On the causes of the shrinking of Lake Chad

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Abstract

Over the last 40 years, Lake Chad, once the sixth largest lake in the world, has decreased by more than 90% in area. In this study, we use a hydrological model coupled with a lake/wetland algorithm to simulate the effects of lake bathymetry, human water use, and decadal climate variability on the lake’s level, surface area, and water storage. In addition to the effects of persistent droughts and increasing irrigation withdrawals on the shrinking, we find that the lake’s unique bathymetry—which allows its division into two smaller lakes—has made it more vulnerable to water loss. Unfortunately the lake’s split is favored by the 1952–2006 climatology. Failure of the lake to remerge with renewed rainfall in the 1990s following the drought years of the 1970s and 1980s is a consequence of irrigation withdrawals. Under current climate and water use, a full recovery of the lake is unlikely without an inter-basin water transfer. Breaching the barrier separating the north and south lakes would reduce the amount of supplemental water needed for recovery.

Keywords: Lake Chad, lake bathymetry, irrigation, climate variability, hydrological model, inter-basin water transfer

1. Introduction

Lake Chad, once the sixth largest lake in the world, straddles the borders of Nigeria, Chad, and Cameroon. It is a vital water resource in the semi-arid Sahel corridor on which more than 30 million people rely for their livelihoods (Sarch 2001). The Lake Chad basin is the world’s largest endorheic basin with an area of about 2500 000 km² (8% of the African continent). Annual precipitation in the Lake Chad basin decreases rapidly from the southern part of the basin (more than 1000 mm yr⁻¹) to the northern part (less than 100 mm yr⁻¹) (Nieh et al. 2005). Consequently, more than 90% of the inflow to Lake Chad comes from the Chari/Logone River system in the southeast part of the basin. Although the western part of the basin is semi-arid, its southeastern part includes about 300 000 km² of floodplains which constitute the 8th largest area of wetlands in the world.

From the 1960s to the 1980s, the area of Lake Chad shrunk from 22 000 km² to about 300 km² (Singh et al. 2006), which has imposed a significant social–economic impact in the region (Sarch and Birkett 2000). Studies by Coe and Foley (2001) and Birkett (2000) have suggested that the shrinking was due to persistent droughts (Campbell 2008) and increased irrigation withdrawals. However, this theory fails to explain why the lake’s deeper portion—its northern part—went completely dry in the 1980s. Furthermore, questions remain regarding the impacts of irrigation withdrawals relative to climate change on the lake size, and regarding the required inflows necessary for the lake to recover to its previous extent and storage levels.

We use a physically based semi-distributed hydrological model, the variable infiltration capacity (VIC) model (Liang et al. 1994, 1996, Bowling and Lettenmaier 2010, Mishra et al. 2010), to help answer these questions. Unlike most land surface models, VIC accounts for lake bathymetry, which is
critical for the proper simulation of Lake Chad’s dynamics. One important feature of Lake Chad’s bathymetry is a shallow ridge or ‘great barrier’ (Olivry et al. 1996), approximately 40 km wide, that runs between the northern and southern parts of the lake (figure 1). On the north side of the barrier, the lake is deeper by about 3 m on average than on the south side. The barrier rises about 7.25 m above the bottom of the north lake. When the water level is at or above the barrier on both sides, there is a single lake. Otherwise the lake splits and behaves as two smaller lakes, with flow spilling from south to north when the south lake is more than 1.5 m deep.

Figure 1. N–S cross-section of Lake Chad’s bathymetry based on SRTM elevation. When the water level is at or above the barrier, there is a single lake. Otherwise the lake splits and behaves as two smaller lakes, with flow spilling from south to north when the south lake is more than 1.5 m deep.

In this study, we first simulated the observed dynamics of Lake Chad for the period 1952–2006. We then designed and conducted a suite of modeling experiments to analyze the impacts of lake bathymetry, human water use, and decadal climate variability on the lake’s level, surface area, and water storage. Finally, the prospect for Lake Chad’s recovery was explored.

2. Methods

The VIC model (Liang et al. 1994, 1996, Bowling and Lettenmaier 2010, Mishra et al. 2010) version 4.1.2, with its lake/wetland parameterization was first used to simulate inflows to Lake Chad and then to simulate water levels and spatial extent of the lake itself. In the model, a lake/wetland system is comprised of a depression where surface water may be impounded. In this context, the impounded water is called the lake (which applies to both permanent lakes and temporary flooding of wetlands), and its surrounding land is called the wetland. The lake and wetland exchange water as follows: all drainage from the wetland discharges directly to the lake; when the lake expands, it must recharge water to the wetland to saturate the newly flooded area. In all other respects, the wetland is simulated in the same way as other land cover classes. If a lake rises above a threshold level, excess lake water flows into the local channel network as flow over a broad-crested weir. The lake model parameters include: \( n_1 \) (number of lake layers); \( d_{\text{min}} \) (lake depth below which channel outflow is 0); \( w_{\text{frac}} \) (width of lake outlet, as a fraction of the lake perimeter); \( d_0 \) (initial lake depth); \( r_{\text{wct}} \) (fraction of runoff from the grid cell’s non-wetland vegetation tiles that enters the lake); and the bathymetric profile (lake depth and area at each layer). More details of the algorithm are provided in Bowling and Lettenmaier (2010).

Inclusion of the lake/wetland algorithm is important for simulation of the hydrology of the Lake Chad basin and Lake Chad itself as otherwise the model would underestimate the evaporation from the catchment’s wetlands and overestimate inflows into the lake. The global lakes and wetlands database (GLWD; Lehner and Döll 2004), together with 90 m digital topographic data collected by the Shuttle Radar Topography Mission (SRTM; Farr et al. 2007), were used to produce bathymetric profiles for the lake/wetland portions (excluding Lake Chad) in each 1° × 1° grid cell. Other lake/wetland parameters were taken to be uniform throughout the basin (\( n_1 = 10; d_{\text{min}} = 0 \) m; \( w_{\text{frac}} = 0; d_0 = 0 \) m; \( r_{\text{wct}} = 0 \)). Within the VIC model construct, soil parameters fall into two categories: those that are fixed and those that are subject to calibration. Fixed soil parameters include all physical properties that can be derived from soil texture (e.g., porosity and hydraulic conductivity). These were taken from the global gridded 1° data set of Sheffield et al. (2009), aggregated from the UNESCO-FAO Soil Map of the World (FAO 1998). Parameters subject to calibration included the thicknesses of the model’s three hydrologic soil layers, the shape of the moisture infiltration capacity distribution \( b_{\text{infilt}} \) and the shape of the relationship between bottom layer moisture storage and baseflow \( (D_1, W_s, \text{and} D_{\text{max}}) \) (Liang et al. 1994). These parameters were estimated via Monte Carlo sampling of the parameter space with the objective of minimizing the mean squared error between the modeled and observed discharge of the Chari/Logone river system at N’djamena, Chad for the period from 1952 to 1963, during which there were essentially no irrigation extractions (hence actual and naturalized flow were identical). Because the discharge from the Yobe River (which enters Lake Chad from its north part) contributes only a small portion of the total inflow for the lake (about 2%), we estimated the discharge by prorating the N’djamena discharge. The meteorological forcings (precipitation, surface air temperature, surface air pressure, vapor pressure, wind speed, and downward shortwave and longwave radiation) were 3-hourly records, both directly observed and derived, at 1° latitude–longitude spatial resolution (Sheffield et al. 2006). The model was initialized by iterating to steady-state over the period 1948–1951. The model was then run at a 3-hourly time step with the estimated parameters to simulate naturalized flow (assuming no human impact) for the remaining years for the period 1952–2006. The parameter estimation process served two purposes: first to provide soil parameters for the Lake Chad catchment and second to produce a simulation of the potential water supply to Lake Chad in the absence of irrigation. In our subsequent simulations, the irrigation water was taken from the river flowing into the lake (rather from
the lake itself), and the amount of the net extractions was estimated as the difference between simulated naturalized flow and observed flow.

For the simulation of Lake Chad, we created a single $3^\circ \times 3^\circ$ grid cell surrounding the lake (figure 2 inset). When there was a single lake, the simulation was conducted using this single cell. When the lake split, the south lake and the north lake were simulated as two separate cells, divided along the 'great barrier'. For both cases, the lake bathymetry (depth–area relationship) was determined using SRTM digital elevation data. Other lake parameters are listed in table 1. Unlike the simulations for the non-lake basin cells, the lake simulation used observed and/or simulated inflow as an additional forcing along with the meteorological forcings which provided the basis for estimating precipitation and evaporation over the lake area. As with the inflow simulations, the lake simulations used the period from 1948 to 1951 for model spin-up, with an initial lake level of 10 m.

Table 1. Lake/wetland model parameters for Lake Chad simulations. (Note: Lake bathymetric profile (pairs of depth and area at each layer), shown in figure 1, is not listed in this table.)

|          | $n_1$ | $d_{min}$ (m)$^a$ | $w_{min}$ (fraction) | $d_0$ (m)$^a$ | $r_{ext}$ (fraction) |
|----------|-------|------------------|----------------------|--------------|---------------------|
| One lake | 12    | 12               | 0                    | 10           | 1.0                 |
| South lake | 9    | 1.5              | 0.0002               | 4.25         | 1.0                 |
| North lake | 12   | 12               | 0                    | 7.25         | 1.0                 |

$^a$ Depths represent position of lake surface relative to lake bottom at deepest point. Bottom of south lake is 3 m higher than the bottom of the north lake.
Whether to model the lake as one or two grid cells was determined by the water level. When the water level was above the barrier on both sides, the lake was modeled as a single lake; otherwise two separate lakes were modeled. In the former case, water was shared, and there was only one water level. For the latter case, water was transported from the south to the north with the rate and amount controlled by the water level in the south lake. The water transfer in the two-lake mode fell into one of the following scenarios: (1) when the south’s water level was marginally above/equal to the top of the barrier but the north’s water level was below it, the south was assumed to maintain a level equal to the top of the barrier and transferred all the excess water to the north; (2) when the south’s water level retreated beneath the top of the barrier, but was still above the minimum depth (1.5 m) under which outflow could not occur, the south lake transferred water to the north in the manner of flow over a broad-crested weir; and (3) when the south’s water level was below the minimum depth, they were completely separated. The north was never allowed to be higher than the south, as the south is of higher elevation and gets most of its inflow from the Chari River, which is the main driver of the entire lake system. The VIC model was modified to check (at the end of each month) whether the lake retained its previous mode, or transitioned between modes (split from one lake to two lakes, or merged from two lakes to one).

3. Results

The lake model was first forced by observed discharge and used to reconstruct the historic Lake Chad. Figure 2 shows that the modeled results agree well with both gauge (RMSE = 0.37 m) and altimetry observations (RMSE = 0.48 m), and with aerial photograph and Landsat satellite images (biases = −8%, 3%, and 5% of 1963 area on 10/31/1963, 12/25/1972, and 1/31/1987, respectively) (see appendix for details of the sources of above observational data). Although there was no lake level gauge in the north part of the lake, the gauge in the south represented water levels in both the north and the south prior to the split in 1972 (lake levels on both sides were the same). After the split, the Landsat water classification in 1987 indicates the north part was depleted, which is consistent with modeling results. From 1965 to the early 1970s, continuing droughts caused the lake depth to decrease rapidly and, as a result of the unique bathymetry, the lake split into two parts (in 1972). Before the lake split, seasonal variations in the lake’s level were about 1 m. Afterward, the seasonal variations increased to about 2 m in the south lake due to the reduction of lake size (for the same variation in inflow, water level variations are larger for a smaller lake). The north lake’s level continually decreased until 1986 when it dried out completely. Water reappeared in the north lake in 1999 after a few years of wet weather. During the transition from a single large lake to two separate lakes and then to a single but much smaller southern lake, the lake area and volume underwent a tremendous change: in 1986, the single southern lake had only about 12% and 2% of the area and volume, respectively, of the large combined lake in 1963.

Having reconstructed historic lake behavior (figure 2), we next examined the impact of irrigation. Irrigation water use in the Lake Chad basin was small until the early 1970s, but it increased rapidly thereafter. During the 1990/1991 cycle, the lake inflow from the Chari River was about 11.5 km$^3$ yr$^{-1}$ after having lost about 8 km$^3$ yr$^{-1}$ upstream to irrigation (Birkett 2000). Determination of the impacts of irrigation withdrawals on lake size is complicated by large year-to-year water consumption variations. Previous studies have relied on simple approximations of irrigation water use from limited observations (Coe and Foley 2001). To estimate the role of irrigation in the observed lake changes, we used the VIC model to simulate naturalized flow (lake inflows that would have occurred absent human effects) from 1952 to 2006. The difference between modeled and observed runoff should equal irrigation withdrawals. Figure 3(a) shows that, without irrigation withdrawals, the north lake not only would have survived the droughts in the 1980s but would have merged with the south lake again for a brief period around 2000.

A second simulation was designed to explore the response of the lake if the barrier between its two sections was breached (e.g. via a channel whose bottom is at the same level as the bottom of the south lake). This experiment applied the model parameters for the single lake, regardless of the lake level. Two sets of runs were performed: one forced by observed inflow to represent the lake’s actual history, and one forced by naturalized inflow to remove the impact of irrigation. Even

![Figure 3](image-url)
without irrigation (figure 3(b)), by 1986, the depth of the single lake would have dropped to below 3 m, i.e., below the lowest point of the southern portion. Other than the large drop (more than 2 m) in 1972–73, the seasonal variation of lake level was about 1 m. The simulation without irrigation shows that the lake level would have increased substantially in the last 25 years.

We also investigated the impacts of irrigation and bathymetry on lake area and volume (figure 4). With neither irrigation nor a split (barrier breached), the lake area in 2000 would have been 82% of the 1963 area, but the volume would have been only 59% of that in 1963. This suggests that the climate conditions in the 1990s, while more favorable than those in the prior decades, were not conducive to a full recovery of the lake. While irrigation withdrawals played a key role in preventing a recovery, the lake bathymetry exacerbated the loss of lake area and volume. The major reason is attributable to the difference in average depth (volume to surface area ratio) in the southern (shallower) and northern (deeper) lakes. Because of the barrier, when the lake splits proportionately more water is stored in the shallower southern lake, which is subject to both greater aggregate evapotranspiration and to subsurface storage than in the deeper northern lake. If the barrier is breached, water in the shallower south flows into the deeper north, reducing both evapotranspiration and the recharge requirement as the lake fills.

To investigate Lake Chad’s steady-state response to observed climate change in the last half century alone, we employed a set of climate scenarios based on the naturalized (non-irrigated) inflows. First, the climatology from 1952 to 2006 (33 km$^3$ yr$^{-1}$ inflow, 178 mm yr$^{-1}$ precipitation over the lake) was repeated for all years of the simulation (using the average historical partitioning of annual to daily values). Under this reference scenario, the lake would have gone through a stage of split–merge–split from 1958 to 1961, and remained split afterward. The two lakes would have equilibrated at average depths of 4.5 m and 6.8 m in the northern and southern parts, respectively. Similar results were obtained in experiments that used random resampling of historical inflows and precipitation. These results clearly show that even without irrigation withdrawals, the 1952–2006 mean climate state does not favor a single lake. In additional experiments, the 1952–2006 mean precipitation was multiplied by a series of factors (1.06, 1.1, 1.2, and 1.3), and the inflows were estimated using an elasticity (fractional change in runoff divided by fractional change in precipitation) of 1.09 (calculated from annual precipitation and runoff data after Sankarasubramanian et al. 2001). Under these test conditions, the lake remains as one-pool with average equilibrium depths of 8.1 m, 8.5 m, 9.7 m, and 10.8 m, respectively. The results show that, depending on the climate conditions, both the one-lake and two-lake modes can reach steady states. The threshold for transitioning between the modes is roughly 1.06 times mean precipitation and 1.15 times mean inflows (38 km$^3$ yr$^{-1}$) from the 1952–2006 climatology, just slightly wetter than the long-term climatology. We also tested the impact of temperature change by increasing the annual average air temperature by 2 K (approximately the observed temperature increase from 1952–2006), and found that modeled inflow decreased by about 10% relative to climatology due to increased evapotranspiration. In this scenario, the lake would have remained split from 1960 on. After the split, both the north lake and south lake levels decreased about 0.1 m relative to the reference scenario.

Finally, to address the question as to what it would take for Lake Chad to recover fully, we conducted experiments using inflows in which we multiplied the historical maximum annual inflow (50 km$^3$ yr$^{-1}$) by a series of factors to force simulations of the two separate lakes post-2006. The precipitation over the lake was from climatology. Figure 5 shows that with a recurring net annual inflow of 50 km$^3$ yr$^{-1}$, the two lakes would have merged into one in about four years, and a total of 10 years would be required for the lake to resume its 1963

![Figure 4](image-url) Impact of lake bathymetry and irrigation water usage on modeled lake size. (a) Lake area. (b) Lake volume.
size (9.25 m annual minimum lake level). For an annual inflow of 60 km$^3$ it would take five years to recover to the 1963 size. A larger annual inflow not only implies a shorter time but also a smaller total volume needed for recovery to a given size. However, because 1963 was one of the wettest years in the study period (and had low irrigation withdrawals), it is unlikely that an equivalent/larger inflow (after irrigation usage) will occur for even one year, let alone multiple consecutive years, under foreseeable climate conditions.

To achieve such large inflows, inter-basin water transfer (from Oubangui, a major tributary of the Congo River) might be an alternative (Onuoha 2008). From 1997 to 2006, the observed inflow to the lake was 24 km$^3$ yr$^{-1}$, suggesting that an average diversion of 26 km$^3$ yr$^{-1}$ for 10 years would be required for a recovery to the 1963 lake size. Without irrigation withdrawals, the 1997–2006 average inflow would have been 37 km$^3$ yr$^{-1}$, implying a need for 13 km$^3$ yr$^{-1}$ of supplemental inflow from diversion. Breaching the barrier could help reduce the amount of water transfer required to restore the lake; modeling results suggests that it would take one year less when using the 50 km$^3$ yr$^{-1}$ inflow scenario (26 km$^3$ less water transferred) for the lake to recover fully.

Compared to the construction of a canal 2400 km in length for inter-basin-transfer, breaching the 40 km barrier to help replenish the lake seems much more feasible and cost effective. Clearly though, because the lake covers parts of three countries, there are socio-economic and international legal issues that go well beyond the scope of this letter.

4. Summary

In this letter, we used a physically based hydrologic model to reconstruct the historic Lake Chad. We further applied the model to a set of scenarios to study the causes of the shrinking of the lake. In summary, our experiments show that:

(a) The split of Lake Chad in 1972 occurred as a combined consequence of the lake bathymetry and severe droughts. Failure of the lake to merge back into a single lake following wetter conditions in the 1990s is a result of irrigation withdrawals—without irrigation, the lake would have merged in 1999, although it would have split again in 2004.

(b) The 1952–2006 climatology does not favor a single lake. It takes about 106% of the climatological precipitation and 115% of the historical mean inflow to avoid a split in the lake, even without irrigation.

(c) For the lake to recover from its 2006 size to its 1963 size would necessitate a continuous net inflow of 50 km$^3$ yr$^{-1}$ for 10 years (or 9 years if the barrier was breached), which implies a supplemental inflow of about 26 km$^3$ yr$^{-1}$ given current irrigation withdrawals of about 13 km$^3$ yr$^{-1}$.

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Appendix

The observations shown in figure 2 were taken from three different sources. The gauge measurements were taken from the record for Bol, Chad (13.5°N, 14.7°E), with readings made the first day of each month (Olivry et al 1996). The surface level of the south lake (13.2°N, 14.1°E) from 1992 to 2006 was provided by Geodesy, Oceanography et Hydrologie from Space (GOHS) based on altimetry data from ERS-1 & 2, Envisat, and Jason-1 (Cretaux and Birkett 2006) at a 35 day overpass interval. The original aerial photographs and Landsat images were from USGS Earth Resources Observation and Science Center (EROS). We classified the images to obtain an estimate of the open water area of the lake. The open water area estimated from the aerial photographs was generated based on differences in intensity levels. Classes were determined through an unsupervised clustering approach. The different classes were then merged to two classes, open water and non-open water. In order to generate open water products from Landsat images the ratio of the mid-infrared band and the green band (bands 5 and 2) was derived (Luck et al 2010), where ratio = ((TM band 5)/(TM band 2 + 0.0001)) × 100. The lower ratio values represent open water and therefore a threshold was applied to discriminate open water from all other classes. Three Landsat scenes on 12/25/1972 and two scenes
on 01/31/1973 were combined to derive a water cover map for comparison with the model water cover on 12/25/1972. Four Landsat scenes on 01/24/1987, and two scenes on 01/31/1987, and 02/07/1987 were combined to derive a water cover map for comparison with the model water cover on 01/31/1987.

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