Confronting Models with Observations for evaluating Hydrological Change in the Lake Chad Basin, Africa

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ABSTRACT

Lake Chad is located at the southern edge of the Sahara Desert in north-central Africa. It is a shallow fresh water endoreic lake whose mean depth is about 4 m while its basin (2.5 10^6 km^2) is the largest endoreic catchment area in the world. Due to its position in the Sahelian belt, Lake Chad is a vital source of water for surrounding populations regarding irrigation, fishing, and trade. However, owing to its low depth and the high variability of its semi-arid climatic conditions, Lake Chad has experienced several regressions and extensions in the past. The last significant variation was recorded during the last decades, with the contraction of the lacustrine surface area from 25,000 to 1,500 km^2 during the 1970s and 1980s. Consequently, the extreme sensitivity of the Lake Chad hydrosystem requires efficient and reliable hydrological models in order to investigate the lake's evolution with regard to basin characteristics, climatic change and water resource management.

Two distributed models were applied. They are based on a water routing model, THMB (formerly HYDRA), in which runoff and subsurface flows are routed along the drainage network unless the water is stored in a depression: in this case, the (P-E) balance is applied. In the first model, IBIS+THMB, runoff is generated off-line using a Land Surface Model, IBIS, whereas in the second, GR+THMB, runoff is directly computed by the GR2M using 2 internal parameter production modules. The first parameter is the Water Holding Capacity as deduced from the FAO soil map, and the second, C, is equivalent to an interception coefficient whose calibrated value is about 0.27.

Simulations by the two models of the monthly flow of the Logone-Chari River at N'Djamena (95% of lake tributary input) were compared. Simulated discharge was generally underestimated by 35% for the GR+THMB model and 26% for the IBIS+THMB model whereas the Nash index was higher for GR+THMB (0.77) than for IBIS+THMB (0.55). Regionalisation of parameter C significantly improved the GR+THMB model as shown by Nash index and volume deviation (0.80 and -21%). Concerning Lake Chad itself, the monthly water level variability was correctly simulated as the correlation coefficients for the 2 models were about 0.85.

However, these agreements hide some local discrepancies: for example, the simulated Komadougou River flow appears to be overestimated and partly compensates for the underestimation of the Logone-Chari volume for the two models. Moreover, additional analysis revealed that the lake volume is very sensitive to irrigation withdrawals and lake-bottom infiltration parameterisation, as well as DEM quality. These points are currently under development in order to evaluate the hydrological consequences in response to future climatic change and water resource scenarios.

KEYWORDS: regional hydrology, model, runoff, Lake Chad

INTRODUCTION

The dynamics of Lake Chad are a characteristic example of the response of a regional hydrosystem to climatic fluctuations and the constraints linked to water use. At a latitude of 13°N and longitude of 14°E, Lake Chad, which is shared between Chad, Niger, Nigeria and Cameroon, is situated in the Sahelian Zone. It is a shallow endoreic lake (average depth between 3 and 4 m), whose catchment area extends over a total surface area of 2 500 000 km^2 (Olivry *et al.*, 1996). These two characteristics, being situated in a semi-arid zone and low depth, make Lake Chad extremely vulnerable to the consequences of climatic variations. After the drought periods of the 70s and 80s, the water surface area of the lake went from 25 000 to 5 000 km^2 on average (Lemoalle, 2004). By contrast with the current epoch, Lake Chad was very much larger during the Holocene humid period (~ 6 000 BP) when it was a veritable inland sea, called Mega-Chad with a surface area of nearly 340 000 km^2 (Leblanc *et al.*, 2006; Sepulchre *et al.*, 2007).

Due to its hydro-climatic characteristics, Lake Chad has always played a primordial role in human activities and the lives of the societies around it. Beyond purely social phenomena where water has played a historic role concerning religions, languages and sometimes justice systems, water has also affected the organisation and hierarchisation of societies between communities of fishermen, farmers and livestock raisers (Roubinet, 2007). In addition, the lake enabled the establishment of commercial exchanges through the transportation of merchandise by boat. At present, certain activities are jeopardised due to of the shrinking of the lake. For example, overfishing threatens the survival of certain species. However, paradoxically, the fall in water level of the lake has freed up areas of land suitable for agriculture. Moreover, seasonal variations in the size of the lake provide annual fertilisation of these newly uncovered lands (Magrin, 2008). Finally, the lake's main tributaries, the Chari, Logone and Komadougou Yobé, make a major contribution to agricultural development by means of the irrigation networks developed in recent decades.

Under these conditions, any large-scale planning must take into account the main components of the water balance of the lake and its catchment area, together with an estimation of the future functioning of this hydrosystem on the basis of future climate scenarios. Despite numerous uncertainties, hydrological modelling is one of the most effective tools for estimating the current and future evolution of the water volume dynamics of Lake Chad and its basin.

The aim of this paper is to present the first results of the simulation tools developed to model the surface hydrology of the Lake Chad Basin. In the first part, we present the hydro-climatic context of the Lake Chad Basin. In the second part, we describe the two hydrological models used in our study, together with the available data. We then perform a comparative study of the simulated discharges for each of the models used. Finally, based on various simulations of the water level of the lake, we show the considerable sensitivity of the models for correctly reproducing the dynamics of Lake Chad.

The Lake Chad Basin

Geography and Climatology

The catchment area of Lake Chad (Lake Chad Basin, LCB) is situated in the centre of the African continent, between latitudes 5°N and 25°N and longitudes 7°E and 27°E. It extends over approximately 2 500 000 km^2 across the territory of Niger, Nigeria, Chad and Cameroon, and the borders of Algeria, Libya, Sudan and the Central African Republic, making it the largest endoreic basin in the world (Figure 1). Enclosed between mountain ranges (Tibesti, Darfour) and high plateaus (Adamoua), this entire hydrographical network converges on a central depression, in which Lake Chad was formed. Apart from these conterminous highlands, the LCB is relatively flat.

The climate of this region is linked to the movement of the InterTropical Convergence Zone (ITCZ) (Olivry *et al.*, 1996). In the north of the ITCZ, the Harmattan produces a dry climate, whereas in the south, the monsoon flow brings heavy precipitation. As it moves during the course of the year, the ITCZ sweeps over the south of the LCB in particular.

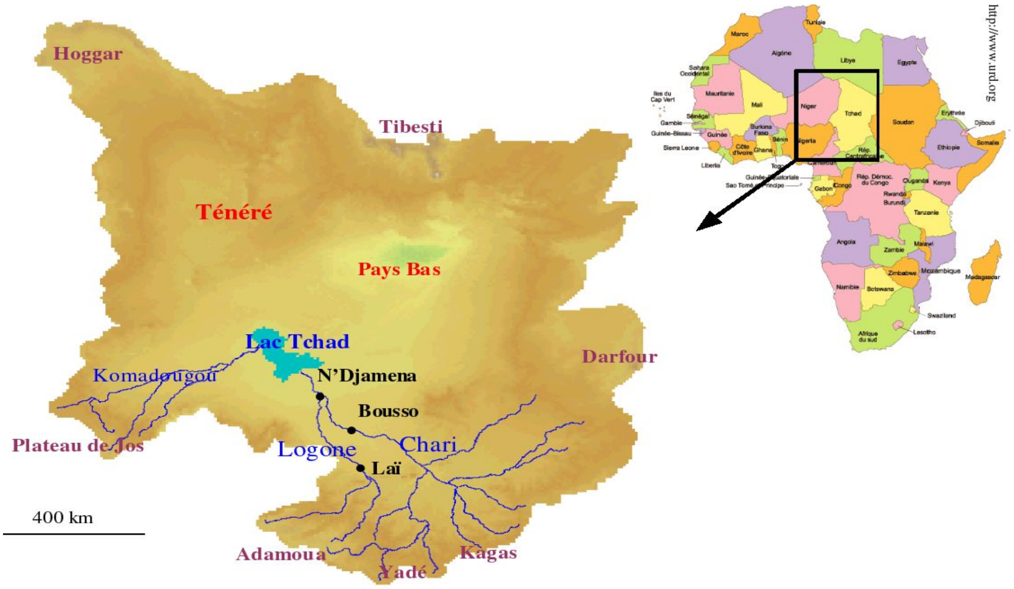


Figure 1. The Lake Chad Basin

Thus, in the south of the LCB, the climate is of Sudano-Guinean type (hot season – wet season) and the wet season caused by the monsoon flow lasts up to 8 months. Maximum precipitation is in August, with an annual average above 1 500 mm. More to the north, at the level of Lake Chad, the climate is of Sudano-Sahelian type (cool dry season - hot dry season - wet season) because the ITCZ only reaches this zone in July-August, a period during which total average precipitation barely exceeds 300 mm. Finally, in the northern half of the LCB, the climate is of Sahelo-Saharan type and precipitation is negligible. Annual average temperatures, above 25°C over the whole basin, tend to increase towards the south but in a relatively moderate way (Gac, 1980).

Since the late 1960s, the whole of West and Central Africa has been affected by a drought of exceptional duration, intensity and extent (Ardoin-Bardin, 2004). As a result, particularly in the LCB, annual precipitation has considerably decreased (Figure 2).

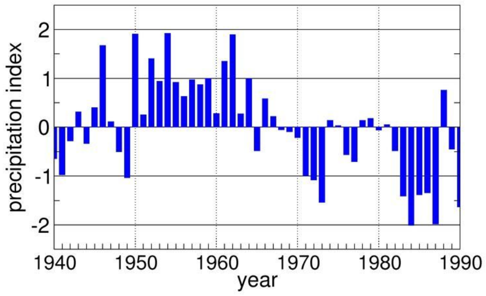


Figure 2. Precipitation index of the Lake Chad catchment area for the period 1940-1990

Hydrography of the LCB

Only the southern part of the LCB is hydrologically active. This zone extends over 700 000 km^2, of which 600 000 km^2 correspond to the Chari and Logone sub-basins. The source of the Chari, the largest river in the LCB, is in the Yadé Mountains of the Central African Republic. The Logone rises in the Adamoua Massif in the Cameroon and joins the Chari at N'Djamena, after having crossed vast floodplains, the Yaérés. After the confluence of the two rivers, the Logone-Chari takes on a delta-like appearance and its water flows into Lake Chad.

While there are considerable annual and inter-annual variations, the annual discharge of the Logone-Chari for the period 1956-1975 was 1 200 m^3/s, 60% of which was from the Chari and 40% from the Logone (Gac, 1980). The low-water period lasts from December to June and flooding reaches its maximum levels in September-October (Figure 3). Between 1975 and 1990, the drought led to a reduction in the volumes transported by the river, with the average annual discharge falling to less than 700 m^3/s.

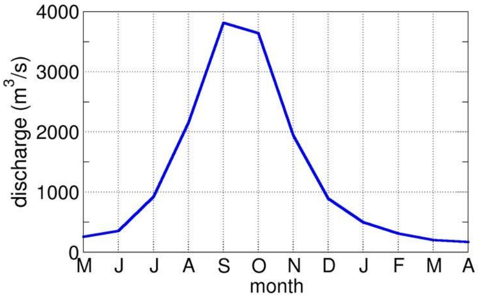


Figure 3. Annual Chari-Logone discharge during the period 1956-1975 (Gac, 1980)

Morphology of Lake Chad

The morphology of the lake is very irregular, and two main parts can be distinguished (cf. Figure 4): the South Basin and the North Basin, separated by a zone of sand spits: the Great Barrier, covered in dense vegetation (Lemoalle, 2004). When the water level is low, this barrier can emerge, leading to the separation of the lake into two independent basins. The North Basin is then fed by the low discharges of the Komadougou Yobé, whereas the South Basin receives the more abundant water of the Chari-Logone.

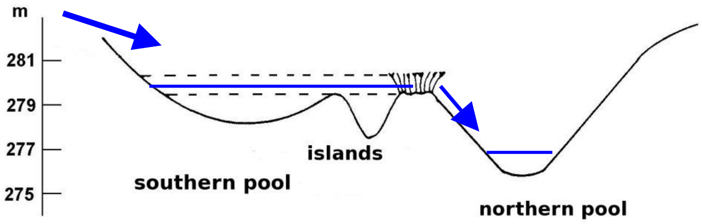


Figure 4 . SE-NW profile of the lake when separated into two basins

The Water Balance of the Lake Chad Basin

The water balance of the lake is represented in Figure 5. The data was compiled from several studies: Roche (1973), Gac (1980), Vuillaume (1981), Olivry et al. (1996). During the period preceding the 1970s, the Chari-Logone supplied Lake Chad with nearly 90% of its tributary water, a volume of 37 km^3/yr. The other significant tributary into the lake is the intermittent Nigerian river the Komadougou Yobé. Its discharges are nonetheless very much lower than those of the Chari-Logone (average annual discharge estimated at about 20 m^3/s for the decade 1960-70, i.e. about 1 km^3/yr). Precipitation over the lake contributes 6 km^3/yr. Concerning losses, evaporation is the dominant process, accounting for an average annual volume of 43 km^3/yr. Losses due to infiltration are estimated at 3 km^3/yr.

Concerning the period 1970-1990, we can estimate that the lake's inflows and outflows were globally halved with respect to the period prior to the 1970s.

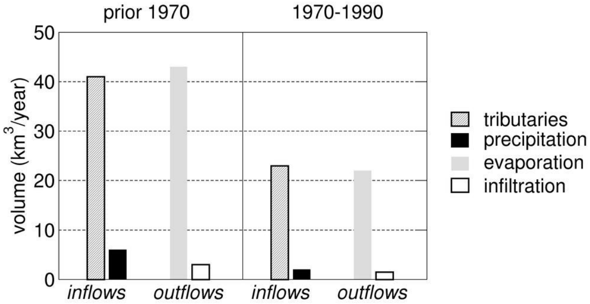


Figure 5. Annual water balance of Lake Chad inflows and outflows before and after the drought of the 1970s

HYDROLOGICAL MODELLING OF THE LAKE CHAD BASIN

The selection of an appropriate hydrological model for the Lake Chad Basin is subject to three constraints:

- the need for a spatialised model to take into account the spatial heterogeneity of the basin and the climate forcing;
- the capacity of the model to simulate the hydrological functioning of depressions and extreme variations in lacustrine water level;
- the possibility of developing and testing specific modules within an existing code.

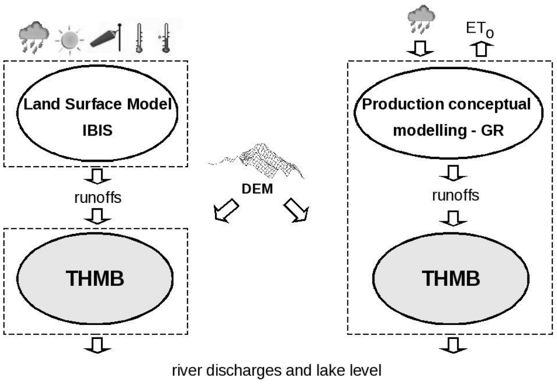
For these reasons, we opted for the Terrestrial Hydrology Model with Biogeochemistry (THMB, formerly HYDRA) developed by Coe (1999).

The THMB model

This model (cf. Figure 6a), which applies to spatially discretised catchment areas, enables differentiation between flooded entities, “lakes”, where water can accumulate, and "catchment" entities where water runs off. Each entity is redefined at each time step, according to the calculated volume of water in each grid cell of the basin. The input data for the THMB are of three types:

- surface and sub-surface runoffs, calculated “off line” using the IBIS Land Surface Model (Foley *et al.*, 1996) on the “catchment” grid cells;
- rainfall and evaporation, for calculating water flows on the “lake” grid cells;
- data describing the elevation: altitude, potential depressions and their outlets, drainage network~~s~~.

For each “catchment” grid cell, the water flow is simulated by combining three linear reservoirs: surface and sub-surface runoffs and the flow coming from upstream grid cells. The water is thus channelled by the hydrographical network towards the outlet. If the water crosses a depression, it is stored in the corresponding “lake” grid cells and is subject to rainfall and evaporation fluxes. It should also be noted that a grid cell can be both “catchment” and “lake”, expressed by a coefficient between 0 and 1 in function of the water volume of the grid cell and its geomorphology. The THMB therefore enables simulation, at each time step, of the water flows through all the grid cells and of the position, surface area and volume of the flooded zones.

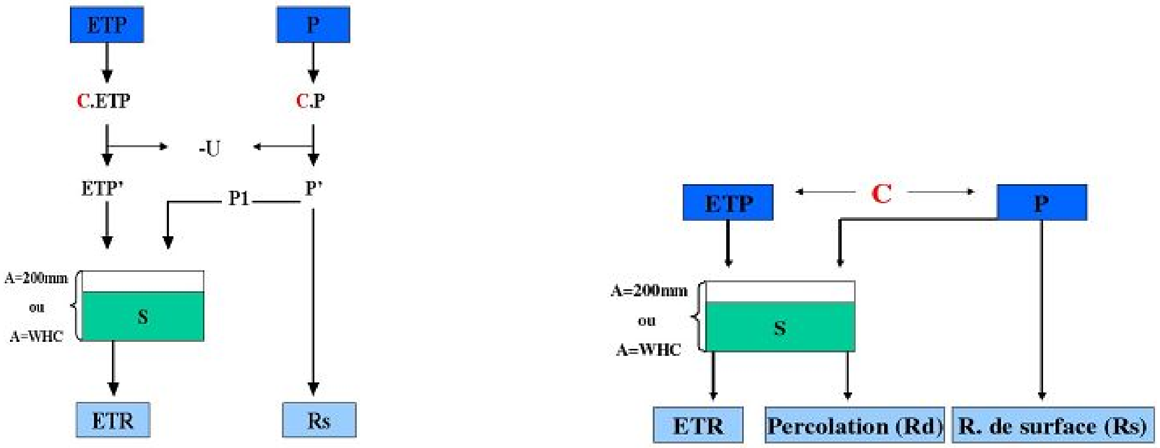


a) THMB *b) GR+THMB*

Figure 6. The two versions of the model used for Lake Chad Basin

The GR+THMB Model

The IBIS model calculates runoffs using equations expressing the water, radiation and vegetation physical exchange processes between the atmosphere and the land and water surface. Consequently, a large amount of climate forcing data must be precisely documented. Due to the vast extent of the LCB and the scarcity of measurements, these data are generally unavailable and cannot be precisely estimated. Moreover, we only had one set of IBIS data at our disposal, which limited the sensitivity tests of the model. We therefore developed a module in the THMB for the direct calculation of runoffs based on Precipitation, P, and Reference Evapotranspiration, ET_0, integrating the GR monthly time step concepts of the production functions developed by Makhlouf and Michel (1994). These concepts, illustrated in Figure 7, are based on a “soil” reservoir from which surface runoff and, possibly, sub-surface runoff (percolation) are calculated.



a) GR_A: production function (Makhlouf and Michel, 1994)

b) GR_B: production and percolation function (Mouelhi, 2003)

Figure 7. Production functions of the GR model. C is the interception coefficient

The forcing data, P and ET_0, are adjusted by multiplying them by an interception coefficient, C. A quantity U is then subtracted from the adjusted inflows. A proportion of the adjusted and neutralised total rainfall feeds into the "soil" reservoir, in function of its level and maximum capacity A. This reservoir empties through Real EvapoTranspiration (ETR), calculated from S and A, together with the adjusted and neutralised ET_0 (ET_0'). The fraction of the rain which does not feed into the "soil" reservoir, Rs, is the surface runoff. Subsequently, a percolation term, assimilated to a sub-surface runoff generator, was introduced by Mouelhi (2003).

Following on from the work of Ardoin-Bardin (2004) and Delclaux *et al.* (2005), the maximum capacity of the soil reservoir, A, was calculated based on the Water Holding Capacity (WHC) maps from FAO, spatialised on a global scale.

DATA

The IBIS surface and sub-surface runoff data were obtained from simulations carried out by Li *et al.* (2004) for West Africa. Precipitation data were obtained from the Climatic Research Unit (CRU) in the form of a chronology of monthly rainfall grids, resolution 0.5°. The reference evapotranspiration ET_0, assimilated to the evaporation of an open water surface, was calculated by applying the Penmann formula to the CRU climate data.

The data concerning the elevation were obtained from the SRTM30 Digital Elevation Model (resolution 30'') derived from the topographical mission of the space shuttle in February 2000. These data were aggregated to 5' (~10km) by means of the nearest neighbour method in order to be used in the models. The GRASS GIS was used to store and generate the derived geomorphological data: altitude, drainage directions, potential accumulation zones and associated outlets.

Irrigation data are very poorly documented. We applied 2 scenarios:

- the estimation of Vuillaume (1981), corresponding to a withdrawn volume of 2.5km^3/yr as from 1965, with seasonal modulations;
- Coe and Foley (2001) conserved these estimations, but with a considerable increase as from 1980 (11 km^3/yr).

RESULTS

Calibration and Validation of the GR+THMB Model

In accordance with the conclusions of Ardoin-Bardin (2004), the calibration and validation periods were

1954-1963 and 1963-1967 respectively. The inflow adjustment coefficient C was set manually in order to maximise the Nash criterion function for the monthly flows of the Logone at Laï, the Chari at Bousso and the Chari-Logone at N'Djamena for the period 1954-1963. The maximum performances, achieved for different values of C at each of these stations, varied according to the model (Table 1). While the performances of the GR_A+THMB and GR_B+THMB were very close in the case of the Logone, the latter model gave considerably higher results for the modelling of the flows of the Chari at Bousso and N'Djamena (+8% and +5% respectively). This observation was confirmed over the validation period (1964-1967).

The water balance criteria indicate that, at all stations, the simulated volumes were considerably under-estimated compared to the observations (-20% to -35% over the calibration period) (Table 1): this is mainly due to an under-estimation of low-water flow. However, at Bousso and N'Djamena, GR_B+THMB modelled more closely the water balances observed.

The introduction of a percolation term therefore improved the performances of the GR model.

Spatial Variability of Parameter C

The optimum values of parameter C in the GR_B+THMB simulations varied considerably between the Laï (0.55) and Bousso (0.25) stations. At the scale of the Logone and Chari sub-basins, this parameter is thus associated with spatially variable processes that can be characterised by "semi-distributed" calibration. A specific calibration for the Logone and Chari sub-basins increased the Nash coefficient from 74.7 to 79.3, calculated at N'Djamena at the Chari-Logone confluence (Figure 8).

Table 1. Comparison of performances of the GR_A-THMB and GR_B-THMB Models

Model	***Station***	***Value of Parameter C***	***Nash Criterion (%) Calibration (1954-1963)***	***Nash Criterion (%) Validation (1964-1967)***	***Water Balance Criterion (%) Calibration (1954-1963)***	***Water Balance Criterion (%) Validation (1964-1967)***
GR_A-THMB without percolation	Laï (Logone)	0.575	61.4	72.6	-21.9	-13.4
	Bousso (Chari)	0.275	46	43.4	-35.8	-45.2
	N'Djamena	0.3	69.8	73.6	-32.4	-38
GR_B+THMB with percolation	Laï (Logone)	0.55	62.3	73.9	-22.6	-13.7
	Bousso (Chari)	0.25	53.6	50.2	-33.5	-41.4
	N'Djamena	0.275	74.7	77.6	-29.6	-35.5

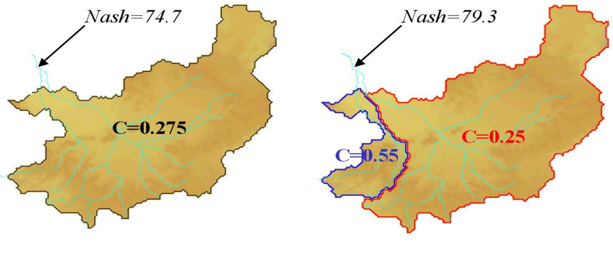


Figure 8. Calibrations of the GR_B+THMB Model: "global" over the Chari-Logone basin and "semi-distributed" over the Chari and Logone sub-basins.

Comparison of the THMB and GR+THMB Models

Table 2 compares the results of the simulation of monthly flows using the GR+THMB (with percolation) and the THMB (plus IBIS) models for the period 1954-1963. The increase in the Nash index (+ 60%) shows a clear improvement provided by the introduction of the GR module into the THMB model. However, as seen in Figure 9, comparison of the simulated hydrograms shows that in both cases the low-water flows were greatly under-estimated. For the GR+THMB model, this result corresponds to the negative values of the water balance criterion in Table 1.

Table 2. Comparative Performances of the GR_B+THMB Model and the IBIS+THMB at N'Djamena: Nash Criterion (%) for the period 1954-1963

Model	GR_B+THMB	THMB (+IBIS)
Nash Index (%)	74.7	46.7

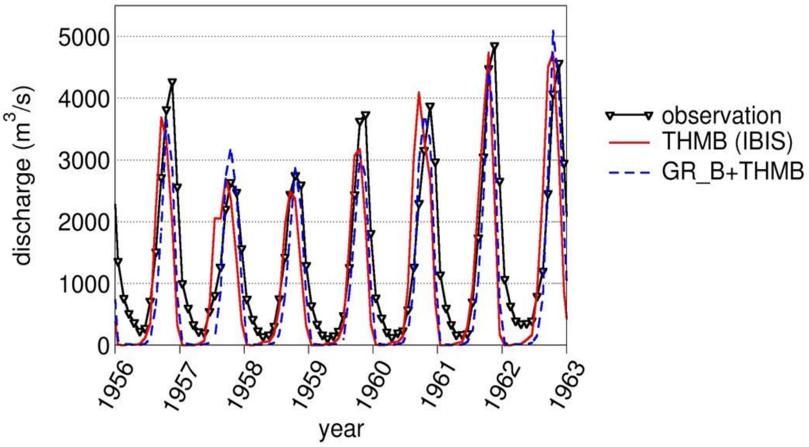


Figure 9. Observed and simulated discharges by GR_B+THMB and THMB+IBIS for the Chari-Logone at N'Djamena.

MODELLING THE WATER LEVEL OF LAKE CHAD

In the following part, we present a sensitivity study of the modelling of the water level of Lake Chad. In the current state of work, we cannot claim to have a model capable of accurately simulating the dynamics of the lake. On the one hand, while the discharges of the Logone-Chari were adequately simulated, the low-water flows were greatly under-estimated, in the order of 30%. On the other hand the dynamics of the lake result from a combination of several processes such as the percolation of ground water, evaporation and the contribution of other inlets (Komadougou, El Beïd, etc.). Moreover, a good description of the bathymetry is also required. We shall now present three examples of the sensitivity of the lake level simulated with GR_B +THMB model to 1) irrigation scenarios; 2) elevation field (DEM); 3) lake infiltration.

First of all, Figure 10 presents the results of the model obtained without irrigation using the original DEM, i.e. the aggregated SRTM30''. Despite the deficit in the Logone-Chari inflow, the simulated lake levels are in good agreement with the observations. This is due to an over-estimation of the various inflows around the lake, particularly the discharge of the Komadougou. However, it is not currently possible to calibrate the model for this river because it is very highly anthropised in its Nigerian section (the Kano region) where numerous dams and irrigation networks have been constructed about which we lack information. In addition, we can note that the model accurately simulates the drop in water level of the lake, which started in the mid 1960s and became accentuated during the drought of the 1970s.

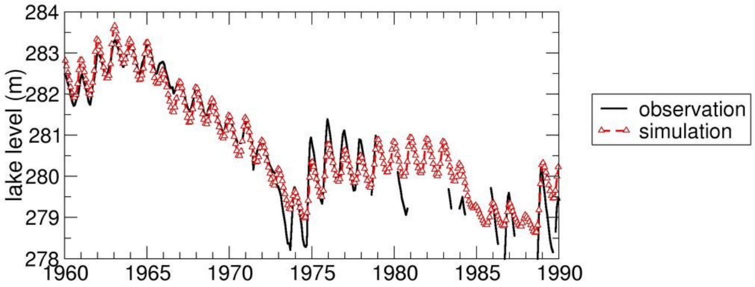


Figure 10. Water level of Lake Chad simulated by the GR_B+THMB model

Irrigation scenarios

For this study, we chose to integrate overall irrigation to the water level of the lake because we did not have sufficiently precise knowledge of the localisation and types of water extraction used. Two scenarios were used. The first, described by Vuillaume (1981), is characterised by an annual volume of 2.5 km^3/yr modulated by a monthly parameter (Table 3). This extraction rate started in 1965. The second scenario (Coe and Foley, 2001) is identical to that of Vuillaume, but with a total annual volume of 11 km^3/yr as from 1980.

The simulation results, represented in Figure 11, effectively show a drop in the water level of the lake compared with simulation without irrigation. In addition, in accordance with the scenario of Coe and Foley, this drop increases as from 1980, reaching approximately 0.5 m. While this drop may seem relatively small, it is far from negligible by comparison with the average depth of the lake, 3 to 4 m. Confronted with these results, we unfortunately lack development data for validating or invalidating the scenarios. However, that work must incontrovertibly be carried out in the perspective of an increase in the utilisation of water resources at the scale of the whole basin.

Table 3. Monthly weightings of the irrigation function (Vuillaume, 1981)

	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	March	Apr.
coef.	0.08	0.15	0.1	0.08	0.1	0.08	0.08	0.07	0.09	0.07	0.04	0.05

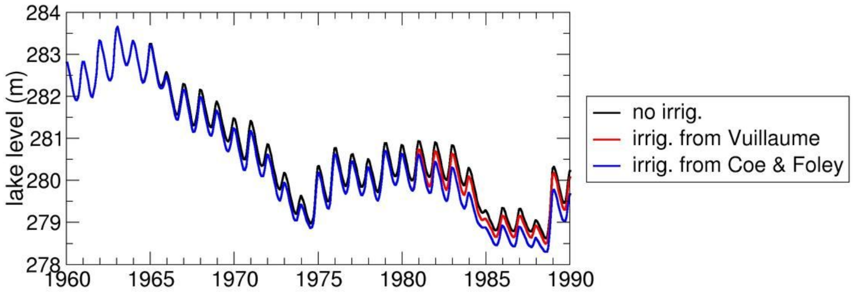


Figure 11. - Influence of irrigated volumes on the simulated water levels of Lake Chad compared to the simulation carried out without irrigation

Elevation field (DEM)

The work of Le Coz *et al.* (under revision) has shown the importance of taking elevation spatial variability into account for simulating the water levels of the lake. This is illustrated by Figure 12, in which three examples of simulations are represented. In the first case, we used DEM SRTM30'' aggregated to resolution 5' using the nearest neighbour method. In the second case, DEM SRTM3'' was filtered in advance on a 40''x40''window then aggregated using the nearest neighbour method. For comparative purposes, a third simulation obtained with DEM SRTM3'' aggregated to 5' using the mean method, is also presented in this figure.

The first two simulations, obtained using the nearest neighbour method, give very similar results, even if the difference between the curves can reach 0.5 m. However, the utilisation of SRTM3'' aggregated using the mean operator shows a considerable over-estimation of the levels, due to excessively high inflows from the basin. This result is due to the fact that the mean aggregation algorithm does not take depressions sufficiently into account: the aggregated elevation field is over-smoothed, masking the depressions. These water storage zones, particularly in the rainy season and during flooding of the Logone-Chari correspond to losses because the water is recycled into the atmosphere. Since these losses are not taken into account, inflows and consequently the water levels of the lake are greatly over-estimated.

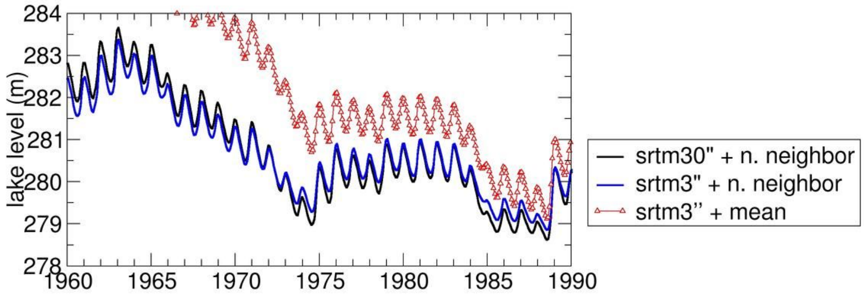


Figure 12. Influence of the modelling of elevation on the simulated water levels of Lake Chad with SRTM DEM aggregated to resolution 5'

Lake infiltration

According to Roche (1973) and Vuillaume (1981), the lake is the high point of the region's hydrogeological system. Given these conditions, the lake is in the situation of providing ground water by infiltration processes whose volume has been estimated at 3 km^3/yr before the drought period of the 1970s. In order to take these process into account, we introduced into the model the calculation of a "surface water to ground water'' flow in the form of a term proportional to the surface area of the grid cell and the load (or water height). The proportionality coefficient, or conductance coefficient, C (s^{-1}), was calibrated to correspond to the estimated volumes of 3 km^3/yr.

Figure 13 shows two curves obtained using two different values of coefficient C, 10-9s^{-1} and 5.10-9 s^{-1}, corresponding to infiltrated volumes of 1.3 and 3.4 km^3/yr respectively. The water levels thus calculated are much lower than the levels simulated without infiltration. However, the infiltrated volumes used are insufficient to explain these drops in levels. As a matter of fact, the infiltration model applies to all free water surfaces, Lake Chad, local depressions and flood zones. Then, the simulated water levels of the lake include not only infiltration losses from the lake itself, but also from all the temporary lakes in the LCB contributing to the filling of the lake by means of the drainage network. Without doubt, the conductance value of 5. 10-9 was over-estimated. Nonetheless, it is clear that supplementary information concerning the hydrogeology, not only under the lake but also all floodable zones, is indispensable for correctly simulating the dynamics of the lake.

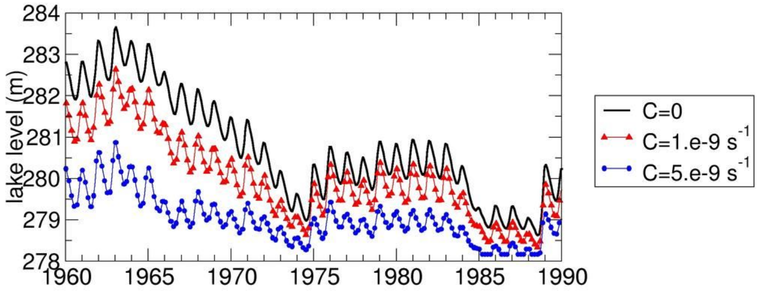


Figure 13. Simulation of lake water levels taking ground water infiltration into account by means of a conductance coefficient

CONCLUSIONS

Studying the dynamics of a hydrosystem such as that of Lake Chad is extremely complex due to its large size and the climatic variability of the region. Moreover, the shallowness of the lake makes it extremely sensitive to any modification of inflows or outflows. Finally, the "transboundary" location of the LCB does not facilitate the collection and homogenisation of the data required for modelling: this is a difficulty confronted by the LCBC, the Lake Chad Basin Commission, charged with coordinating the management and development of the lake. These difficulties require a long-term approach, in which hydrological modelling and data collection must be carried out together.

We have presented and compared the results of two models. The first model, THMB, is based on the routing of runoffs calculated off-line using an LSM. The second, GR+THMB, includes a GR type production function, and propagates the calculated flows towards the lake. With regard to the current period, the second model, calibrated using observations, provides a better simulation of the discharges of the Logone-Chari system. However, this type of model is limited to a narrow time context and must be considered to require a constant parameterisation. In the framework of contrasting situations, such that of the Humid Holocene (5 KY BP) or a future subject to considerable climatic changes, the current parameterisation is likely to be no longer relevant: the complementary approach using an LSM type model would thus be appropriate for describing the evolution of the soil-atmosphere interface and therefore runoffs, among other factors.

Limiting ourselves to the current epoch, the sensitivity tests carried out on the forcing of various settings and processes such as irrigation, relief and infiltration, show that we must be extremely prudent with respect to the interpretation of results concerning the evolution of the lake. These results above all show the need to correctly simulate all the lake's inflows and outflows: tributaries, precipitation, evaporation and infiltration. Concerning the elevation, it can now be correctly modelled by means of the work carried out on the filtering and aggregation of the MNT SRTM3''. On the other hand, the sensitivity of the model to extraction for irrigation and the relations between the lake, rivers and ground water shows that these two aspects must now be developed, in terms of both their conceptualisation and the acquisition of data. This work must cover the whole region of the lake together with the catchment areas of the Chari, Logone and Komadougou. It is essential to improve this knowledge if we really want to assess the relative impacts of climatic change and anthropic activities on the present and future situation of Lake Chad.

REFERENCES

Ardoin-Bardin S. (2004) Variabilité hydroclimatique et impacts sur les ressources en eau de grands bassins hydrographiques en zone soudano-sahélienne. Thèse de doctorat. Université de Montpellier 2. 340 p.

Carmouze J.P., Lemoalle J. (1983) The lacustrine environment. Lake Chad: Ecology and Productivity of a Shallow tropical Ecosystem, Eds. Carmouze J.P., Durand J.-R., Lévêque C. Dr W. Junk Publishers, The Hague (Netherlands), 575p.

Coe M.T., Foley J.A. (2001) Human and natural impacts on the water resources of the Lake Chad Basin. Journal of geophysical research, vol.106, No. D4, 3349-3356.

Coe M.T. (1999) Modeling terrestrial hydrological systems at the continental scale: testing the accuracy of an atmospheric GCM. Journal of Climate vol. 13, 686-704.

Delclaux F., Schweblin M., Coudrain A., Condom T. (2005) Linking lacustrine dynamics to climate variability: application to lake Titicaca basin, South America. EGU, General Assembly 2005, 24-29 avril 2005, Vienna, Austria.

Foley, J.A., Prentice I.C., Ramankutty N., Levis S., Pollard D., Sitch S., Haxeltine A. (1996) An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics Global Biogeochemical Cycles, Volume 10, Issue 4, p. 603-628

Gac J.Y. (1980) Géochimie du bassin du lac Tchad. Travaux et Docu. ORSTOM 123, Paris, 251 p.

Isiorho S.A., Matisoff G., When K.S. (1996) Seepage relationships between Lake Chad and the Chad aquifers. Ground Wat. 34(5): 819-26.

Leblanc M., Favreau G., Nazoumou Y, Leduc C., Stagnitti F., Van Oevelen P., Delclaux F., Lemoalle J., Maley J. (2006) Reconstruction of Megalake Chad using February 2000 Shuttle Radar Topographic Mission data. Palaeogeography, Palaeoclimatology, Palaeoecology (239), 16–27.

Le Coz M., Delclaux F., Genthon P., Favreau G. (under revision) Sensitivity of watershed simulations to relief aggregation in the case of a flat basin, Lake Chad, Africa. Computers ’Geosciences

Lemoalle, J. (2004) Lake Chad: a changing environment. In Nihoul J.C.J., Zavialov P.O., Micklin P.P. (Ed.) Dying and Dead Seas, Kluwer Academic Publishers, pp. 321-340.

Li K.Y., Coe M.T., Ramankutty N. (2004) Investigation of hydrological variability in West Africa using land surface models. Journal of Climate 18 (16), 3173-3188.

Magrin G. (2008) Le lac Tchad n’est pas la mer d’Aral. (http://www.mouvements.info/spip.php?article201)

Makhlouf Z., Michel C. (1994) A two-parameter monthly water balance model for French watersheds. Journal of Hydrology, 162, 299-318.

Mouelhi S, (2003) Vers une chaîne cohérente de modèles pluie-débit conceptuels globaux aux pas de temps pluriannuel, annuel, mensuel et journalier. Thèse de Doctorat, ENGREF, Cemagref Antony. 323 p.

Olivry J.C., Chouret A., Vuillaume G., Lemoalle J., Bricquet J.P. (1996) Hydrologie du lac Tchad. Monographie hydrologique 12. ORSTOM éditions. 266 p.

Perrin C. (2000) Vers une amélioration d'un modèle global pluie-débit au travers d'une approche comparative. Thèse de doctorat. INPG(Grenoble) / Cemagref (Antony), 530 p.

Roche M.A. (1973) Traçage naturel salin et isotopique des eaux du système hydrologique du lac Tchad. Paris : ORSTOM. 398 p.

Roubinet D. (2007) Variabilité hydrologique du lac Tchad : passé, présent et perspectives. Sujet de synthèse bibliographique. M2 R2E. Université de Montpellier 2. 14 p.

Vuillaume G. (1981) Bilan hydrologique mensuel et modélisation sommaire du régime hydrologique du lac Tchad. Cah. ORSTOM, sér. Hydrol., vol. XVIII, n°1, 23-72.