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# Human and natural impacts on the water resources of the Lake Chad basin

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**Abstract.** An integrated biosphere model (IBIS) and a hydrological routing algorithm (HYDRA) are used in conjunction with long time-series climate data to investigate the response of the Lake Chad drainage basin of northern Africa to climate variability and water use practices over the last 43 years. The simulated discharge, lake level, and lake area of the drainage basin for the period 1953-1979 are in good agreement with the observations. For example, the correlation coefficient ($r^2$) between the simulated and the observed level of Lake Chad for the 288 months of available observations is 0.93. Although irrigation is only a modest portion of the hydrology in the period 1953-1979; representing only 5 of the 30% decrease in simulated lake area for the decade 1966-1975, the simulated lake level and area are in better agreement with the observations when irrigation is included. For the period 1983-1994 the observed water use for irrigation increased fourfold compared to 1953-1979. A comparison of the simulated surface water area, with and without irrigation, suggests that climate variability still controls the interannual fluctuations of the water inflow but that human water use accounts for roughly 50% of the observed decrease in lake area since the 1960s and 1970s.

## 1. Introduction

The Lake Chad drainage basin is a large (2.5 x $10^6$ km$^2$), hydrologically closed drainage system in North Africa (Figure 1). It has a monsoon climate, with the majority of the rainfall occurring in the southern one third of the basin (falling during the months of June, July, and August); arid conditions dominate the northern two thirds. As a result, significant runoff is generated only in the southernmost regions of the drainage basin. The Chari/Logone River system transports about 90% of the runoff generated within the drainage basin, with the remaining 10% coming from the Komadougou Yobé [Famine Early Warning System (FEWS), 1997]. Because of the relatively dry conditions within the drainage basin, Lake Chad, the terminal lake of the drainage system, has historically occupied less than about 1% of the drainage basin area (25,000 km$^2$).

Rainfall over the Chad drainage basin has decreased greatly since the early 1960s, largely because of a decrease in the number of large rainfall events [Nicholson, 1988, 2000]. At the same time, the use of water for irrigation has increased dramatically [FEWS, 1997], partially in response to changing climate. Discharge losses due to irrigation in the early 1960s were close to zero, while they now account for about 10 km$^3$/yr (S. Isiorho, Dep. of Geosciences, Indiana Univiversity-Purdue Univiversity, personal commmunication, 1999 (hereinafter referred to as I99)).

Taken together, climate variability and increased human water consumption have caused large changes to the water balance of the Chad drainage basin. For example, the discharge of the Chari/Logone river system at N'Djamena has decreased by almost 75% over the last 40 years, from about 40 km$^3$/yr in the early 1960s to about 10-15km$^3$/yr in the 1980s and 1990s [*Olivry et al.*, 1996].

Lake Chad responds rapidly to precipitation and runoff changes, in part due to the shallowness of the lake (less than 7 m). As a result, Lake Chad has been reduced from an area of open water covering approximately 25,000 km$^2$ in 1963 to a small area covering 1350 km$^2$ today [*Grove*, 1996]. This desiccation has lead to enormous changes in the lives and livelihoods of the ~750,000 people living in the area [*Hutchinson et al.*, 1992; *FEWS*, 1997].

Birkett [2000] showed that there is a strong correlation between the height of the Chari River during the 1990s (upstream of the major irrigation extractions) and the level of Lake Chad one to two months later. Birkett concluded that the seasonal fluctuations of the lake level are still primarily controlled by climate, not water management practices. However, the degree to which the long-term lake level and surface area are affected by local water management practices is not well understood. For the foreseeable future water demands in the Lake Chad drainage basin are expected to increase, as the population becomes more dependent on irrigated agriculture [Hutchinson et al., 1992; FEWS, 1997, 1998]. Therefore it is important to learn more about the response of this very sensitive system.

A modeling study of the Lake Chad basin was performed by Vuillaume [1981] for the period 1968-1977 and was extended by Olivry et al. [1996] for the period 1953-1977. Both studies used a simple mass balance model, relating input from observed mean monthly river discharge to water losses and lake height, in order to understand how water management practices affected the equilibrium level of the lake. Olivry et al. concluded that the small amount of water extraction (about 5% of the total input to the lake) had little affect on the lake system.

The objective of this study is to quantify the relative affects of long-term climate variability and water management practices on the behavior of the Lake Chad drainage basin since the middle 1950s. This study extends the previous modeling studies of Lake



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**Figure 1.** Chart of Africa showing 2.6 x $10^6$ $km^2$ Chad basin (dark gray), the Chari/Logone river system, and location of N'Djamena, Chad.

Chad in terms of model complexity and length of investigation. Two models recently developed at the University of Wisconsin are used: IBIS (the integrated biosphere simulator) a land surface biophysics / ecosystem process model [Foley et al., 1996; Kucharik et al, 2000], and HYDRA (the hydrological routing algorithm), a surface hydrology transport model [Coe, 2000]. IBIS simulates the surface water balance (including evapotranspiration, changes in soil moisture, surface and sub surface runoff, among other variables) from prescribed meteorological forcing (including temperature, precipitation, and solar radiation). HYDRA transports the runoff across the land surface to calculate the river discharge and lake and wetland areas as a linked system. IBIS and HYDRA are used in conjunction with time-transient climate data to examine changes in the land surface hydrology for the period 1953-1995.

## 2. Model Descriptions

Both IBIS and HYDRA are thoroughly described in previous publications [*Foley et al.*, 1996, *Kucharik et al.*, 2000; *Coe*, 2000]; only a brief description is provided below.

IBIS represents land surface processes (energy, water, and momentum exchange among soil, vegetation, and the atmosphere), canopy physiology (canopy photosynthesis and conductance), vegetation phenology (bud burst and senescence), and long-term ecosystem dynamics (vegetation dynamics and carbon cycling). These processes are organized in a hierarchical framework and operate at different time steps, ranging from 60 min to 1 year. This allows for explicit coupling among ecological, biophysical, and physiological processes occurring on different timescales.

IBIS simulates the exchange of energy, water, and $CO_2$ between vegetation canopies, soils, and the atmosphere. It borrows much of its basic structure from the land surface exchange (LSX) land surface package [*Thompson and Pollard*, 1995]. The model includes two vegetation layers (i.e., "woody plants" and "herbaceous plants") and 8 soil layers (to simulate soil temperature, soil water, and soil ice content). Physiologically-based formulations of $C_3$ and $C_4$ photosynthesis, stomatal conductance, and respiration are used to simulate canopy exchange processes.

HYDRA simulates the time-varying flow and storage of water in terrestrial hydrological systems, including rivers, wetlands, lakes, and human-made reservoirs [*Coe*, 1998, 2000]. This model currently operates on the global scale on a 5 minute latitude by longitude grid (~10 km at the equator) spatial resolution and with a 1-hour time step. HYDRA requires the following boundary conditions: topography (from digital elevation models), evaporation from water surfaces (estimated from climate data, using a simple Penman energy balance model), surface runoff (supplied by IBIS), base flow (drainage from the soil column, supplied by IBIS), and precipitation (from climate data).

The model derives river paths and potential lake and wetland volumes from digital elevation model (DEM) representations of the land surface. The physical land surface of HYDRA is coupled to a linear reservoir model to simulate (a) the discharge of river systems, and (b) the spatial distribution (and volume) of large lakes and wetland complexes. Rivers, lakes, and wetlands are defined as a continuous hydrologic network in which locally derived runoff accumulates and is transported across the land surface via rivers, it fills lakes and wetlands, and is eventually transported to the ocean or is evaporated from an inland water body.

IBIS and HYDRA have been extensively tested and applied to large, temporal and spatial-scale problems. For example, IBIS has been used to investigate global patterns of water balance, carbon cycling and vegetation cover [*Foley et al.*, 1996], as well as the potential impact of deforestation and increasing $CO_2$ concentrations on the hydrology of the Amazon basin [*Costa and Foley*, 1997]. Additionally, IBIS has been extensively tested against detailed biophysical measurements from a wide range of flux tower sites [*Delire and Foley*, 1999], as well as spatially extensive ecological and hydrological data [*Foley et al.*, 1996; *Kucharik et al.*, 2000; *Lenters et al.*, 2000]. HYDRA has also been tested globally, against observed annual mean discharge and lake area [Coe, 1998] and has been used to investigate the accuracy of general circulation model simulations of equilibrium surface hydrology (Coe, 2000). IBIS and HYDRA have been used together to evaluate the simulated hydrology of the National Center for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) climate reanalysis for the period 1963-1995 over the continental United States [*Lenters et al.*, 2000]. This study represents the first application of IBIS and HYDRA to investigate the time-transient response of a linked river, lake, and wetland system.

## 3. Methods

IBIS and HYDRA were used to investigate the changes to the water balance of the Lake Chad drainage basin between 1953 and 1995. IBIS was used to derive estimates of the land surface water balance, using long-term climate data. The IBIS simulations of runoff (including surface runoff and sub-surface drainage) were used as input to the HYDRA model to estimate changes in river discharge, and the volume of water stored in wetlands and lakes of the Chad drainage basin.

In this study, two separate experiments were conducted with HYDRA: one where irrigation losses were subtracted from the simulated river discharge (referred to as IRR in the text) and another where irrigation losses were not included (referred to as NoIRR in the text). These two simulations allow the characterization of the separate and combined effects of climate variability and human water management practices on the water balance of the Lake Chad drainage basin.

Long-term climatic data from the Climate Research Unit of the University of East Anglia, Norwich [*New et al.*, 2000; (hereinafter referred to as CRU05)] were used to provide meteorological forcing to IBIS and HYDRA. CRU05 is a global, monthly mean data set of temperature, precipitation, humidity, and cloudiness, at 0.5° by 0.5° latitude/longitude resolution, for the period 1901-1995.

IBIS was run on a 0.5° by 0.5° latitude/longitude grid, extending over the entire Lake Chad drainage basin (24°-5°N; 7°-25°E), for the period 1936-1995. The first 10 years of the IBIS simulation allowed the soil moisture to come into balance with the prescribed climate and were subsequently ignored. The remaining 50 years of IBIS results, extending from 1946 to 1995, were used in the HYDRA simulations along with the climate data (precipitation and estimated lake surface evaporation) after interpolation to the 5' resolution grid of HYDRA. The hourly output from HYDRA was then averaged to monthly mean values for comparison to observations

The impact of water management practices in the Lake Chad drainage basin were explicitly included in the simulations. There are no time series estimates of monthly total irrigation losses for the Lake Chad drainage basin. Therefore, two annual mean estimates of irrigation losses were used in conjunction with a monthly weighting function to reproduce a monthly irrigation time series for the periods 1965-1977 and 1980-1995. For the period 1965-1977 water loss was estimated by *Vuillaume* [1981] to occur at a rate of about 2.5 $km^3$/yr, predominantly in the Chari River system. I99 documented irrigation losses of about 11.2 $km^3$ in the 1990-1991 season for the entire Lake Chad drainage basin: about 10 $km^3$ for the Chari/Logone River system and about 1 $km^3$ for the Yobé. The Vuillaume estimate was used for the period 1965-1977. Although the irrigation rate is believed to vary by as much as 25-50% per year during the 1980s/1990s [I99], no estimates of irrigation were available for individual years. Therefore the 1990-1991 season estimate was applied to all years in the period 1980-1995. In the irrigation experiment, estimates of water loss were subtracted from the discharge of the Chari River at N'Djamena and the Yobé River upstream of the lake at each time step. Similar to a study with a simple lake level model by *Vuillaume* [1981] and by *Olivry et al.* [1996], the annual withdrawal rate was modified by a monthly weighting function, taken from Vuillaume (see Olivry, p. 188), to account for monthly water use differences.

The simulated river discharge, surface water level, and lake area for the period 1953-1995 are compared to the observations of *Olivry et al.* [1996]. The observed river discharge was taken from mean monthly data collected at N'Djamena on the Chari/Logone River system. River discharge is generally calculated from a measurement of river water level and converted into a discharge volume using a rating curve. The major sources of error in calculating river discharge probably result from direct measurement, which is often made under difficult conditions, and the use of the rating curve, which assumes a constant stream cross-sectional area [*Cogley*, 1989]. The accuracy of the Olivry discharge measurements is not given in the original data. However, *Dickinson* [1967] and *Cogley* [1989] have investigated the potential error in river discharge measurements in detail. Their research suggests that 10-15% is a reasonable estimate of the error in observed annual mean discharge. It is assumed that the error decreases with longer time averages.

The observed lake level data were taken from mean monthly measurements at Bol, Chad (13.5°N, 14.7°E). The lake level measurements were made by directly reading the daily water height on a permanent gauge at Bol and averaging to monthly means [*Olivry et al.*, 1996]. The major sources of error most likely involve direct measurement from the gauge, and are dependent upon the lake surface being only minimally effected by winds. As with the discharge, no estimates of error are given by the authors. However, the daily lake level values show a small variation of about 15 cm or less (possibly related to wind-driven changes in lake level). The lake level varies seasonally by about 1-1.5 m, therefore 10-15% is probably a reasonable estimate of the error in the observed daily lake level. This error should be less for the monthly and annual means, unless the winds are very persistent in direction and intensity. Although the winds in this region do show seasonal persistence, the error in the monthly and annual mean lake level measurements is probably still less than 10%.

Errors in the simulated river discharge, lake level, and lake area are associated with two primary sources: the topographic representation of the drainage and lake basin and the simulated water budget. The model representation of the drainage basin was thoroughly compared and corrected with maps of the basin [Rand McNally, 1999] to conform to the observed drainage basin area and lake basin elevation. Therefore, the error due to the basin definition is probably small. The greatest portion of the error is most likely due to the simulated water budget. Because of the complexity of the models and the large amount of data used as input, it is difficult to assess the individual sources of error. However, the most obvious sources of potential errors include (1) the accuracy of the input data sets (such as precipitation, cloudiness, and temperature), (2) the calculation of evapotranspiration, soil moisture, and runoff within IBIS, and (3) the calculation of the water transport within HYDRA. Any one of these sources of error is potentially large. However, in constructing and testing these models we have attempted to minimize the potential errors.

Another source of error in our analysis relates to the magnitude and seasonality of infiltration of waters from Lake Chad into the surrounding groundwater pool. This process is complex and poorly understood [*Olivry et al.*, 1996]. It has been estimated that groundwater seepage may represent as much as 10-15% of the monthly mean water budget [*Isiorho and Njock-Libii*, 1996] but perhaps less on the annual mean [*Olivry et al.*, 1996]. Because of the uncertainties we do not include infiltration in these simulations.

## 4. Results

Comparison of the simulated river discharge, surface water level, and lake area to observations is made over two periods: 1953 –1979 and 1983-1994. These periods correspond to available observed discharge records and a major transition in irrigation losses (which increased dramatically after 1980).

### 4.1. Period 1, 1953-1979

Averaged over individual decades (1956-1965, 1966-1975), the simulated river discharge is in good agreement with observations (within the assumed 10% error of the observations) (Table 1). The magnitude and timing of the simulated (NoIRR) annual mean discharge (Figure 2) at N'Djamena for period 1 is in good agree-

**Table 1.** Simulated and Observed River Discharge at N'Djamena in $km^3/yr$ Averaged for Given Decades

| | OBS | NoIRR | IRR |
|---|---|---|---|
| 1956-1965 | 43 | 40 | 40 |
| 1966-1975 | 31 | 32 | 29 |
| 1985-1994 | 17 | 25 | 16 |
| % dif | -45 | -22 | -45 |

The difference in discharge in percent between the decades 1985 to 1994 and 1966 to 1975 is provided in the final row. NoIRR is the simulation without irrigation. IRR is the simulation with irrigation.

ment with the observations. The simulated annual mean discharge is within the assumed error of the observations (≈15%) for 18 of the 25 years (Table 2). Only two years, 1972 and 1979, have a simulated difference greater than about 20% from the observations. The models correctly simulate the decreasing discharge trend after 1963 and simulate the years of maximum and minimum discharge fairly well. Relative discharge maxima are simulated in 1962 and 1968 compared with 1961 and 1967 in the observations (Figure 2). The CRU05 precipitation maxima occur in 1962 and 1968 also. Therefore the discrepancy between the simulated and the observed maxima is most likely a result of the input data rather than the models themselves.

The models also simulate the magnitude and timing of the monthly mean discharge at N'Djamena in fairly good agreement with the observations. The correlation coefficient ($r^2$) between the magnitude of the simulated and observed monthly mean discharge for the 324 months available for comparison is 0.74. The simulated peak discharge generally occurs in October or November, which is consistent with the observations (monthly discharge not shown). The peak discharge delay (the difference between simulated and observed peak discharge month, PDD) is within 1 month of the observations for all of the 27 years in period 1. Seventeen months have a PDD of zero, while the remaining 10 years have a PDD of −1 month (Table 2).

**Table 2.** Observed and Simulated Annual Mean Discharge in $m^3/s$ and the % Difference Between Simulations and Observations

| Year | OBS | NoIRR | % Dif NoIRR | IRR | % Dif IRR | PDD | PLD |
|---|---|---|---|---|---|---|---|
| 1953 | 1204.1 | 999.8 | -17.0 | 999.8 | -17.0 | -1 | |
| 1954 | 1490.8 | 1201 5 | -19.4 | 1201.5 | -19.4 | -1 | 0 |
| 1955 | 1654 4 | 1431.5 | -13.5 | 1431.5 | -13.5 | 0 | 0 |
| 1956 | 1591.8 | 1318.7 | -17.2 | 1318.7 | -17.2 | -1 | 0 |
| 1957 | 1157.9 | 1059.2 | -8.5 | 1059.2 | -8 5 | 0 | -1 |
| 1958 | 1107.8 | 1051.7 | -5.1 | 1051.7 | -5.1 | 0 | 0 |
| 1959 | 1248 4 | 1139.4 | -8.7 | 1139.4 | -8.7 | 0 | 0 |
| 1960 | 1345 7 | 1355.8 | 0.8 | 1355.8 | 0 8 | -1 | 1 |
| 1961 | 1673.1 | 1395.2 | -16.6 | 1395.2 | -16.6 | 0 | 0 |
| 1962 | 1598.3 | 1568.9 | -1.8 | 1568.9 | -1.8 | -1 | 0 |
| 1963 | 1442.6 | 1329.3 | -7.8 | 1329.3 | -7 8 | 0 | 0 |
| 1964 | 1368.4 | 1252.2 | -8.5 | 1252.2 | -8.5 | -1 | -1 |
| 1965 | 1008.2 | 1155.4 | 14.6 | 1076.2 | 6.7 | 0 | -1 |
| 1966 | 1041 8 | 1172.2 | 12.5 | 1093.0 | 4.9 | 0 | -1 |
| 1967 | 1180.8 | 1134.9 | -3.9 | 1055.6 | -10.6 | -1 | 0 |
| 1968 | 1048.8 | 1189.9 | 13.5 | 1110.7 | 5.9 | -1 | 0 |
| 1969 | 1058.8 | 993.2 | -6.2 | 913.9 | -13.7 | -1 | -1 |
| 1970 | 1179.5 | 1012 8 | -14.1 | 933.5 | -20.9 | 0 | -1 |
| 1971 | 992 6 | 899.8 | -9.3 | 820.5 | -17.3 | 0 | -1 |
| 1972 | 652 7 | 877.2 | 34.4 | 797.9 | 22 3 | 0 | 0 |
| 1973 | 575.7 | 697.7 | 21.2 | 618.4 | 7.4 | 0 | 0 |
| 1974 | 922.7 | 1003.8 | 8.8 | 924 6 | 0.2 | 0 | -1 |
| 1975 | 1121 8 | 1039.9 | -7.3 | 960.6 | -14.4 | 0 | 0 |
| 1976 | 930.3 | 1066.8 | 14.7 | 987.5 | 6.1 | 0 | -1 |
| 1977 | 815.9 | 980.8 | 20.2 | 901.5 | 10 5 | 0 | 0 |
| 1978 | 933 6 | 1018.8 | 9.1 | 939.5 | 0.6 | 0 | |
| 1979 | 648.7 | 883.9 | 36.3 | 804.6 | 24 0 | -1 | |
| 1980 | | 1007.0 | | 927.7 | | | |
| 1981 | | 975 3 | | 683.3 | | | |
| 1982 | | 950 5 | | 658.4 | | | |
| 1983 | 544.7 | 932.3 | 71.2 | 640.3 | 17.6 | -1 | |
| 1984 | 236.3 | 784.7 | 232.1 | 492.6 | 108.5 | 0 | |
| 1985 | 524.8 | 760 1 | 44 8 | 468.1 | -10.8 | 0 | |
| 1986 | 483.6 | 751.7 | 55.4 | 459.6 | -5.0 | 0 | |
| 1987 | 313.0 | 663.5 | 112.0 | 371.5 | 18 7 | 0 | |
| 1988 | 859 9 | 975.8 | 13.5 | 683.7 | -20.5 | -1 | |
| 1989 | 519.6 | 901.6 | 73 5 | 609.6 | 17.3 | 0 | |
| 1990 | 390.1 | 809.1 | 107.4 | 517.0 | 32.5 | -1 | |
| 1991 | 601.9 | 789.1 | 31.1 | 497.0 | -17.4 | 0 | |
| 1992 | 646 2 | 866.9 | 34.1 | 574.8 | -11.0 | 0 | |
| 1993 | 464.6 | 806.0 | 73.5 | 513.9 | 10.6 | -1 | |
| 1994 | 649.7 | 674.8 | 3.9 | 382.7 | -41.1 | 0 | |

PDD is the peak discharge delay. PLD is the peak level delay. PDD and PLD represent the difference, in months, between simulated and observed maximum discharge at N'Djamena and lake level at Bol, Chad respectively No observations are available for discharge in 1980-82 or for the lake level before 1953 and after 1977. NoIRR is the simulation without irrigation. IRR is the simulation with irrigation estimates.

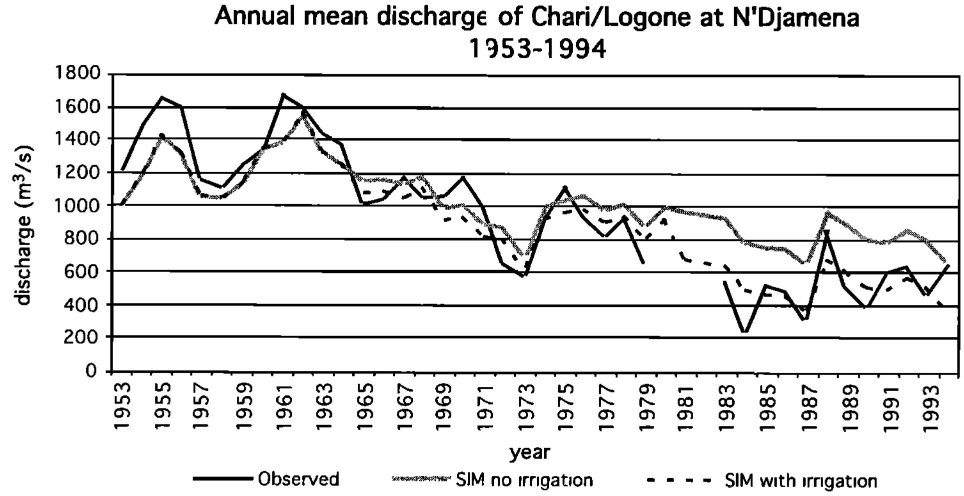


**Figure 2.** Annual mean discharge at N'Djamena (12°N; 15°E) from 1953 to 1994 for observations (black curve, [*Olivry et al.*, 1996]), the IBIS/HYDRA simulation without irrigation (grey curve), and the IBIS/HYDRA simulation with estimated irrigation losses (dashed curve).

HYDRA also simulates the timing of the seasonal and interannual variability of the lake level in good agreement with the observations (Figure 3). The correlation coefficient ($r^2$) between the simulated and the observed monthly mean lake level for the 288 months of available observations is 0.93. The simulated month of peak lake level generally occurs in December or January, which is consistent with the observations. The peak level delay (PLD) (the difference between the month of simulated and observed peak lake level) is within 1 month for all 24 years, for which observations are available (1954-1977). The PLD is zero for 14 of the 24 years while 9 of the remaining 10 years have a PLD of −1 (Table 2).

The slight bias toward early simulation of PDD and PLD is most likely related to our parameterization of the flow velocity within HYDRA. The bias indicates that future improvements could be achieved through a more thorough investigation of the velocity relationships in the Lake Chad drainage basin.

Before 1972 The model captures the magnitude of the seasonal fluctuation of the lake level (approximately 1 m) in good agreement with the observations of Olivry (Figure 3). After 1972, the observed seasonal variation increases to almost 2 m while the simulated variation remains at about 1 m. However, the apparent change in the observed variability after 1972 may not reflect a real change in the water input to the lake basin. As explained by *Olivry et al.*, [1996], during 1973 and 1974 the lake level dropped to levels at which the gauging station was no longer connected to the open lake. Additionally, vegetation rapidly grew in these shallow and exposed regions, decreasing the transport of water from the open lake. As a result, after 1972 the gauging station may document changes in level of a small water pool and may be

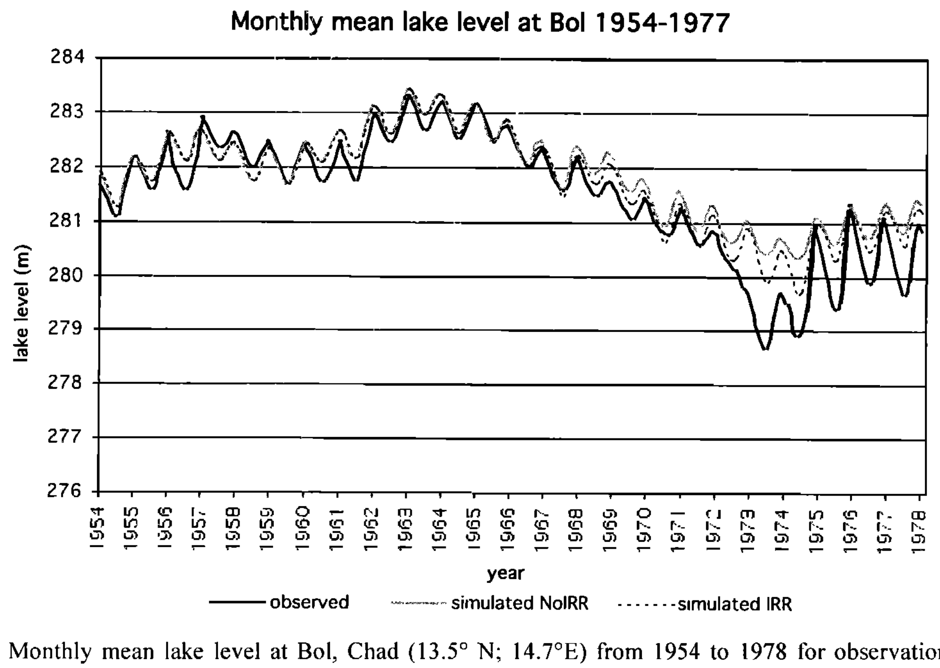


**Figure 3.** Monthly mean lake level at Bol, Chad (13.5° N; 14.7°E) from 1954 to 1978 for observations (black, [*Olivry et al.*, 1996]), the IBIS/HYDRA simulation without irrigation (NoIRR, grey), and the IBIS/HYDRA simulation with irrigation (IRR, dashed).

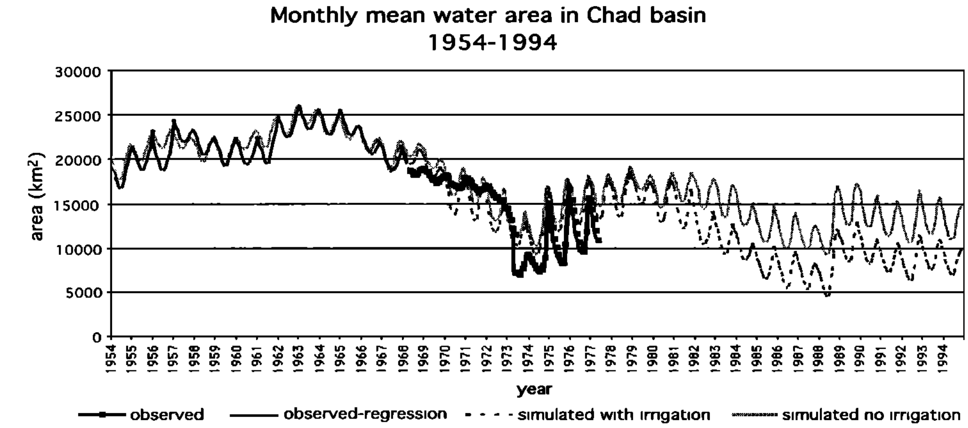


**Figure 4.** Monthly mean lake area from 1954 to 1994 for the observations (black; [*Olivry et al.*, 1996]). The IBIS/HYDRA simulation without irrigation (grey), and the IBIS/HYDRA simulation with irrigation estimates (dashed). The observed lake area values for the years 1969-1976 were calculated by Olivry and are shown with squares. From 1954 to 1968 the observed lake area is estimated in this study from observed lake levels and an estimate of the ratio of area to level (solid black curve; see text for details).

far more sensitive than the main lake. The topography of the HYDRA (≈ 10 km) is too coarse to capture these small-scale pools. The simulated lake level location is still part of the open lake and as a result, the magnitude of the simulated seasonal variability does not change after 1972.

The model also correctly simulates the trend of the lake level changes over the 24 year period. There is a nearly 2 meter rise in lake level from 1954 to 1963, then a decline of about 3 m to the lowest levels in the early 1970s, which is consistent with the observations. After 1966 the simulated lake level in NoIRR is often 10 cm (or more) greater than the observed.

Estimates of the monthly mean surface water area are only available between 1969 and 1976. However, a monthly estimate of lake area was derived from a linear regression of the observed annual mean surface water area against the observed surface water level of *Olivry et al.* [1996]. The equation for the line relating the lake area and level for the years 1968-1976 was applied to the observed monthly mean water levels from 1954 to 1967 to derive a proxy of observed monthly mean lake area (Figure 4). The simulated lake area is in good agreement with the inferred lake area in period 1 (Figure 4). Furthermore, the peak water area of 25,000 km$^2$ agrees well with independent estimates of water area [*Grove*, 1996].

The calculation of lake area depends on two factors: the land surface topography and the calculated water budget. The good agreement between the simulated and the observed area suggests that the land surface topography used in HYDRA adequately describes the relationship between lake level and lake area, despite the relatively coarse (≈10 km) resolution. Furthermore, because the topography is relatively coarse, the strong agreement suggests that an accurate calculation of the surface water budget is relatively more important than an exact representation of the topography for Lake Chad.

In addition to the NoIRR simulation, a second simulation was performed with estimates of irrigation losses (IRR) in which water was withdrawn at an annual rate of 2.5 km$^3$/yr from the simulated Chari River at N'Djamena.

The impact of human water management practices can be estimated by comparing the results of the two experiments. Including irrigation in the simulation reduces the simulated lake level (Figure 3) and lake area (Figure 4) after 1966. As a result, the IRR experiment is in better agreement with the observations than NoIRR after 1966. In NoIRR there is a ≈25% decrease in simulated average lake area for the decade 1966-1975 compared to the decade 1956-1965 (Table 3). In IRR the lake area decreases by ≈30% between the two decades in good agreement with the observational estimate of a 30% decrease. Therefore these simulations show that consistent with the results of *Vuillaume* [1981] the observed decrease of lake level (Figure 3) and of lake area (from about 25,000 km$^2$ in 1963 to about 10,000 km$^2$ in 1973) can be largely attributed to climate variability. Human water use accounts for only about 20% of the change in the area of surface waters in period 1 (1953-1979).

### 4.2. Period 2, 1983-1994

Between 1983 and 1994 precipitation continued to decline. The precipitation rates during this period were consistently at or below

**Table 3.** Simulated and Observed Surface Water Area (km$^2$) for Individual Decades

| | OBS | NoIRR | IRR | IRR-OBS % | IRR-NoIRR % |
|---|---|---|---|---|---|
| 1956-1965 | 22563' | 22858 | 22858 | 1 | 0 |
| 1966-1975 | 15730 | 17572 | 16681 | 6 | -5 |
| 1985-1994 | * | 13314 | 8909 | | -33 |
| % dif | | -24 | -47 | | |

The percent difference in water area between simulated with irrigation (IRR) and the observations is in column 5. The difference between simulations with irrigation (IRR) and without irrigation (NoIRR) is in column 6. The percent difference in water area between the decades 1985 to 94 and 1966 to 75 for each experiment in the last row.

levels of the 1970s; with the driest years occurring in the middle to late 1980s [*Hulme*, 1992; *Olivry et al.*, 1996, *Tucker and Nicholson*, 1999]. In direct response to this change in climate, large-scale irrigation projects were developed upstream of N'Djamena [*Isiorho and Njock-Libii*, 1996]. Irrigation increased about fourfold, compared to the 1960s-1970s rates [I99]. As a result of the climate variability and human water use, the observed discharge at N'Djamena averaged for the decade 1985-1994 decreased by about 60% compared to the decade 1956-1965 (Table 2).

As with period 1, NoIRR and IRR simulations were performed with HYDRA by removing a total of 11.2 $km^3$/yr from the Chari and Yobé River systems after 1980. The annual irrigation withdrawals were modified with the same monthly weighting function used in Period 1.

The simulated annual mean discharge at N'Djamena in experiment IRR is in relatively good agreement with the observations. The simulated average discharge for the decade 1985-1994, of 16 $km^3$/yr, agrees well with the observed estimate of 17 $km^3$/yr (Table 2); compared to about 25 $km^3$/yr for NoIRR. The annual mean discharge in IRR is within 20% of the observations for 8 of the 12 years in the period (Table 1). Irrigation losses account for nearly 33% of the potential discharge (NoIRR) of the Chari River basin (Table 2).

The interannual variability of the irrigation losses is estimated to be large (about 25-50% of the 1990/1991 estimates, I99). Birkett [2000] showed, with satellite altimetric data, that the seasonal variability in lake level is well correlated with the water level of streams in the headwaters of the Chari River system. She concluded that while irrigation losses are large compared to discharge, seasonal and annual variations in lake level are still predominantly determined by climate variability.

In general, the simulated interannual variability in discharge at N'Djamena agrees with the observations; years of maxima and minima tend to coincide (Figure 2). If the annual mean discharge did not agree with the observations for each year, then the difference could be partially attributable to the variability in the irrigation, which is not accounted for in these simulations. This suggests, consistent with the results of Birkett, that although humans are appropriating a significant portion of the available water, the interannual variability of the river discharge is still controlled by climate variability and not by changes in human water use.

The impact of human water use on the long-term lake area during Period 2 can be assessed by comparing the results of the IRR and NoIRR simulations (Figure 4, Table 3). In NoIRR the area of Lake Chad is about 25% less in 1985-1994 than in 1966-1975. This 25% decrease solely represents the response of the lake area to the climate variability between the two decades. In IRR the difference in simulated surface water area between the two decades increases to about 45%. Therefore these results imply that the observed shrinkage of Lake Chad since 1975 can be attributed, in roughly equal parts, to climate variability and water use by humans.

## 5. Conclusions

The hydrology of the Lake Chad drainage basin has undergone large changes in the last 40 years. From a peak in the early 1960s, Lake Chad has shrunk from about 25,000 $km^2$ to less than 1350 $km^2$ today. The decreased lake area resulted from decreased precipitation and increased water losses from irrigation. The goal of this study was to quantify the contribution of climate variability and water management practices to the observed changes in basin hydrology.

The IBIS ecosystem model and the HYDRA surface hydrology model were used together to explicitly simulate runoff, river discharge, and surface waters from historical climate records. The results indicate that IBIS and HYDRA reproduce the time dependence of hydrology in the Lake Chad basin quite well, and that they are appropriate tools for investigating the impacts of climate variability and water management practices on regional scales.

Between 1953 and 1978 the models reproduce the monthly mean discharge, lake level, and lake area in good agreement with the observations, particularly when irrigation losses are included. Our simulations suggest that the 30% decrease in lake area observed between the decades of 1956-1965 and 1966-1975 can be attributed primarily to long-term climate variability. Only ≈5% of the decreased lake area can be attributed to water management practices. These results are consistent with the previous simulations using a simple water balance model [*Vuillaume*, 1981; *Olivry et al.*, 1996].

After 1983, precipitation continued to be low, and the irrigation withdrawals increased fourfold compared to rates in the previous two decades. The simulated river discharge is in good agreement with observations when irrigation is included. Between the 1980s/1990s and the 1960s/1970s the simulated lake area decreased by about 45%. Our analysis suggests that the drastic decline in lake level and area since the 1970s can be attributed in nearly equal parts to the continued decrease in precipitation over the basin and to the large increase in irrigated agriculture.

This study illustrates the importance of considering human activities on water resources, even in very large hydrologic systems. Interestingly, in this case, human activities acted to strongly amplify the response of the Lake Chad basin to a downward trend in precipitation. The onset of dry climate conditions (in the early 1970s) induced people to dramatically increase irrigation activity, thereby almost doubling the loss of water from Lake Chad.

Future studies of the Lake Chad basin could be improved through more accurate input data sets, characterization of model parameters, and improvements to the models themselves. For example, more accurate and higher-resolution digital elevation models may improve the simulation of the lake area at very low water levels by better defining the basin topography. More accurate irrigation data can allow for more thorough understanding of the impact of water management practices at monthly and annual timescales. Furthermore, analysis of the simulated soil characteristics and discharge velocity should improve the simulation of the water budget within IBIS and HYDRA. Finally, adding explicit overbank flooding and backwater affects to HYDRA will extend the model capabilities. We anticipate that these models could be valuable tools for investigating other sensitive and/or highly modified basins to climate variability and water management practices.

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