Impacts of climate variability and population pressure on water resources in the Lake Chad Basin

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Abstract

The Lake Chad Basin is located in the central part of northern Africa and expands over Niger, Nigeria, Cameroon, Central African Republic, Chad, Sudan, Libya, and Algeria. It is an endorheic basin of about 2,300,000 km^2 with hyper-arid to arid climate in the north, semi-arid or sahelian in the centre, and subtropical in the south. Mean annual precipitation varies from less than 50 mm in the north to over 1,000 mm in the south. High temperatures throughout the whole year lead to levels of annual evapotranspiration of around 2,200 mm.

From the hydrological point of view, the basin is subdivided by the 14° north parallel into an inactive basin in the north and an active in the south. Two main river sub-basins feed the Lake Chad, the Chari-Logone that brings water from the South and the Komadugu-Yobe that flows mostly in a west-east direction along the Sahel zone. Both hydrological sub-basins are very sensitive to climatic variability and sort of over-react to droughts, which are well-known as devastating in the region. For example, the last long-term drought period from 1973 to 1984 led to the reduction of the lake open water surface from 17,620 km^2 to 1,920 km^2.

This work will show the effect of climate variability on water availability for the last 60 years based on field data. Precipitation has increased since the mid-80's to reach almost the levels of pre-drought. However, due probably to ground water level decline and population pressure, discharges do not increase as expected and the lake does not recover.

Keywords
Lake Chad Basin, Sahel region, climate variability, river discharge

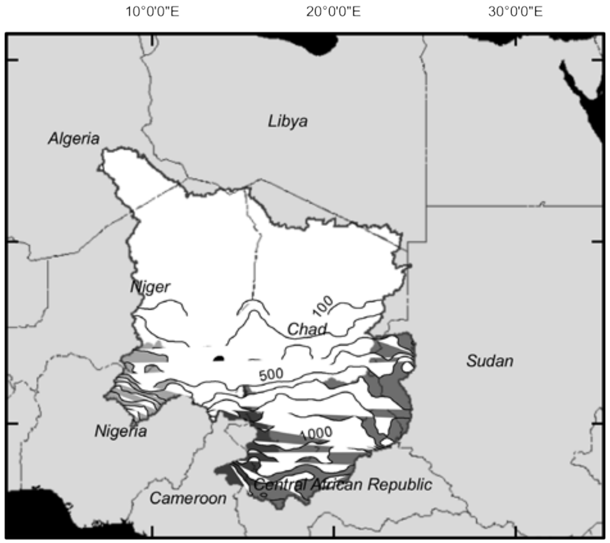
Introduction

Following a period of reduced rainfall (70ies and 80ies) with severe droughts during 1973 and 1984 Lake Chad, a terminal fresh water lake at the fringes of the Sahara Desert, did not recover from a substantial drop of its lake level that reduced its open water area from about 17,620km^2 to 1,920km^2. The open water area is currently limited to a southern pond separated from a deeper, northern pond by a morphological barrier. The low rainfall period and the following years after 1984 were not only marked by high precipitation variation and a temperature increase of approximately 1°C, but also saw a significant population increase, leading to extensive dam constructions, ground water pumping, and land cover / land use changes.

Main tributaries to Lake Chad are the Chari and Logone River (Figure 1). Minor contribution used to come from the Komadugu-Yobe River whose discharge, however, has become insignificant during recent years because of flow retention and diversions. All river systems are linked to extensive wetland systems that are believed to play a crucial role in ground water recharge.

Several authors claim Lake Chad to be predominantly precipitation driven (Chouret and Mathieu, 1976; Lemoalle et al., 2005; Olivry et al., 1996) concluding, it will recover as precipitation amounts increase. We argue that ground water, and its lowering in particular, has become a critical factor in the water balance of Lake Chad. At this stage we are collecting evidence from different data sources with the aim to identify relevant parameters and understand the mechanisms and feed backs that control the lake level of Lake Chad. With only limited ground water data available, evidence comes from the analyses of satellite data, lake level measurements, climate- and river discharge

Figure 1. Location Map Lake Chad Basin.



data, isotope and chemical analyses, comparative studies, and results from hydrologic modelling. From our findings we intend to construct a model that includes a surface – ground water exchange component that will explain water level variations.

Impacts of post-drought precipitation increases

Biomass

The most visible change since the droughts of the 70ies and 80ies is the strong rebound of green biomass in the northern Sahel (Anyamba and Tucker, 2005; Hermann et al., 2005). A trend analyses (1982 – 2006) of the annual maximum NDVI (Normalized Difference Vegetation Index, used as a surrogate for green biomass) taken from AVHRR satellite data[1] shows biomass increases of up to 70% (Figure 2). The pattern of strong biomass increases north of the 600mm isohyete and more or less unchanged biomass values south of it expands from the West coast of the African continent to Ethiopia. As shown in Figure 3 for an area in the Lake Chad Basin, biomass increases are strongly linked to increases in precipitation (use of fertilization in the region is very low and can thus can be discarded).

Using an approach described in Evans and Geerken (2004), we can show that many areas even respond increasingly better to rainfall, indicating improving growing conditions for vegetation.

As already indicated this development is most apparent in the northern Sahel. Though these areas do not form a substantial surface water contribution to Lake Chad, they most strikingly emphasize the positive changes the region experienced during the past two decades.

Different to the overall biomass improvement in the northern Sahel, we see several anomalies indicating deteriorating vegetation covers that do not fit into the general trend of precipitation increase. The largest such area, showing the strongest, negative trends are the Manga Grasslands, west of Lake Chad. Figure 3 displays graphs of biomass (annual NDVI maximum) and precipitation averaged over the deteriorating area. Biomass and precipitation are strongly correlated until 89 but the relationship becomes rather erratic from 89 onwards. While precipitation continuously increases, biomass decreases. For the sudden decoupling between precipitation and biomass we have only one explanation that is a drop of the ground water level, disconnecting vegetation from its water supply. Overgrazing and population pressure could also be driving forces, but they are homogenous and strong everywhere and not only in the Manga Grasslands.

[1] The normalized difference vegetation index (NDVI) is a product derived from the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17.

Edmunds et al. (1999) describe the elevated area of the Manga Grasslands as a net recharge area for Lake Chad, indicating that there is a connection between ground water and Lake Chad. However, this information does not provide an explanation what is the cause of the ground water drop (ground water pumping, reduced ground water renewal, dropping lake levels) or what may be cause and what may be consequence inside the system of ground water and lake levels.

Climate, river discharge

The comparison of precipitation anomalies with river discharge anomalies shows how minor changes in precipitation cause significantly larger river discharge variations (Figure 4). This is probably an intrinsic characteristic of the sub-watersheds, defined by the water holding capacity of their soils, their infiltration-, and run-off characteristics. Since the mid 80ies we see a continuous recovery of annual precipitation, a trend even more strongly reflected in river discharge amounts. In all sub-watersheds shown, except Bahr Azoum which has a larger share of areas with a semi-arid climate, vegetation remains unaffected from this trend, due to generally high precipitation amounts in the southern sub-watersheds and/or a deeper rooting vegetation covers.

The open water area in the southern pond of Lake Chad remained more or less unaffected by these trends as water levels cannot increase beyond the spill point that transfers water into the northern pond once water level reaches a height of about 281m above mean sea level (m amsl). Water spilling over into the northern, deeper pond rarely forms open water bodies but rather densely vegetated, seasonal or perennial wetlands. Similar areas that are densely grown by typha are found in the southern pond. Their variable spatial distribution and temporal occurrence, as well as uncertainties in the amount of water transpired from the wetland vegetation form a particular challenge in calculating sound water budgets.

To understand the seasonal, spatio-temporal variability of wetland areas, we classified vegetation cycles using an approach described

Figure 2. Annual NDVImax trends between 1982 and 2006.

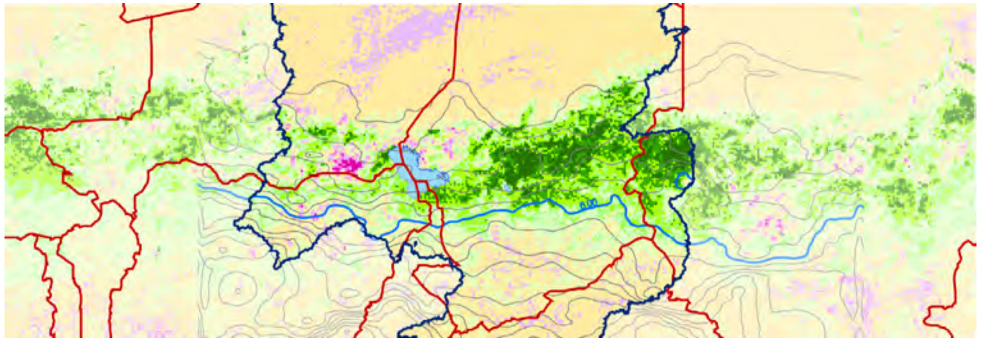
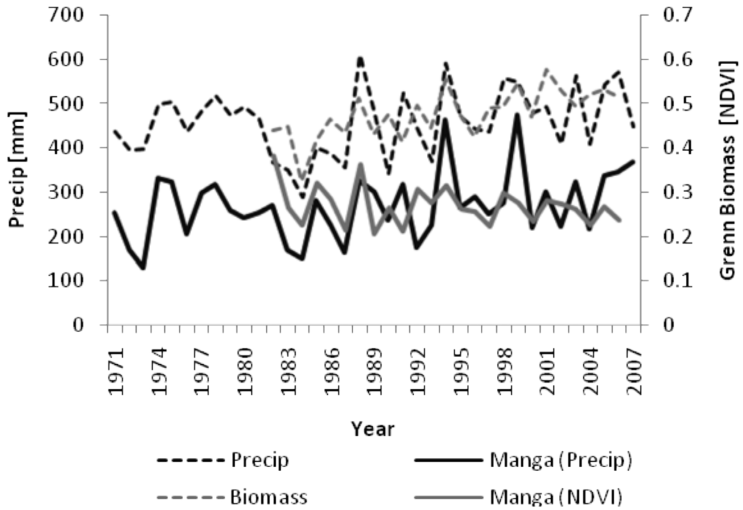


Figure 3. Averaged rainfall and biomass trends for the degrading area of the Manga Grasslands and the improving area east of Lake Chad.



in Geerken (2009). Assuming that vegetation in an arid environment should follow the seasonality of rainfall, any vegetation cover maintaining high biomass amounts beyond the wet season must receive water from some other source. This allows us to track water flow within the shorelines of Lake Chad offering a possibility to approximate water losses due to evapotranspiration and infiltration. Each class in Figure 4 represents distinct phenology (NDVI shape) providing information about spatio-temporal vegetation conditions.

Progression of water flow from the southern to the northern pond becomes visible in a second green up of vegetation cover that occurs after the end of rainy season (graphs with blue arrows in Figure 5) and marks the arrival of the flood wave from the spill over. The induced green up is temporally shifted to later times as we move north. The drop in green biomass after the rainy season may indicate senescence (biological aging of vegetation) or the formation of small, open water bodies from the spill over, creating mixed signatures (vegetation and water) which result in lower NDVI values. The latter is certainly true for the most northern phenology in Figure 4 where NDVI values drop below zero. This area coincides with the deepest part of the 'Lake'.

The timing and the temporal shift in flood arrival also recommends that this water does not originate from the Komadugu-Yobe River but from waters spilling over from the southern pond.

The spill over and spatio-temporal characteristics in wetland distribution will form an essential part in water budget calculations.

Lake level variations

Pre-drought seasonal lake level variations were limited to 0.5 to 1 meter. Today we see seasonal variations of up to 2 meters and more[2]

[2] *Because the gauging station 'Bol' is located at the dead-end of a channel in the archipelago region (to the north of the southern pond), it is disconnected from the main water body during times of low water levels. For studying recent lake level variations we rather relied on satellite altimetry measurements made available by LEGOS (data starts from 1992).*

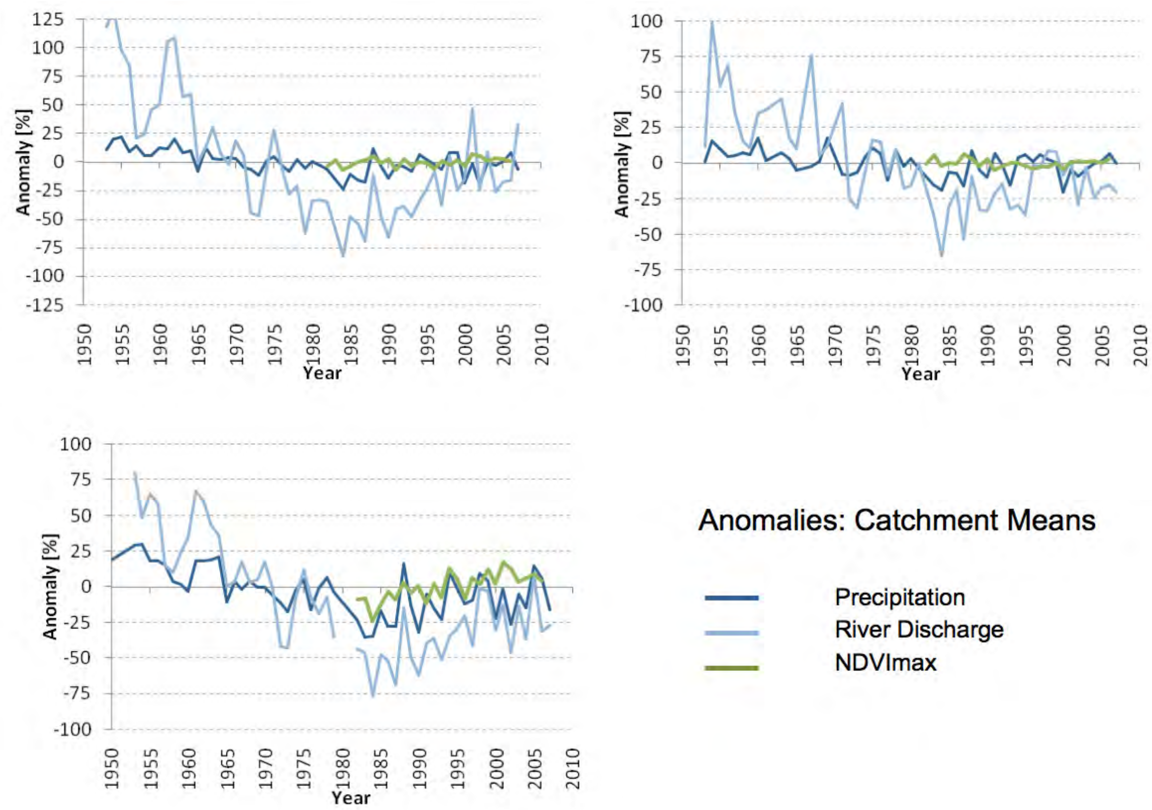


Figure 4. Anomalies calculated from annual means for selected watershed areas: Chari watershed at Mailao (UL), Logone watershed at Logone-gana (UR), and Bahr Azoum watershed at Tarangara (LL).

(Figure 6). Average annual evaporation over the southern pond is around 2480 mm per year. This is too little to explain post-drought water losses leading to lake level drops of up to 2 meters just over a period of seven months. The additional water losses can only be explained by infiltration into ground water, especially considering that the lake lies on a very flat plane of quaternary sands.

In contrast, pre-drought lake level drops are far less than the potential evapotranspiration, with incoming river discharge being too little to explain water level variations. Accordingly, ground water must have recharged the Lake during the dry season. Also, during times of rising lake levels (pre-drought situation), substantial amounts of water from the lake must have recharged the aquifer, as more water was discharged into the lake than could be evaporated from its surface area.

Like during pre-drought times we expect the post-drought lake to loose water to the aquifer when lake levels rise, but we did not calculate this scenario because of likely errors introduced through water losses due to the spill over into the northern pond that we cannot yet quantify. The extraordinary seasonal rise in lake level of up to 2 meters is because river discharge is only discharged into the southern pond until it spills over.

To summarize these finding: the interaction between lake and ground water switched into a different mode, with the lake today permanently loosing water to the underground where there once existed a seasonal exchange of waters between lake and aquifer. While seasonal rainfall controls seasonal lake level variations, ground water level acts on a longer time scale. At lower ground water levels, its stabilizing influence is lost, also increasing water losses from the lake. This we see as a major reason for the slow recovery of Lake Chad which barely responds to the positive trends in rainfall and river discharge since 1984.

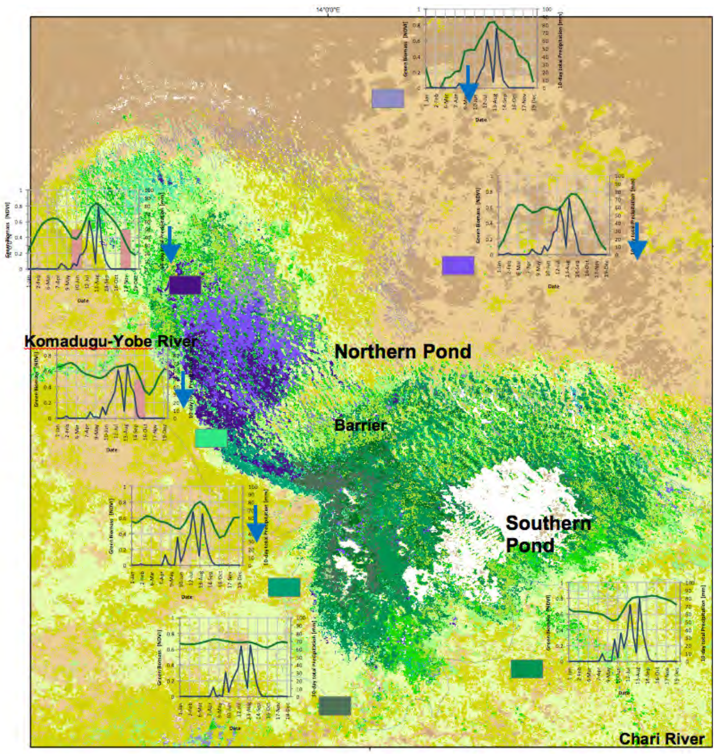


Figure 5. Fourier Component Classification of a MODIS NDVI time series (MOD13Q1) from 2007. NDVI graphs (green line) indicate well watered soil conditions after the end of the rainy season (blue line) and the progression of the flood wave into the northern pond as water spills over from the southern pond once water levels exceed the spill point (~ 281 to 281.5 meters) formed by a natural barrier separating the two ponds. Areas in white colors represent open water (Southern Pond) or unclassified pixels (north of former Lake Chad shore line, blue line).

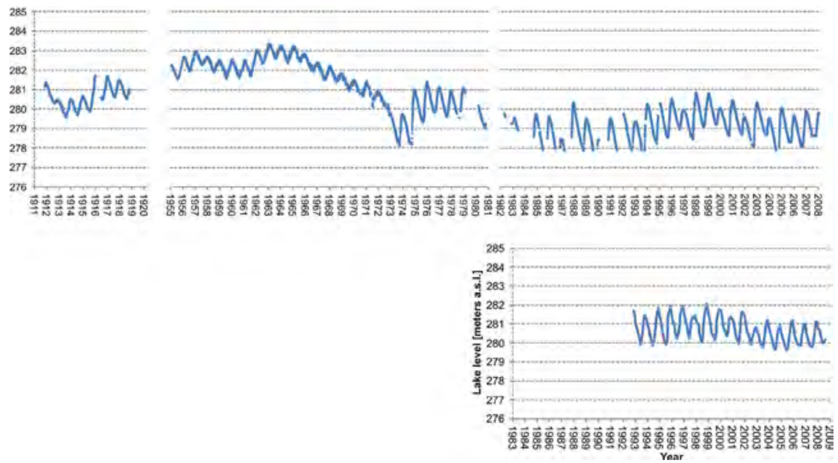


Figure 6. Lake level variations of Lake Chad measured at Bol station (top) and from satellite altimetry measurements (bottom), published by LEGOS.

Isotope/chemical analyses

The connection of Lake Chad to the underlying aquifer has been subject of investigation for many years. However, it is not yet completely understood how ground water and especially regional ground water level fluctuations affect the lake.

Chouret and Mathieu (1996) and Olivry (1996) indicate the presence of a leakage from Lake Chad towards a hydrological depression in the Bol region (NE of the southern basin), which is located some 10 km from the former lake shoreline.

Roche (1970), considering an homogeneous salt content along the lake shoreline, estimates the water losses by percolation along the shoreline at 7.7% to 9.5% of the water input by river discharge and precipitation. Carmouze (1973), using the ion sodium as a stable tracer, calculates water losses through infiltration equivalent to 4% to 7% of the hydrological inputs.

Isiorho and Matisoff (1990) and Isiorho (1996) have shown leakage of Lake Chad towards the SW in the Nigerian territory using sodium as a tracer. They estimated seepage velocities within a range of 0.002 mm/d to 11.7 mm/d (mean value of 1.15 mm/d).

We have performed an intensive environmental isotope campaign (^{2}H and ^{18}O) in the Chadian part of the basin. The results show leakage of Lake Chad towards the SE and the plume is still perceived at distances as far as 80 km from the shoreline (Figure 7).

Lemoalle et al. (2005) report a sulphate concentration of 210 mg/l in lake water measured in February 2004 in the northern pool. Due to the fact that high sulphate concentrations are unusual for rainfall and river water, they propose seepage of ground water as a possible source. However, other than ground water seepage, this may also be caused by dissolving the sulphate that had formed on the surface when water evaporated (surface- or capillary water).

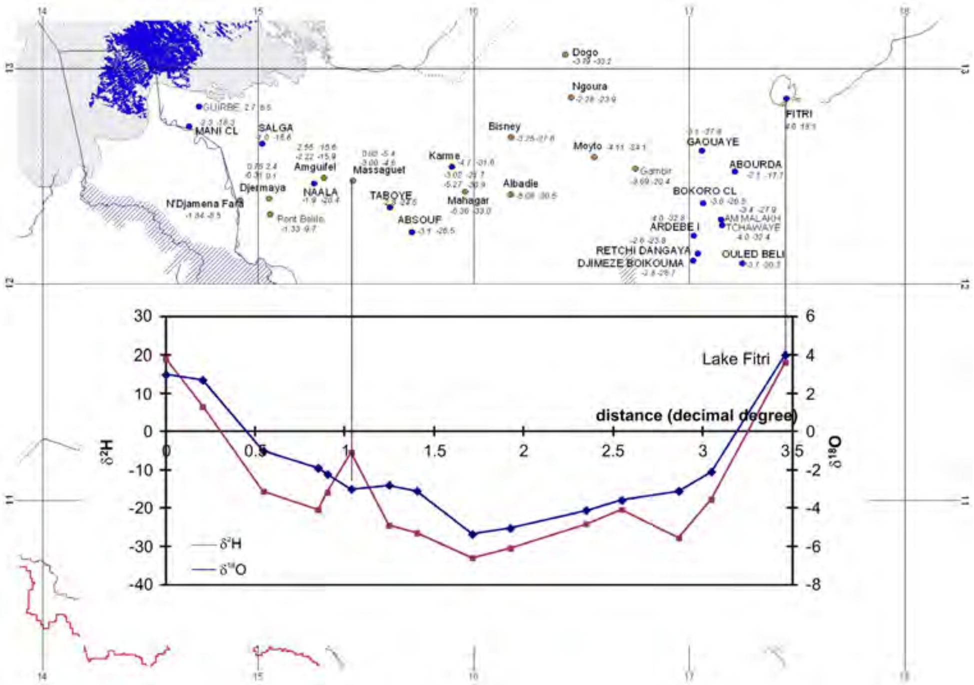


Figure 7. Regional ground water flow direction is indicated by the blue arrows, which is confirmed by the fact that the isotopes δ18O and δ2H decline with increasing distance to the lakes Chad and Fitri. The sudden increase of the isotope values at Massaguet is an indication of recharge by surface water, probably a palaeo-channel from the River Chari (Djoret 2000).

Conclusions

Studies from various authors and our own research clearly show there is an exchange of waters between Lake Chad and ground water. However, because of missing continuous measurements, the seasonally changing mechanisms (discharge and recharge) are not fully understood. Existing data suggest that the lake used to be recharged by ground water during the dry season but lost water to the aquifer during the rainy season. This system showed a stable equilibrium until beginning of the 70ies even during short periods of dryness. Due to the slow responsiveness of ground water to droughts, evaporative losses could be compensated by the aquifer thus ensuring higher lake levels. This system was then disturbed by a long period of reduced rainfall (70ies and 80ies), but also by human interventions that together resulted in lower river discharge rates and lower ground water renewal rates. The construction of dams during the 70ies and 80ies further reduced the discharge of rivers which in turn could not supply downstream wetlands with the water flow that is needed to recharge the aquifers. The situation grew worse through excessive ground water pumping. With the stabilizing effect of ground water gone, the lake is now trying to level the imbalance between lake level and ground water level. Today lake levels are controlled by surface water input, evaporation and infiltration. Our studies and personal communications point to a considerable drop in ground water levels particularly in the Komadugu-Yobe Basin. The Komadugu-Yobe basin is the most densely populated watershed in the Lake Chad Basin. Though, river discharge of the Komadugu-Yobe River was never considered substantial (about 12% of total river inputs) its ground water is likely to have a more crucial influence on the water budget of the lake.

Initial hydrologic model runs where we simulated a temperature increase of 1 to 1.5°C show only minor changes in surface water availability and are far too little to explain the water losses in the lake. This is further supported by the situation of Lake Fitri situated 200km east of Lake Chad. After it almost disappeared in 1984, Lake Fitri fully recovered to its pre-drought extent, more or less excluding a purely climate driven cause. Modelling results also showed that the effective surface catchment area of Lake Chad may actually be too small to support a lake equivalent to its pre-drought size. With a mostly flat topography, run-off is only produced along the basins southern periphery, making ground water a vital component in the preservation of Lake Chad.

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