Data scarcity in the large semiarid Lake Chad basin: incorporating environmental tracers as *a priori* information for groundwater modelling

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Abstract The large unconfined Quaternary aquifer of the Lake Chad Basin is located in the Sahelian climatic zone. Due to a vast extent of the region and difficulties in its access, traditional hydrodynamics data (such as K, S, h) are limited in time and space. To cope with data scarcity, the following groundwater modelling methodology was retained. First, we used *a priori* hydrochemical and geomorphological information to create a conceptual model of regional recharge-discharge. Second, we calibrated absolute values of effective recharge keeping fixed a single mean value of hydraulic conductivity and specific yield. Third, we estimated uncertainty of the results. The model simulated a steady state groundwater water balance in the 1960s and a piezometry drop in response to decreasing rainfall in 1960s-2000s.
Key words semiarid regions; groundwater flow model; isotopes; model uncertainty

INTRODUCTION AND SITE DESCRIPTION

The Lake Chad basin is the largest endoreic basin in the world. It is located in a rift system and extends from the vicinity of the equator to the north of the tropic of Cancer.

Most of the water used by inhabitants is consumed from the 500,000 km^2 Quaternary aquifer that is made of aeolian and fluvio-lacustrine sediments (Fig. 1).

The piezometry of this unconfined aquifer presents large natural anomalies – two domes and five depressions (UNESCO/PNUD/LCBC, 1972), whose origin and evolution are not yet well characterized. Piezometric levels vary from 390 m in the west (highest surface elevations) to 230 m in the centre of the Chari-Baguirmi depression. Seasonal variations of the water table reach 2 m near the rivers and are much lower everywhere else.

Water scarcity has always existed in the Lake Chad basin due to its arid and semiarid climate, but it has worsened during the last decades as a consequence of the regional decrease in rainfall (Niel *et al.*, 2005) or/and because of intensifying of water exploitation. The average water table drop since the 1960s was estimated to be of 0.10 m $year^{-1}$ for piezometric domes and 0.05 m $year^{-1}$ for alluvial plains and piezometric depressions (Ebershweiler, 1993).

Among the numerous hydrogeological studies that have been performed in the region (UNESCO/PNUD/LCBC, 1972; Greigert, 1979; Schneider & Wolff, 1992), only few (Ebershweiler, 1993; Leblanc, 2002) gave quantitative estimates of the water balance. An explanation is that data acquisition is difficult due to a vast extent and hard accessibility of the region. Additional problems in simulation of the hydrogeology are caused by heterogeneity of the continental sediments, complex geomorphology and strong role of evapotranspiration.

Our paper shows how *a priori* information on hydrochemistry and geomorphology can be combined with traditional hydrogeological data to simulate the regional groundwater flow. An important issue was to understand on which questions we could answer by our model within a range of uncertainty of the results.

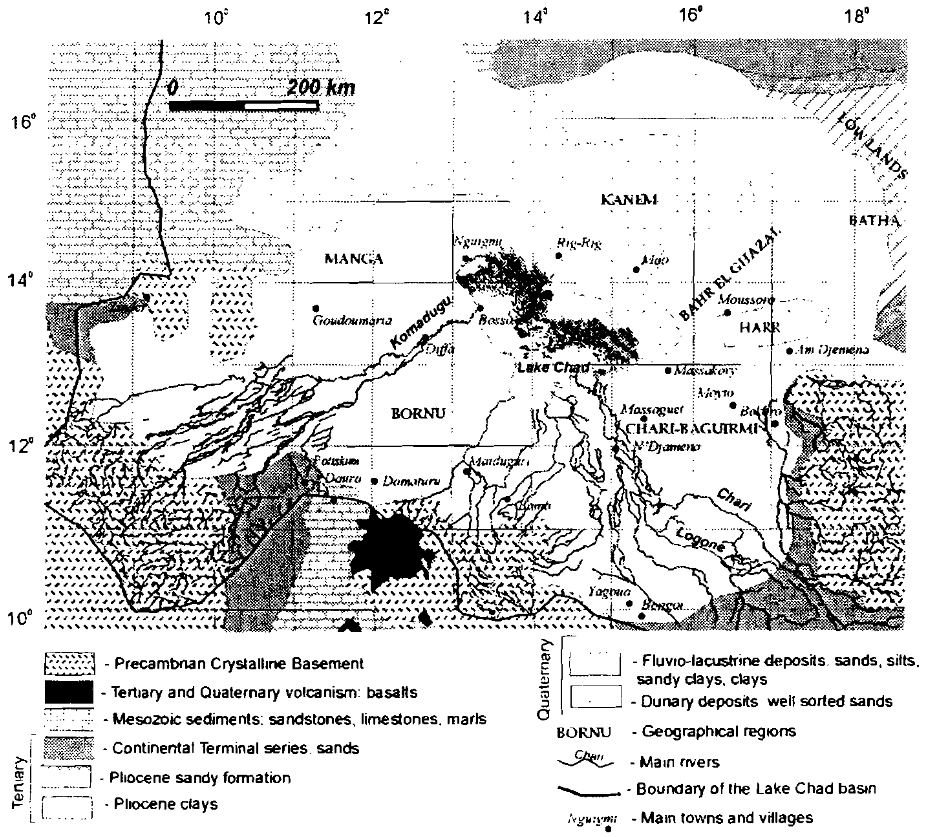

Fig. 1 Geography and geology of the Quaternary aquifer and surrounding areas

ANALYSIS OF HYDROCHEMICAL DATA

For this study, we used published data (Fontes *et al.*, 1969; Leduc *et al.*, 2000; Edmunds *et al.*, 2002) as well as those presented in technical reports (UNESCO/PNUD/LCBC, 1972; Schroeter, 1973) and in PhD theses (Djoret, 2000; Gaultier, 2004). Overall, the database comprised isotopic (^{3}H, ^{14}C, ^{2}H, ^{18}O) and major ion chemistry for 675 water samples (among them: rainfall - 80, surface water - 171, groundwater - 424) collected on more than 400 locations.

The evaporated Lake Chad waters present higher $\delta^{18}O$ / $\delta^{2}H$ than those from rivers and rainfalls; such high isotopic values in the lake ($\delta^{18}O \geq +5$ ‰) result from evaporation. Thus, higher electrical conductivities and ionic contents (e.g., Cl) can also be used as tracers of the "lake origin". However, it was not possible to separate river waters from those coming from rainfalls because both display similar compositions.

The $\delta^{18}O$ distribution reveals that evidence of mixing of lake waters with the groundwaters is limited to few kilometres inland from the shore (Fig. 2). High $\delta^{18}O$ contents in several locations of the Harr dunes (east from the lake) are related to local interdunal ponds whose water compositions are influenced by evaporation.

Any detected ^3H (≥0.5 TU) in groundwater was considered as a signature of modern (last 55 years) recharge. The conclusion from the study of 216 groundwater samples is that there is an evidence of modern recharge almost everywhere except in central parts of the piezometric depressions. However, presence of modern waters does not necessary mean that recharge exceeds evapotranspiration.

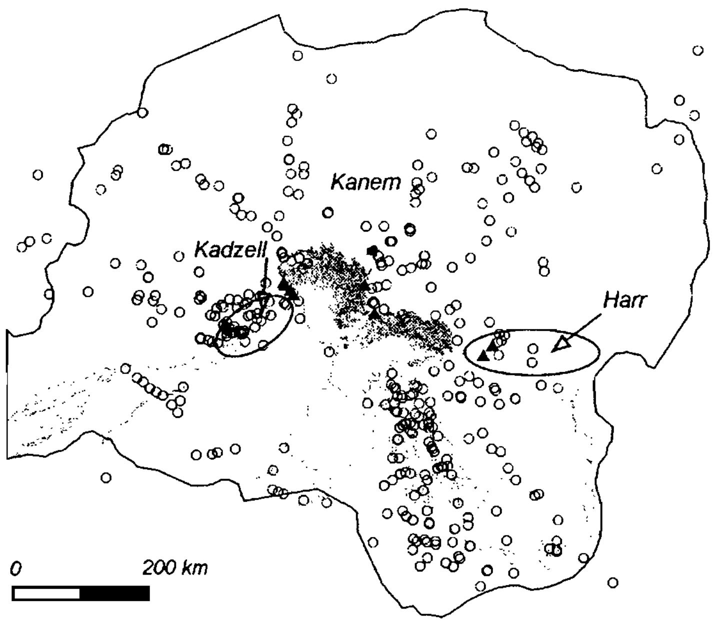

Fig. 2 $\delta^{18}O$ distribution in groundwaters: circle: $\delta^{18}O < +5$ ‰, triangles: $\delta^{18}O \geq +5$ ‰

Due to the possible presence of continental carbonates in the deposits, ^{14}C activities (ranging between 12.1 and 153.5 pCm for 53 groundwater samples) could not be used for water age dating; however, the ^{14}C pattern still provides information on groundwater flow. For instance, in the Kadzell depression (Fig. 2), the "oldest" groundwaters are located in the centre of the depression while the "youngest" are associated with its edges (Gaultier, 2004). This supports the hypothesis of low flow velocities toward the centre of the depressions. In the Kanem dome (Fig. 2), on the contrary, "the youngest" groundwaters are located in the centre, surrounded by the "older" ones – that corroborates the perception of domes as areas of higher recharge.

NUMERICAL MODELLING OF THE GROUNDWATER FLOW

Steady state model

The model was developed on the base of the FEFLOW finite-element code. The aquifer was approximated by a single unconfined layer discretized in 11,427 triangular prismatic elements.

In Lake Chad and in external boundaries, a constant head was set up with values read from the map of UNESCO/PNUD/LCBC (1972).

For model calibration we used 2183 values of depths to the water table averaged for the years 1960-2004. Because seasonal and long-term variations were comparatively small (< 3 m), uncertainties of the steady state model due to observations from different periods were considered negligible.

104 pumping tests resulted in log-normally distributed hydraulic conductivities (K) between 10^{-6} and 10^{-3} m s^{-1}, with a geometrical mean of 1×10^{-4} m s^{-1}. The spatial distribution of K does not show any representative zonation; thus, for the numerical model, a single K value of 3×10^{-5} m s^{-1} was arbitrarily considered. In the fluvial plains of the Komadugu and in the Bahr-el-Ghazal area, it was not possible to achieve satisfactory agreement between simulated and observed piezometry. Since there was no evidence (from hydrochemistry, geomorphology) of higher evapotranspiration, we imposed a lower K value for these regions that are associated with higher clay content than in Manga and Kanem (UNESCO-PNUD-LCBC, 1972; Ebershweiler, 1993).

In a sensitivity analysis, we increased and decreased all cell values of K by a factor of 3 and subsequently calibrated recharge and evapotranspiration. Generally, all water balance components had to be also multiplied or divided by 3 to achieve a satisfactory agreement between measured and simulated heads.

We specified recharge-discharge zones *a priori* from hydrochemical and geomorphological indicators, while their values were results of model calibration. Zones of effective recharge (positive balance) were associated with the flood plains (Komadugu, Chari, Logone) and with the dune fields (Kanem, Manga). In other regions a tiny excess of evapotranspiration was considered. The highest evapotranspiration was assumed to be around Lake Chad to satisfy, in one hand, significant outflow from the lake estimated from chemical balance (Roche, 1980), and, on another hand, negligible influence of the lake water on the groundwater ($\delta^{18}O$ data).

In calibration procedure, by varying values of recharge-evapotranspiration zones, we aimed to achieve the best agreement between a majority of observed and simulated piezometry. The final variant was accepted because: 1) $\frac{\Sigma\sqrt{(Hsim - Hobs)^2}}{n} = 5.6$ m (relatively small), 2) average simulated error was 0.14 m, thus indicating a rather symmetrical distribution of positive and negative errors; 3) spatial distribution of positive and negative errors was quite homogeneous (Figure 3).

Table 1 presents the calculated regional groundwater balance. Major evapotranspiration (83%) occurs from the narrow zone (< 5 km) around the lake; other groundwater budget components are very small compare to, for example, the mean Chari River discharge (40×10^9 m^3 $year^{-1}$, 1950s-60s).

Table 1 Steady state water budget of the Quaternary aquifer (reference simulation variant).

Quaternary Aquifer water balance components	Inflow (10^6 m^3 yr^{-1})	Outflow (10^6 m^3 y^{-1})
Constant head boundaries	305.3	21.1
Including :		
Infiltration from the lake Chad	280.1	
Total effective recharge/evaporation	70.3	354.6
Including :		
Komadugu fluvial plain	7.6	
Chari-Logone fluvial plain	9.0	
Kanem dune fields	40.5	
Harr dune fields	4.0	
Evaporation from the groundwater table around the lake		294.4
TOTAL:	375.6	375.8

The regional K value chosen as the reference variant (3×10^{-5} m s^{-1}) is usually associated with fine sands; increasing this value by a factor of 3 would correspond to well sorted sands, rarely described in the Quaternary aquifer. Thus, we consider the highest, in sensitivity analysis, recharge and evapotranspiration rates as strict (probably over-estimated) maximum, while a model variant with a lower K is still realistic. For this type of deposits, K could be as low as 1×10^{-6} m s^{-1}. Such a value would further lower calibrated recharge and evapotranspiration rates.

Transient model

A gradual reduction of groundwater storage, coinciding in time with a regional decrease in rainfall, was observed in the second half of the 20th century. By transient modelling, we aimed to understand how much should have declined recharge over the years 1960s-2000s to cause the observed drop in water levels.

In construction of a transient recharge-discharge distribution we implied a gradual decrease in recharge for the period 1961-1971 and its constant rate afterwards, reduced (50% as maximum in Kanem) compared to the steady state. The whole calibration procedure was limited by varying regional value of a specific yield (S) and a corresponding value of reduction of a recharge for the year 1971 compare to the steady state. The calibration criteria was a fit between observed and simulated drawdowns in wells over the period 1960-2004.

Assuming S = 3%, we achieved a satisfactory agreement between observed and calculated drawdowns in case of reduction in the groundwater storage, due to excess of evapotranspiration, of 3.1×10^{10} m^3 for 1961-2004. Although recharge amount was not considered to have changed after 1971, the system has not yet arrived to steady state and would result in further drawdowns of the water table.

On the assumptions of lower (0.5%) and higher (10%) regional S value the transient model gives a good agreement with observed piezometry in case of reducing of a groundwater storage by 6.1×10^9 m^3 and 6.5×10^{10} m^3 respectively.

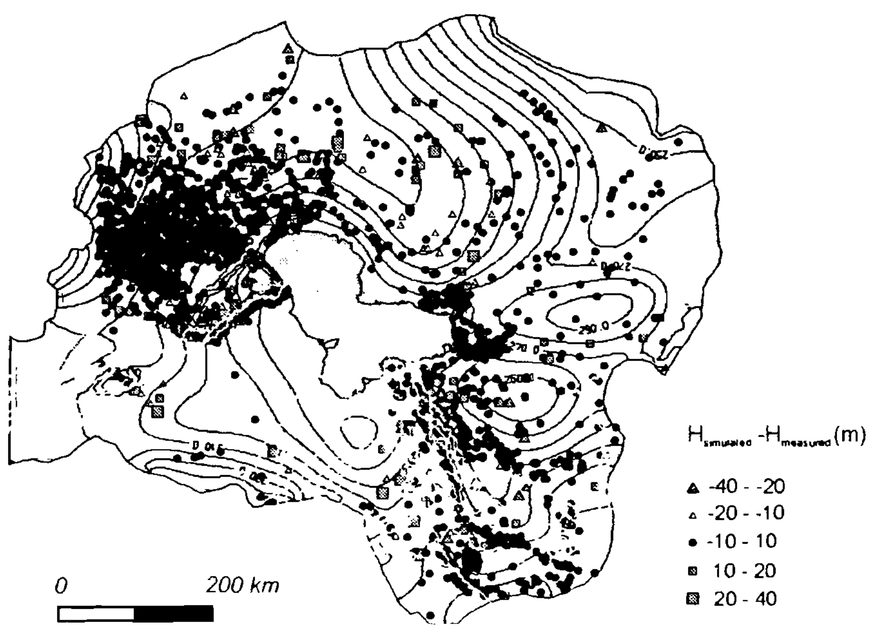

Fig. 3 Model results: piezometric map and spatial distribution of simulated errors

Water consumption from the Quaternary aquifer in the Chad Republic was around 11×10^7 m^3 $year^{-1}$ in 2002 (SDEA, 2003). However, water exploitation was concentrated in the southern part of the aquifer (N'Djamena) with nearly *zero* in the northern territory, where decrease in the water table levels is higher (Kanem). Additionally, the water table decrease started from the beginning of the 1960s when water extractions were lower by a half. Thus, the second half of 20th century piezometry drop was probably caused by the regional long-term decrease in rainfall.

CONCLUSIONS

In our study, we simulated groundwater flow in the Quaternary aquifer of the lake Chad basin and we obtained calibrated datasets for transmissivity, recharge and evaporation. As a result, we obtained a regional water balance with a range of estimated uncertainty.

The recharge and evapotranspiration rates are very small: recharge in the dune fields lies between 0.5 and 4.5 mm $year^{-1}$, infiltration from the rivers and flood plains between 0.8 and 1.2 mm $year^{-1}$, while regional evaporation is less than 0.5 mm $year^{-1}$ (5 mm $year^{-1}$ for evaporation in the vicinity of lake Chad). These estimates are generally lower than the figures obtained by Ebershweiler (1993) and Leblanc (2002).

Since the beginning of the 1960s a gradual drop of the water table has been observed; the corresponding reduction of groundwater storage was simulated to be 3.1 $\times 10^{10}$ m^3. The drop of the groundwater table was caused by decrease in annual rainfall rather than groundwater exploitation.

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