and with an annual evaporation E of 2.17 m as has been calculated for Lake Chad, the water surface area S_{eq} that would allow for a balance between the losses and inputs Q_r and direct rain P is

$$S_{eq} = Q_r/(P-E)$$

which gives an area of 21,1 km^2 in the wet period 1950-71 and of 10,8 km^2 during the dry period 1972-89. With this first approximation, it may be considered that the observed level and area of the lake are in accordance with the inflows measured at N'Djamena.

5.2 Water abstraction for irrigation

As the rain-fed agriculture in the basin does not provide sufficient output for local subsistence, a number of irrigation schemes have been implemented along the rivers valleys flowing into the lake and around lake Chad itself. The water abstraction resulting from these irrigation schemes is still poorly documented, but an order of magnitude can be estimated. We shall here consider successively the rivers, the lake surroundings and the lake bed.

Recent estimations of water abstraction in Chad along the Chari and Logone rivers amount to 100 Mm^3 (Rép. du Tchad-PNUD, 2003). Part of this volume is used for traditional irrigation, i.e. water overflowing onto the floodplains which would in any case be lost to the lake. An other portion (40 Mm^3) is used for sugar cane near Sahr, in Southern Chad. The Maga Reservoir, in Cameroon upstream of the Logone floodplain, has a capacity of 400 Mm^3 with a surface area of 90 to 360 km^2. It was constructed in 1979, together with a system of dams along the River Logone, in order to retain part of the natural input to the floodplain for the development of paddy. However, it contributed to the destruction of the floodplain ecosystem by severely decreasing the water input. After a preliminary test in 1994, the whole irrigation system has subsequently been modified to allow seasonal inundation of the floodplain and to provide the necessary water resources for fisheries, farmland and rangeland. Its impact on the water budget is low since most of the river input to the floodplain is naturally lost through evaporation (Wesseling et al., 1996 ; Olivry et al., 1996).
Two large reservoirs have been constructed on the upper basin of the River Yobe basin in Nigeria : Tiga Dam (1492 Mm^3, in 1974) and Challawa Dam (972 Mm^3, in 1992) while a third one (Kafin Zaki) is currently under study. They are used for drinking water supplies and for irrigation, but it appears that their effect on the discharge in the R. Yobe

lower basin and to Lake Chad is more important on the seasonal flow pattern than on annual discharge which remains close to 650 Mm^3/year (Goes, 2001).
After successful tests at a pilot scale south of Lake Chad in Nigeria, the South Chad Irrigation Project (67000 ha) and the Baga Polder Project (20000 ha) were inaugurated respectively in 1979 and 1982. Their full operation would have needed 2.5 km^3 of water per year. They both had long intake canals to pump water from the lake, but the lake recession did not allow for the irrigation of more than 7000 ha in the first years of operation before a complete halt in operations (Thambyahpillay, 1983 ; Hollis, 1990).
A number of polders have been constructed in the eastern archipelago of Lake Chad. According to the dam construction and irrigation system, their water needs have been estimated at between 6,000 to 16,000 m^3/ha/year. When these irrigation needs are compared with 21,000 m^3/ha/year of lake surface evaporation, it appears that the creation of polders does not contribute to a net water loss from the initial whole lake extent. At present there is total area of 5000 ha of polders, with plans to extend this to 12000 ha in the near future.

Currently, therefore, and with the available data, it is estimated that less than 200 Mm^3 are abstracted from the Chari-Logone system upstream of N'Djamena where discharge is measured. The gross uptake for the polders is 75 Mm^3, but this is less than would have evaporated from the lake surface had they not been implemented. The net uptake for irrigation in the Lake Chad basin probably therefore amounts to some 200 Mm^3/year. This value is much lower than estimates presented elsewhere, and would not contribute substantially to the present low level of the lake (Coe and Foley, 2001).

5.3 The conditions for a recovery to a Normal Lake

A simple hydrological model has been set up in order to evaluate some local and more general environmental issues. It has been used to estimate the necessary inflow to restore "Normal" Lake Chad levels with a single water body covering all basins. It has also been used to investigate how the sills between the sub-basins in a lake contribute to the maintenance of a lacustrine environment during low level periods.
The model uses the stage-area relationship partially derived from satellite data (Lemoalle, 1978), observed monthly levels or areas in the lake and

measured inflow from the River Chari for 1990-94 (data from DREM, Chad). The monthly rainfall and evaporation have been set as constants (Vuillaume, 1981) and it is assumed that seepage is a constant fraction of evaporation (i.e. a function of lake area). The daily transfer of water over the sills through the overlying vegetation is a fraction of the volume of water situated in the southern pool above the sill altitude (2.5 % for the northern basin and 1 % for the archipelago).

Once calibrated for the 1990-94 period, the model indicates that one annual inflow of 38 to 40 km^3/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.

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 km^3/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 period. 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, this volume) which is useful in lowering salinity and maintaining lacustrine communities when evaporation over the whole lake would exceed inflows.

6 Discussion

Since 1973-76, when the lake split into different water bodies and the first total desiccation of the northern basin took place, Lake Chad has been in a of Small Chad. equilibrium state. It decreased in level and area between 1965 and 1973 but has not subsequently. Contrary to news reports in the Press or on the web (e.g. NASA, 2003), Lake Chad is, at the time of writing (2003) neither shrinking, disappearing nor dying. It is just a Small Lake Chad, as it has been several times in the past prior to recovering Normal or Large Lake Chad levels.

The present status of the Small Lake Chad is highly dependent on the annual Chari discharge, which itself can vary according to natural (or global) as well as man-made local causes. A significant decrease in the discharge, down to about 12 km^3/year, would lead to a permanent

desiccation of the northern basin of the lake but would maintain the present functioning of the southern basin.
A recovery of the inflow to its 1950-70 values would allow for full recovery of the Normal Lake Chad.
The models presently available on global climate change do not allow for reliable estimates of trends in the rainfall over the Lake Chad basin over the coming decades. Although the models do not forecast significant changes in annual rainfall over the Chari-Logone basin, some modifications in the intensity and distribution over the rainy season may occur, in association with a net increase in mean air temperature (Dokken et al. , 2001; Climatic Research Unit, 2003). It is thus not possible to predict whether the natural Chari discharge will decrease or increase as a result of global change. Future human development in the basin may increase water abstraction through new or rehabilitated irrigated schemes along R. Chari and R. Logone. The possibility of water supply augmentation is also under study through water transfers from the upper Ubangui-Zaïre basin to the Chad basin (LCBC, 2000). At least part of the projected 40 km^3/year transfer would be discharged into Lake Chad, with the objective of maintaining a Normal or Large Lake.

With the decreased rainfall in the Sahel since the end of the 1960s, and the severe droughts of 1972, 1973 and 1984, many people have lost access to their livelihood resources (either pastures or rain-fed agriculture). Some communities have moved toward places where water would be less limited, especially along the shores of Lake Chad where intensive fisheries, cattle grazing and cultivation in the draw down zone have developed. The increased seasonal level variation of the Small Lake Chad in the southern basin provides a larger area for the growth of aquatic macrophytes which are grazed by the cattle before the cultivation of cereals or legumes (Kolawole, 1988; Sarch and Birkett, 2000). The fisheries have adapted to the new conditions and to the new dominant fish species of the marshy areas (Jolley and Neiland, 1998; Oualbadet et al. 1996). In the northern basin, the variability from year to year is particularly high, but the use of the natural resources of the lake bed has also increased. The high-density population in close proximity of the lake has been exploiting the natural resources of a Small Lake Chad since the beginning of the 1970s, and has been able to cope with its natural variability.

These services should be taken into account in the planning of future water resources management in the basin, either in the case of increased inputs by water transfer, or in the case of decreased water inflows to the lake through the development of irrigation along the rivers and around the lake itself. Superimposed onto these man-made modifications, the natural variability in Lake Chad levels will most probably remain an important driving force.

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