

# **A hydro(geo)logical model for the Holocene history of the SW part of the Nubian Sandstone Aquifer System using climate model scenarios and analyses from Lake Yoa (Chad) sediments: Can the use of information contained in lake sediments improve the level of knowledge of the aquifer?**

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## **ABSTRACT**

Recent lake sediment analyses in the Ounianga region (NE Chad) provide a unique climate archive in the Saharan region from Mid-Holocene on. A multidisciplinary project to reconstruct the environmental conditions is presented here, focussing on hydro & hydrogeological modelling as a key link between climate and lake-proxy. On the other hand, for such a large aquifer as the Nubian Sandstone Aquifer System, water resources evolution forecasting and management requires the knowledge of its properties as well as its long transitory trends. Improvement in the characterization of the history of the aquifer as well as the issue of the constraining power of lake sediment analysis on aquifer properties are addressed here.

**Key words:** NSAS, Chad, hydrological model, climate proxy

## **1. INTRODUCTION**

The Nubian Sandstone Aquifer System (NSAS) is one of the largest African Aquifer systems, spreading over 4 countries (Chad, Sudan, Egypt, Libya). Its large extensions - roughly 2 millions of km and maximum depth of 4000 m (Gossel *et al.*, 2004) for a fresh water composition provide very large water reserves. The estimation of the available water volumes and of the aquifer hydraulic properties represents a first step to develop a pumping strategy including locations and associated rates. But the assessment of the impact of long term pumping strategies can't be computed considering for instance steady state conditions. Indeed, for such a large aquifer as the NSAS, the present piezometric conditions are the result of a long history of recharge and discharge events that require a transitory reconstruction of its paleo-evolution (for instance (Mahamoud, 1986) computes water velocities of 1 m/y proving that even if some lateral recharge through boundaries is possible, water movement to topographic depressions is too slow to create steady state conditions). Similarly, future evolution corresponds to the continuation of this transitory trend with additional human activities (e.g. water pumping, Great Man Made River) or in conditions of climate change. Several hydrogeological models were developed to account for the transitory evolution of its water levels and to study the impact of various pumping strategies to exploit its water resources (Gossel *et al.*, 2004; Heintz & Brinkmann, 1989).

Nevertheless, the level of uncertainties remains large. Especially focussing on the SW part of the NSAS which is studied in the present paper, the local boundary conditions for the limits of the NSAS are coarse and differ between these authors and other sources (Schneider, 2004). The same is true for instance for system properties (3D heterogeneity vs 2D approach for nearly homogeneous aquifer) and recharge history. Present water head measurements interpolations differ among authors and are not all coherent with former models (Mahamoud, 1986; Schneider, 2004; Gossel *et al.*, 2004). Moreover, to our knowledge, no water analysis was carried on for the Chadian part of the NSAS, including for instance water dating (measurements reported by (Mahamoud, 1986) in Kufra Oasis in Lybia provides 10 Ky waters above 500 m depth and 30 Ky below). This indeed reflects the purpose of (Gossel *et al.*,

2004; Heintz & Brinkmann, 1989), studying the impact of water pumping in far away Egypt and the actual lack of recent characterization efforts for this Chadian part.

Recently, (Kröpelin *et al.*, 2008) published the analysis of Lake Yoa sediments (at Ounianga Kebir, see Fig. 1) allowing for a reconstruction of climate conditions from 6000 KyBP until now. They obtain a gradual change from a Savannah type landscape to semi-arid environment to present day hyper-arid conditions. The issue considered here is to what extent can this information be used to improve the knowledge of the NSAS history and reduce the uncertainties in its properties (e.g. flow parameters, boundary conditions, main geometrical features).

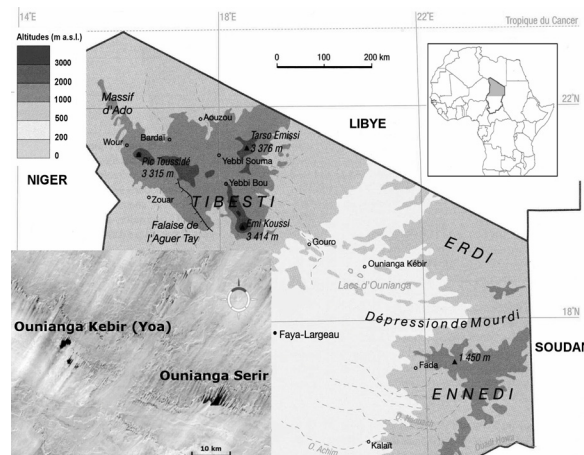


Fig. 1: Geography of the Ounianga region (NE Chad), aerial view of the desert landscape with two major lakes, Ounianga Kebir (including Yoa) to the West and Ounianga Serir to the East, fed by the NSAS.

## 2. APPROACH

The reconstruction of the SW part of the NSAS hydrogeology and hydrogeology (see Fig. 1) is addressed here. We mainly focus on the reconstruction of hydrogeological features. In this sense, it is complementary to (Grenier *et al.*, in prep) where the hydro(geo)logical models are presented in details and the ability to reconstruct the lake levels and composition is studied and compared with results issued from lake sediment analyses by (Kröpelin *et al.*, 2008). In the following, we present how the climate forcing history was constructed (treated in section 2.1), and the main characteristics of the hydro(geo)logical modelling approach (see section 2.2).

### 2.1. Selection of a climate scenario with an approach combining climate reconstruction from proxies and climate simulations

Reconstruction of paleo-hydro(geo)logy relies on good quality reconstruction of climate history, the forcing term for surface and underground flow. Advances were obtained for the region from the combined use of 1) a recent review of hydrological proxies (Lezine *et al.*, in prep) (time period 15 KyBP to present), 2) the recent analysis of Yoa lake sediments by (Kroepelin *et al.*, 2008) corresponding to the 6 KyBP to present, 3) climate simulations results from PMIP2 considering a local box around the Ounianga region, 4) dedicated climate simulation models with smaller grids and exploring some various aspects and hypotheses (e.g. with/without presence of large lakes in Africa; with/without freshwater inputs in Northern Atlantic).

Lake sediments provide through multi proxy analysis, a refined view of the evolution of the local system (roughly at the scale of a catchment area). We used the analysis from (Kröpelin *et al.*, 2008) providing major features of climatic evolution and estimation of precipitations. In addition, some of the information contained can be interpreted as hydrological proxies. For instance, until 4.7 KyBP, the large input of *Erica Type* pollens (plant growing in high altitude regions) shows that a river connection with the Tibesti existed. By 4.3 KyBP, the lake turned rapidly to a highly saline environment as a probable indication of the lake becoming endorheic. For older time periods (before 6 KyBP), the

review of (Lezine *et al.*, in prep) was considered to build a humid scenario from 11 KyBP on. The limitation of this approach based on proxy analyses is that these do not include quantification of uncertainties in the reconstruction. Further, an estimation of precipitation is provided but other variables required for the hydro(geo)logical models are not provided (potential and real evaporation rates for instance).

Climate modelling results provide independent quantitative estimates of all variables involved in the hydro(geo)logical modelling. The drawbacks associated with climate modelling is that the simulation grid size is large (e.g. of the order of 200 km for most PMIP2 cases, Paleoclimate Modeling Intercomparison Project, Phase II, site <http://pmip2.lsce.ipsl.fr/>) so that the impact of the relief is poorly included and the representation of monsoon regimes and time evolution should be improved. For the present study, specific efforts were put in 1) simulating with smaller grids (100 km), 2) simulating several scenarios. Here, the scenario including the presence of large lakes at 9.5 and 6 KyBP on a refined model (IPSL coupled ocean-atmosphere model and zoomed version of the atmospheric component of the coupled model - LMDz) was retained and provided a base to our climate scenario.

A best scenario was finally chosen, based on common discussions along the various scientific communities involved and combined used of proxies and climate simulation information. Table 1 provides precipitation and potential evaporation history selected for the best scenario. It results from joint proxy analysis and climate simulation snapshots at 9.5, 6, 4 KyBP. The reader is referred to (Grenier *et al.*, in prep) for further details.

	10.5 Ky	9.5 Ky	6 Ky	4 Ky	2.7 Ky	0 Ky
<i>Precip. (mm/y)</i>	317.8	317.8	308.2	183.4	5.0	5.0
<i>Pot. Evap. (m/y)</i>	1.0	2.0	3.0	3.0	6.0	6.0

Tab. 1 : Scenario considered (annual precipitation and potential evaporation rates) derived from snapshots at 9.5, 6, 4 KyBP and information at 2.7 Ky and 0 Ky with linear extrapolations in between.

## 2.2. Hydrological and hydrogeological approach

The hydrological and hydrogeological models were developed within the Cast3M code ([www-cast3m.cea.fr](http://www-cast3m.cea.fr)). The hydrological model is built from topographic analyses and radar pictures to identify the paleo-river network and computation of Lake Yoa water catchment properties (area, former flow network, presence of lakes and their geometrical properties (Grenier *et al.*, 2009; Grenier *et al.*, in prep). Lake Yoa water catchment area includes several major depressions treated in the model as lakes (Lake Yoa, Ounianga Serir and 8 other "lakes"). The hydrological model computes a simple lake water budget considering precipitation and evaporation balance within the water catchment areas and on free water (lake surface), water losses from upstream lakes to downstream lakes and groundwater inputs obtained from a groundwater model. This hydrogeological model (SW part of the NSAS) is 2D, based on the non-linear Boussinesq equations (unconfined aquifer) with an additional treatment of simulated heads imposed to be lower than topographic elevation. This is achieved by removal of water above topography through a source term providing the groundwater input rate to topographic depressions (Grenier *et al.*, in prep). Results and information from the literature (Gossel *et al.*, 2004; Heintz & Brinkmann, 1989; Schneider, 2004) were included. The hydrological model considers instantaneous balance while the long time scales involved in the transitory evolution are contained in the groundwater input term.

## 3. RESULTS AND DISCUSSION

Results are analysed along two lines. First, the ability to provide a coherent view of the hydrology and the climate is described and some of the major features of underground and surface flows are provided. Second, the level of information contained in the lake sediment proxies to constrain the aquifer properties and parameter values is studied.

The hydrogeological model was run for the climate scenario presented in Table 1. The initial conditions are filled up aquifer by 25 KyBP, followed by a pure discharge (zero recharge

corresponding to long arid period). From 11.5 KyBP, imposed recharge corresponds to 10% of the precipitation history. Results show that the total water volume within the aquifer slowly decreases in the first discharge phase while aquifer recharge is fulfilled within several hundreds of years to reach steady state conditions with roughly 20 mm/y of recharge (60 mm/y for regions above 1000 m asl). The dissymmetry of the answer to long draught and humid periods is related with the fact that for homogeneous aquifer, recharge operates on the total surface of the system while discharge of the aquifer corresponds to lower topographic locations. The variation of the total aquifer volume is provided in Fig. 2. Time evolutions of the groundwater inputs show similar time scales with additional local effects related with local topographic variability acting as reservoirs of various sizes (see Grenier *et al.*, in prep.).

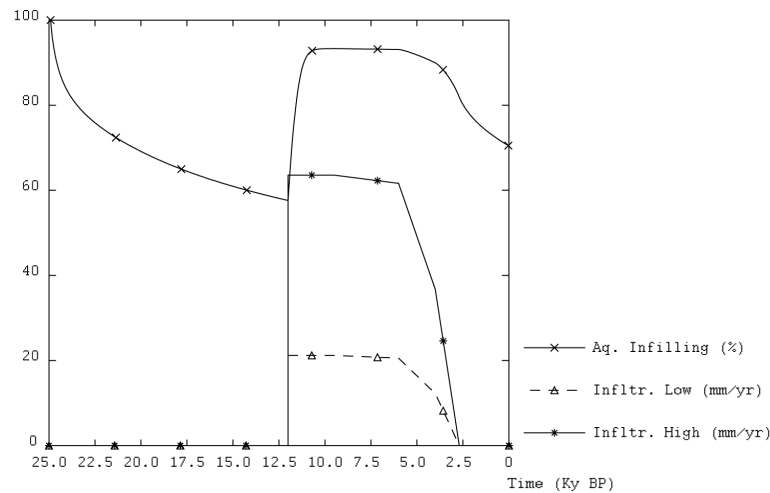


Fig. 2: Aquifer water resources (percentages of initial full filling, 25 KyBP). Recharge history derived from precipitation scenario (no recharge until 11.5 KyBP)

The lake level evolution for the 9 modelled lakes is simulated for the Holocene period. Results for Lake Yoa are easy to constrain to the lake sediment proxies, provided a higher level of precipitation is considered for zones of the water catchment area higher than 1000 m asl (Tibesti mountains). A coherent view of the paleo-hydrology and the climate scenario is thus achieved. The interplay between climatic and hydrogeological features is illustrated in Fig. 3 providing Lake Yoa budget evolution. Results show that Yoa receives no more input from upstream lakes at 4.7 KyBP, the last lake contributing having the Tibesti slopes in its catchment area. From then on its water inputs are dominated by precipitations from Yoa own catchment area (39 000 km<sup>2</sup>, 58% of the total water catchment area). Lake Yoa becomes endorheic by 4.3 kyBP (zero Yoa output) mainly due in its final stage to a reduction of precipitation amplified by the size of the water catchment area. The groundwater inputs vary within a factor of 3 for moderate levels so that the impact of groundwater inputs becomes significant only after 3 KyBP. The present Yoa budget relies fully on underground inputs and the modelled level well balances the present lake surface and evaporation rates.

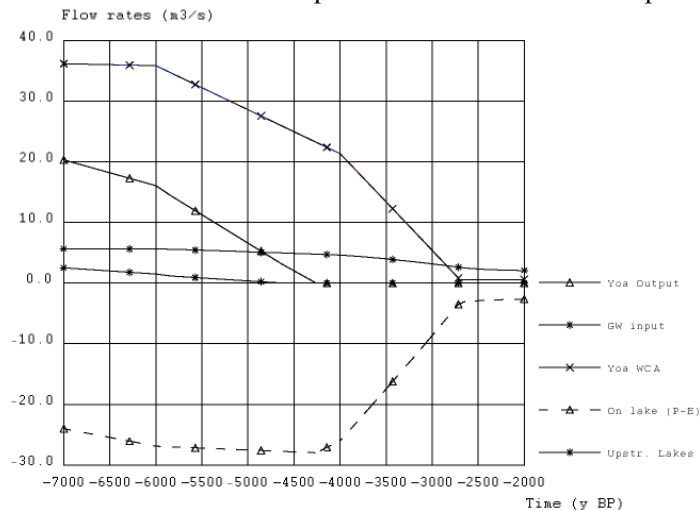


Fig. 3: Lake Yoa budget history including input from groundwater (*GW input*), from Yoa own water catchment area (*Yoa WCA*), from upstream lakes (*Upstr. Lakes*), lake budget (*Precip – Evap*) and Yoa output rate turning to zero when the lakes becomes endorheic at 4.3 KyBP.

A realistic reconstruction of underground flows in the NSAS along the Holocene period is limited by uncertainties in 1) system limits and associated model boundary conditions - differing between authors, e.g. (Gossel *et al.*, 2004; Heintl & Brinkmann, 1989; Schneider, 2004; Mahamoud, 1986) while present day head fields differ as well; 2) aquifer parameters (general agreement in the literature for permeability  $K = 3.5 \cdot 10^{-5}$  m/s, porosity  $\phi = 0.1$  corresponding to sandstone properties but the aquifer is heterogeneous including e.g. some clay units of undefined extensions).

We present here a sensitivity analysis to the permeability,  $K$ , and boundary conditions. The idea is to identify the constraining power of the information contained in the lake sediment proxies in terms of aquifer properties (here  $K$  and boundary conditions). The coupling between the underground flow and the lake model is represented by the groundwater input rate to Lake Yoa. Five simulation cases are considered (see Tab. 2 and results in Fig. 4) exploring the sensitivity of the groundwater input term to variations in permeability (*Base Case* multiplied or divided by a factor of 5 for *Case 1* vs *Case 2*) and modified boundary conditions from full no-flow boundary conditions to non zero flux from (a) the Western Tibesti region (inputs equivalent to infiltrations on a 10 km wide extended zone, *Case 3*); (b) the Eastern limit (similar treatment, *Case 4*); the Southern boundary allowing outflow to the Faya region (outflux corresponding to 90 cm evaporation rate for a 100 km<sup>2</sup> region, *Case 5*). Results show that the sensitivity to permeability is large. Western and Eastern boundary conditions have negligible influence on the groundwater input term at Yoa, probably because they are very distant. The Southern limit has intermediate influence. Former results (see Fig. 3) showed that the groundwater input term plays a dominant role only for recent years (3 KyBP until now). This is due to the large water catchment size of Lake Yoa and the slow and low amplitude variations of groundwater input term. So, while modelling the lake levels is a key step in the modelling strategy to assess the coherence between the hydro(geo)logy reconstruction and the proxy record, the constraining power of lake sediment proxies is limited for the present case. It indeed finally boils down to the constraining power of present inflow rates from the aquifer to the lakes. They can be directly measured from present conditions considering the lake surface and evaporation rates. It is consequently not possible to differentiate *Base Case* and *Case 2* and *Case 3* while groundwater inputs allow some constraining power on permeability and Southern domain limit potentially providing water to sustain the Faya region high water levels. Our base case simulation leads to a 2 m<sup>3</sup>/s value well balancing the present lake surface and evaporation rate.

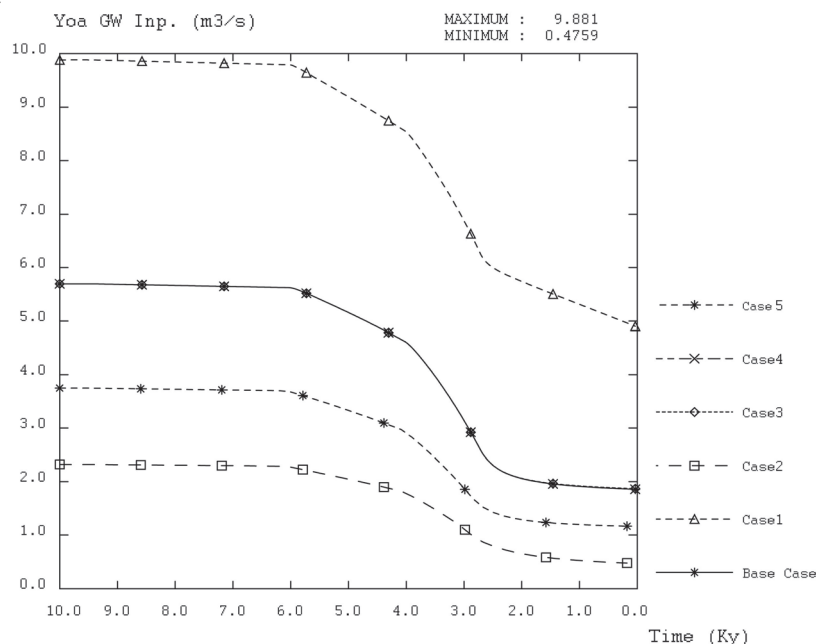


Fig. 4: Groundwater input term (m<sup>3</sup>/s) to Lake Yoa from 10 KyBP to present considering the cases presented in Tab. 2. *Base Case* as well as *Cases 3 & 4* provide identical GW input rate histories.

	K (m/s)	BC North	BC West	BC East	BC South
<i>Base case</i>	$K_0 = 3.5 \cdot 10^{-5}$	No flow	No flow	No flow	No flow
<i>Case 1</i>	$5 \cdot K_0$	No flow	No flow	No flow	No flow
<i>Case 2</i>	$K_0 / 5$	No flow	No flow	No flow	No flow
<i>Case 3</i>	$K_0$	No flow	In flow	No flow	No flow
<i>Case 4</i>	$K_0$	No flow	No flow	In flow	No flow
<i>Case 5</i>	$K_0$	No flow	No flow	No flow	Out flow

Table 2: Overview of the simulation cases included in the sensitivity analysis. *Base case* is for permeability  $K = 3.5 \cdot 10^{-5}$  m/s, porosity  $\phi = 0.1$  and no flow boundary conditions

### 3. CONCLUSIONS

We demonstrate the importance of a good climate signal for the reconstruction of the history of such a large aquifer as the NSAS having such long transient history. In this region where lake sediment analyses were conducted, hydrological simulation plays a key role in simulating the lake levels (ie the lake sediment proxies) and thus assessing the coherence of the interdisciplinary Holocene reconstruction approach. The present knowledge of the SW part of the NSAS nevertheless bears large levels of uncertainties. The information contained in the lake sediments is related to aquifer properties by means of the groundwater input term in the lake budget. In the case of Lake Yoa, the groundwater input term has been a minor component of the water budget until recently (3 KyBP) when almost present conditions installed. So the proxy history has no constraining power on aquifer properties, but serves to assess the climate history which is the forcing term for the aquifer model. Nevertheless, present day values of groundwater inputs computed from lake surfaces and evaporation rates are valuable pieces of information for comparison with simulations. We showed that this information has a strong constraining power on local aquifer properties (similarity with pumping tests but with larger range) and more limited constraining power on boundary conditions situated at further distances. More field measurements are required in this region to obtain a reliable piezometric head database, analyses of water chemistry and water dating that could help distinguishing between aquifer recharge scenarios.

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