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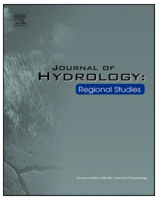

The Lake Chad transboundary aquifer. Estimation of groundwater fluxes through international borders from regional numerical modeling

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ABSTRACT

Study Region: Africa. The Lake Chad transboundary aquifer
Study Focus: To understand transboundary groundwater hydrodynamics and estimate quantitative groundwater fluxes values between aquifer-sharing countries. To enable estimations, we developed an updated 3D 'quasi steady-state' regional groundwater flow model of the Chad Formation based on integrating extensive available information and reflecting the best current conceptual understanding to date. The conceptual model was tentatively assessed by a steady-state numerical model based on MODFLOW.
New Hydrological Insights for the Region: This model simulates lateral groundwater flows between neighboring countries, and also provides insights into the large-scale flow pattern and flows among hydroestratigraphic units. Modeling indicated that groundwater fluxes through international borders exist between Basin-sharing countries, except between Central African Republic and Cameroon, where a buffer area was considered for modeling purposes, leading to more uncertain results. From 14ºN parallel to further north, data are scanty and outcomes should be carefully considered. Forecasting transboundary impacts indicated that changes in recharge rates were more sensitive that changes in groundwater abstraction. To date, abstraction represents a small part of the water balance, but if it increases, it can become a driving factor in the future. Land use change and water use in the source areas (southern area) will have the strongest impact on transboundary groundwater flows due to changes in recharge, which will lead to quantitative changes in groundwater levels, artesian conditions, or even water quality.

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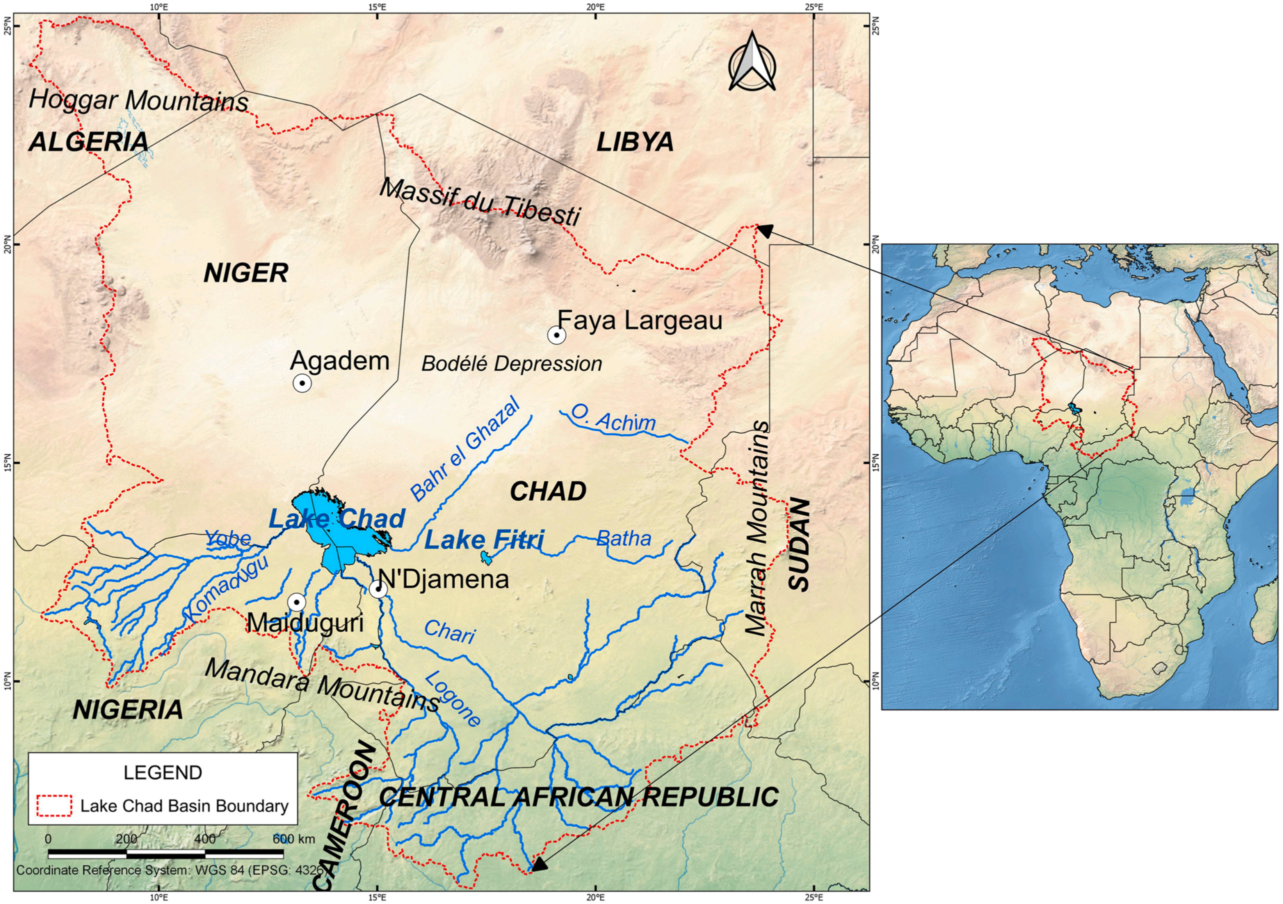

Fig. 1. The Lake Chad Hydrologic Basin (BGR-LCBC, 2009). Present day Lake Chad boundary.

1. Introduction

The Lake Chad Basin is an inland drainage system that includes Lake Chad, and covers an area of about 2355,000 km^2 in the eastern part of the Sahel region, Africa. It is shared by Algeria, Cameroon, Central African Republic, Chad, Libya, Niger, Nigeria and Sudan to a greater or lesser extent. The water resources in the Lake Chad Basin are the source of livelihoods and economic development, and the hydrologic dynamics of the Lake and its basin are closely linked with economic productivity and food security. As Member States make efforts to develop water resources for economic growth, the Lake Chad Basin Commission has the mandate to monitor and understand water resources and their use in order to ensure sustainable transboundary water resources management.

Several aquifers have been identified in the basin, where the sedimentary Chad Aquifer Formation (CAF) is of primary use, and is one of the largest aquifer systems in the world because it extends along the entire basin (IGRAC, 2012; IGRAC, UNESCO-IHP, 2015). In the present-day, while water availability is not a limiting factor in the southern tropical part of the basin, it constitutes the main water resource in the northern area. There is concern about increasing abstractions possibly causing significant impacts on the basin's ecosystems, water level and the Lake Chad extent and groundwater level drawdown in individual countries and local areas, which have led the 'Water Charter' to be adopted (www.cblt.org/en/themes/lake-chad-water-charter-vehicle-sub-regional-integration-and-security). The aim is 'to promote sustainable development through the integrated, equitable and coordinated management of natural resources, particularly the basin's water resources' at the basin level. One key issue involves water availability in sharing countries and further transboundary management (Rivera and Candela, 2018a). Thus, an updated groundwater model that includes all the available information to date is a useful representation to understand the current groundwater dynamics system. Numerical modeling is a key tool used to represent current understanding by putting existing data to good use, informing about new data collection efforts and forecasting behavior. The efforts herein indicated to better understand groundwater dynamics contribute to this goal.

Modeling groundwater resources is no new undertaking in the Chad Basin. For the Chad Aquifer Formation (Quaternary, Lower Pliocene and Continental Terminal aquifers) (Fig. 1), and since the pioneering modeling works of Schneider (1989) and Eberschweiler (1993) with the GARDENIA code based on data from 1960, some hydrogeological models have been developed to date. Only a few of them are on a regional scale, but they do not cover the entire hydrogeological basin and hydro-stratigraphical units of The Chad Formation. Up-to-date information and concerns about transboundary issues have not been investigated. Regionally, Leblanc (2002) mainly focused on the recharge and discharge areas definition for the Quaternary aquifer by combining satellite imaginary data, GIS

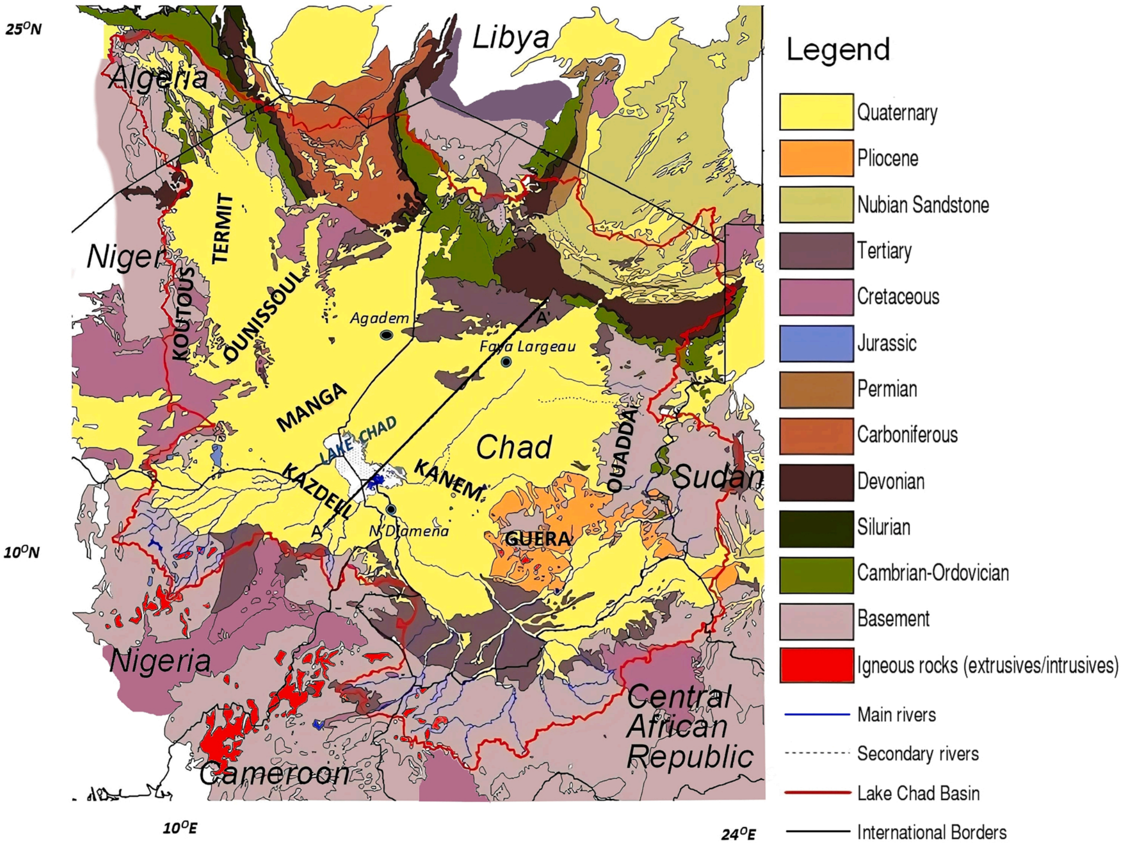

Fig. 2. The red line indicates the Lake Chad Hydrologic Basin limits. Geology of the basin area; geological formations and age (modified from Schneider, 1989; BGR-LCBC, 2009).

methods and MODFLOW 96, based on a single layer of variable grid transient mode. Based on NOAA-AVHRR and GRACE remote sensing data, Boronina and Ramillien (2008) used FEFLOW to simulate the Quaternary aquifer piezometric map, including domes and depressions, with a single unconfined layer. With this regional (transient) modeling, the system extension coverage of the Quaternary aquifer covered about 500,000 km^2, which correspond to the basin central region, Lake Chad and its surroundings and the Chari-Baguirmi area. Their outcomes pointed out data sparseness, the weak aquifer impact of groundwater abstraction and natural recharge spatial variability. Both models reproduced existing piezometric depressions by taking exfiltration to be a discharge mechanism.

Locally, and based mainly on MODFLOW with different hydrological objectives, and after considering diverse areal extension ranges, modeling efforts that focus on the unconfined Quaternary aquifer have been made in certain areas of interest. The result of the steady-state modeling done of the Chari-Baguirmi Quaternary aquifer depression by Massuel (2001) and Abderamane (2012) indicate Lake Chad's limited contribution, major seasonal inputs from the Chari River and the long residence time of the deep groundwater in depressions, as provided by chemical and isotopic data (Abderamane, 2012). To reproduce the Kazdell plain (Niger) piezometric depression (Fig. 2), Gaultier (2004) jointly simulated a change in precipitation in the last 30 years with exfiltration. To evaluate the past and present hydrogeochemical processes of the Kazdell (Niger) and Bornu (Nigeria) areas, Zaïri (2008) defined a monolayer transient model. In the Chari-Logone area, Candela et al. (2014) developed a flow model for the upper aquifer (*Q* and *CT*) that focused on forcing climate parameters to assess groundwater recharge.

In the present study, the hydrogeological conceptual model of aquifer system development in the Chad Formation hydrogeological system's natural extent is defined by linking hydrogeological and geochemical data with the 3D geological model of the Lake Chad Basin. Here conceptualization involves identifying and describing physical processes, heads and flows of the groundwater controlling groundwater movement and storage in the hydrogeological system. It includes data collection, reviews and analyses, while critical data are reviewed to ensure that errors are lacking for further modeling. This is a prerequisite for designing the numerical model.

The aim of developing a numerical groundwater 'quasi steady-state' 3D regional flow model is to provide a quantitative tool that assesses land and water use impacts on the environment and groundwater systems. Model development was based on the conceptual model defined for the 2004–2011 period. The main objectives at the global and transboundary levels were: understanding groundwater flow processes; developing relations between aquifer units, groundwater recharge and extraction locations and rates.

2. Study area. The Lake Chad transboundary aquifer

The Lake Chad Hydrologic Basin lies between 6°N and 24°N latitude, and between 8°E and 24°E longitude (Fig. 1), and covers about 2381,000 km^2. It is shared by the five Member States of the Lake Chad Basin Commission-LCBC (Cameroon, Central African Republic, Chad, Niger, Nigeria), and extends to Algeria and Sudan and a small area of Libya. It is bounded by the edges of Hoggar and Tibesti to the north, and reaches the Marrah Mountains to the east. The southern limit lies north of the Mandara mountains in Nigeria, Cameroun and Chad. The basin is separated to the west by a watershed from the Niger River.

The plain has a low relief landscape with heights from above 3000 m in the north, NW and SW, to 165 m in the center (Bodélé depression). The region extends from the forested savannah in the south, to the savannah in the central part, and to the desert areas in the north. The Conventional Basin's heterogeneously spread population is estimated at about 44 million. The population's water supply is mainly groundwater from a number of shallow wells in all the transboundary countries, but no allocation-sharing agreement has been reached (Nijsten et al., 2018). The most important activity for over 60% of the population is rain-fed or flood recession-based agriculture in the Chari-Logone and Komadougou-Yobé basins, and irrigated agriculture from dams or groundwater. Agriculture is the main water use, with intensive agriculture in areas of Nigeria and Cameroon.

The area is characterized by wide spatial climate variability, with the arid North of N'Djamena zone, a subhumid climate in the central part and a humid climate in the south. The mean annual rainfall ranges between 10 mm and 1900 mm. Most rainfall occurs between April and October. Average temperatures from north to south vary from 41ºC to 18ºC. Potential evapotranspiration (ETP) values of 2000–3000 mm/yr are common.

Lake Chad, in its current 'small Lake Chad' state (around 2000 km^2), is an endorheic surface system supplied by 95% of the annual inflow to the lake by both the Chari-Logone River (Shaofeng et al., 2017) and Komadougou-Yobé River systems, with about 3% (RAF/7/011, 2017); in past times, millennial to centennial superimposed hydrological variations led by periodic climate changes exist leading to outside drainage (Ghienne et al., 2002; Maley, 2010). Lakes Iro and Fitri are hydrologically controlled by the rainy season from June to September. The principal permanent rivers occupy the area below the 15th southern parallel, with the Chari and Logone River system in the basin's southern part, and Komadougou and Yobé in the western part (Fig. 1). From July to December, river plains (Yaéré, Dérésia, Massenya, Salamat and Komadougou-Yobé) are periodically flooded.

Soil types are mainly fluvisols, vertisols, hydromorphic soils (impervious) and aeolian sands (FAO, 1973; LCBC-GIZ, 2016).

Located in the Chad graben region, the Lake Chad area has been it has been well-studied by many authors (Ganwa et al., 2009; Gear and Schroeter, 1973; Genik, 1992; Lopez et al., 2016; Mbowou et al., 2012; ResEau, 2016; Schneider and Wolff, 1992; Swezey, 2001; Vicat et al., 2002, among others). The geology of this area can be described as a succession of marine and continental sediments deposited on the Precambrian basement of the Mesozoic (Cretaceous), Cenozoic (Oligocene–Miocene referred to as Continental Terminal and Pliocene) and Quaternary. Only sedimentary basin filling is herein briefly described.

The in-filling Lake Chad Basin is composed of fine and coarse sands with some gray clays of the Late Cretaceous; the Continental Terminal (*CT*) of sandstone and clay series, generally in discordance with Cretaceous rocks (Schneider and Wolff, 1992); the Pliocene (*Pli*) of fluvial sands (Lower Pliocene, *LPli*) overlain by lacustrine clays; the Quaternary (*Q*) with sandy or sandstone formations. The *CT* outcrops in the southern and northern basin fringes with a depth of 100–300 m in the central part. The Quaternary (BGR-LCBC, 2012),

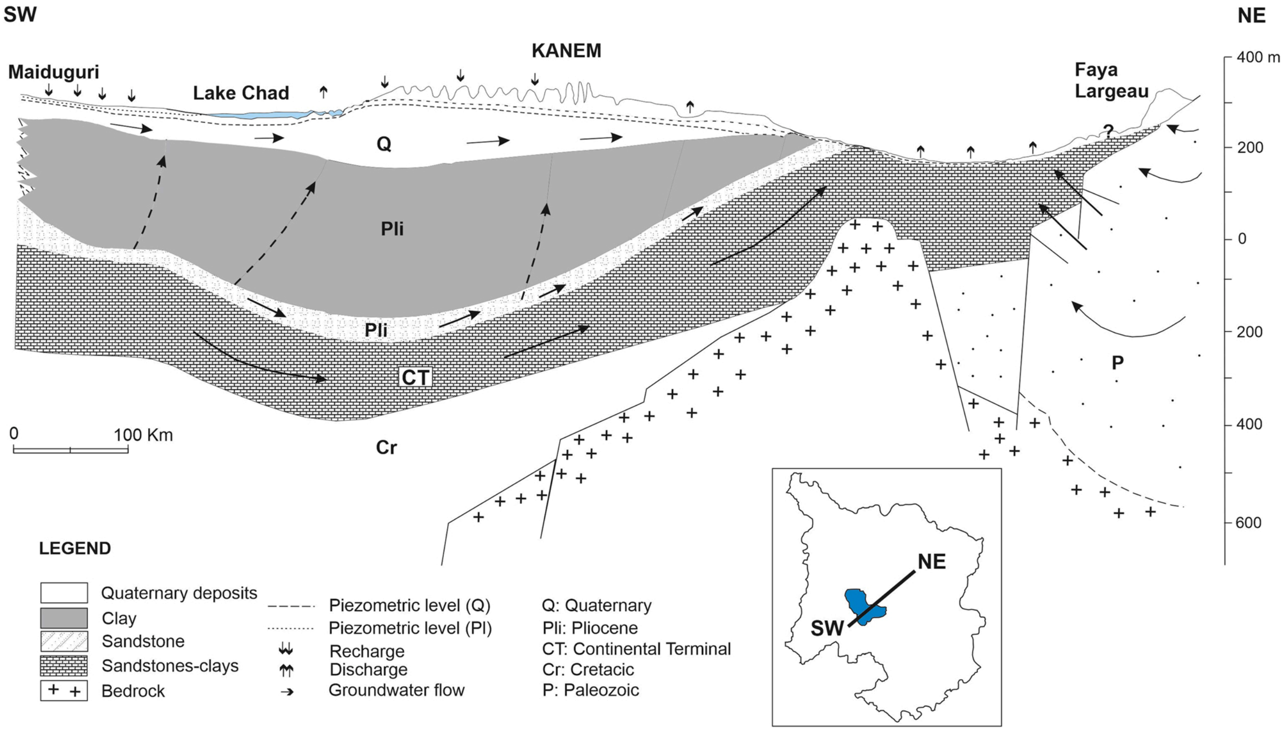

Fig. 3. Cross-section of the basin (after Schneider, 1989). See inset map and Fig. 2 for location.

covering the entire study area, constitutes the uppermost layer and is made up of Moji Series (early Pleistocene), a fluvio-lacustrine clayey series with evaporites (gypsum), and aeolian sand dunes composed essentially of quartz sands of the "Ogolien" age, mainly north of Lake Chad.

Precambrian crystalline rocks (schists, granite, etc.) outcrop on the basin's southern edge and the eastern basin area.

2.1. *Groundwater hydrology*

Three sedimentary aquifers are defined in the Lake Chad Basin: the Chad Aquifer Formation-CAF (Quaternary-Pliocene-Miocene age), the confined Continental Hammadien and the Continental Intercalaire (Cretaceous). On local and intermediate scales, units are heterogeneous, and present wide lateral variability in sediment type and facies distribution with different aquifer levels and varying hydraulic conductivities (laterally and depth-wise). Regionally, hydrogeological research has been carried out by a number of authors (Alkali, 1995; ANTEA/EGIS/BCEOM/CIAT, 2012; Bonnet and Murville, 1995; Eberschweiler, 1993; Leblanc, 2002, 2007; Massuel, 2001; PNUD, 2003; Schneider, 1989; Zaïri, 2008; among others to be cited). In addition, LCBC Member States, funding international agencies (e.g., WB, 2020) and academic institutions have many documented sources.

The Chad Aquifer Formation (FAO, 1973; Schneider, 1989), main objective of modeling, extends along the entire basin and is composed of the following hydrostratigraphical units (Fig. 3): *i*) the upper phreatic aquifer, made up of Quaternary deposits (*Q*); *ii*) the Lower Pliocene materials, the intermediate confined aquifer (*LPli*); *iii*) a deep semiconfined aquifer made up of Continental Terminal deposits (*CT*, Oligocene-Miocene). The Upper Pliocene (*PLi*) constitutes the confining clay layer. Hydraulic connectivity between different aquifers exists, and also between surface water (lakes and rivers) and groundwater. Groundwater exploitation takes place mainly in the Quaternary aquifer and the *CT* in the southern area where it outcrops, and only deep boreholes exploit aquifers in the

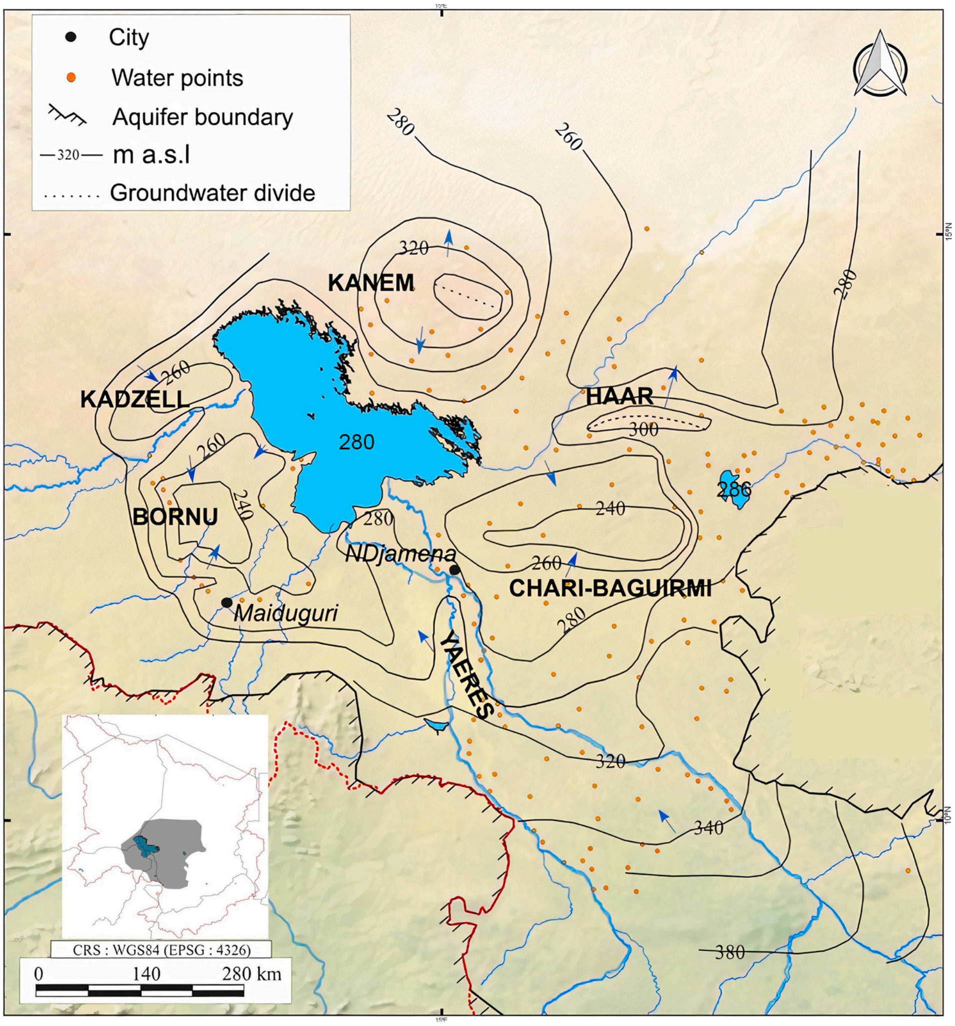

Fig. 4. Upper aquifer potentiometric surface (2008–2011); major rivers within the aquifer boundaries are shown (blue line). Lake Chad reference level 280 m. The inset map (bottom left) shows the location of piezometric map coverage in the Lake Chad Basin areal extension.

most important cities (i.e. N'Djamena).

The Quaternary unconfined aquifer (Holocene and Pleistocene) includes deposits of aeolian sands and fluviodeltaic materials that cover most of the surface area geology. Average thickness is 40 m, and ranges from 2 m to 185 m. The aquifer, considered to be continuous on the LCB scale, is heterogeneous with considerable lateral variability, sediment type and facies distribution. *The Lower Pliocene confined aquifer* consists of lacustrine clay with some alternating alluvial sand layers at the bottom of the formation (red sand). It extends over most of the Chad area toward Niger (Manga), with boundaries on crystalline rocks (W), the Termit Basin (NW) and the Agadem Basin (NE). It is found only in boreholes deeper than 100 m, at around 300 m and 200 m in the central part of Manga in Niger (Sabljak, 1998), and 450 m south of Lake Chad (ANTEA-EGIS/BCEOM/CIAT, 2012). Thickness vastly varies between 30 and 50 m on boundaries, and it may reach 150 m in the central part of Chad. It presents flowing artesian conditions in some areas of the Nigerian part. *The Continental Terminal confined/unconfined aquifer* is made up of sandy-clayey deposits, laterites and iron-sand are present (Bhata area), and it only outcrops in the southern basin part. Thickness is around 25 m on eastern boundaries (Fitri area), and can reach 600 m in existing tectonic grabens, but is generally around 100 m.

The CAF potentiometric surface (water table aquifer composed of *Q* and *LPli-CT*) for the most complete spatial and time period coverage (2008–2011) is plotted in Fig. 4; The scarce groundwater level data for the deep confined aquifer (*LPli-CT*) only allow groundwater contours to be displayed in the southern part. The regional groundwater flow is toward the central and northern basin zones (Bodelé, north of Kanem, Fig. 1). The highest measured groundwater level is 370 m a.s.l. in the southern basin part where the main natural recharge takes place. The groundwater level generally lowers toward Lake Chad and to the upper northern basin part (the Lowlands). However, very little information is available about this latter area. The lowest values are always observed in depressed zones with a minimum value of 240 m a.s.l. (Chari Baguirmi).

Two piezometric domes are present north of Lake Chad, and are associated with the dune-fields recharge area. High groundwater values also appear on the southern margins corresponding to the outcropping aquifer recharge area. Naturally-occurring extended piezometric depressions exist in Bornou and Kazdell (SW of the lake) and Yaéré and Chari-Baguirmi (E of the lake) (Fig. 4), with the groundwater level at a depth of 40–60 m below the soil surface.

For the Q aquifer, compiled information on transmissivity (T) and hydraulic conductivity (K) (Table 1) (Leblanc, 2002) indicates that T values range from 10^{-4} to 10^{-3} m^2/s in the southern and western basin parts, and from 10^{-2} to 10^{-1} m^2/s in the eastern and central basin parts. K values go from 10^{-6} to 10^{-5} m/s in the western part, and from 10^{-4} to 10^{-3} m/s in the eastern part. Therefore, the hydraulic parameters in the aquifer significantly differ. The aquifer-testing data that define key parameters for the *Q* and *LPli-CT* are available in a few locations.

2.2. *The conceptual hydrogeological model*

From top (Holocene) to bottom (Tertiary), the CAF hydrogeological system is formed by three hydrostratigraphic aquifer units (*Q, LPli. CT*) and one aquitard (*Pli* clays). Basin boundaries are crystalline rocks (granite, schists) that outcrop in the eastern and southern parts on the Chad and Nigeria borders, with sandstones (Tibesti and Nubian aquifer system) in the north (Fig. 2). Boundaries are controlled mainly by faults and basal and lateral unconformities.

The unconfined *Q* aquifer (Upper aquifer) is separated from the *LPli* (confined intermediate aquifer) by an aquitard of Pliocene clays. The deep *CT* aquifer is mainly confined and only outcrops in the northern and southern basin parts (Fig. 1, Tertiary) where it is hydraulically connected to the *Q* aquifer. Fig. 5 depicts the Chad Formation hydrostratigraphical units schema, which shows the areas of active recharge and discharge, flow system, and the dominant input-output processes that occur in the basin.

Recharge from rainfall, the main water source, predominantly occurs via infiltration directly to outcropping aquifers (unconfined, upper), and mainly takes place on southern margins (including a narrow zone for the *CT*), where high precipitation occurs, and in the dune systems (Kanem and Harr areas, *Q*) to the north. It accounts for between 0% and 13% of total precipitation (WB, 2020).

The groundwater inflow in the upper aquifer also takes place through river-groundwater interactions during flood periods in eastern and southern parts (Chari-Logone and Komadougou-Yobé river systems). Vertical leakage (or cross-formational flow upwardly) from the aquitard through the overlying Q occurs south of Manga. The lateral inflow from the weathered crystalline bedrock

Table 1
Summary of aquifer formation hydraulic parameters. The *Q*, *LPli* and *CT* aquifers.

Hydrostratigraphical Unit	Thickness m	Storage coefficient (S)	Hydraulic conductivity (k) m/s	Transmissivity (T) m^2/s	Porosity (m) %
Quaternary Fluvio-lacustrine and aeolian sands (aquifer, unconfined)	5–100	10^{-3} to 10^{-5}	10^{-6} to 1×10^{-2}	8.7×10^{-7} to 1.6×10^{-1} 10^{-2} to 10^{-4}	16–32
Pliocene (Middle/Upper) Clays (aquitard)	300 (average)				
Lower Pliocene Alluvial sand (aquifer, confined)	45 (average)	10^{-2} to 10^{-5}	10^{-6} to 10^{-2}	10^{-2} to 10^{-5}	
Continental Terminal Sandy-clay (aquifer, semiconfined)	70–600	10^{-2} to 10^{-5}	10^{-6} to 1×10^{-2}	10^{-2} to 10^{-5}	

* Data from the collected and reviewed information from 81 hydraulic tests; some present little or no useful information due to unknown test procedures or short testing periods.

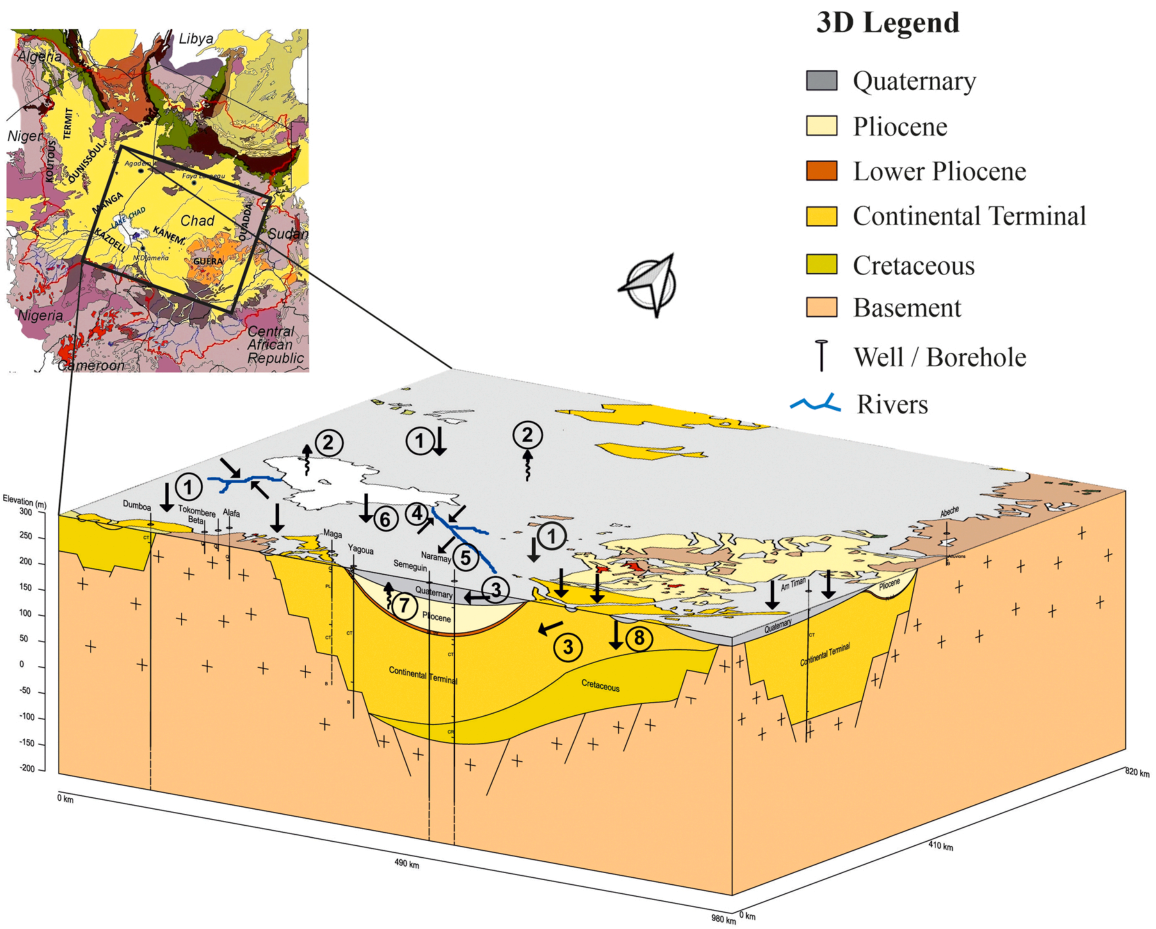

Fig. 5. Input-output hydrologic processes in the aquifer basin. 1) Natural recharge; 2) Evapotranspiration; 3) Groundwater inflow; 4) Recharge from rivers; 5) Discharge from rivers; 6) Recharge from Lake; 7) Upflow from deep aquifers; 8) Vertical recharge from shallower aquifers to deeper ones. Major rivers are indicated with a blue line.

on the southern and western boundaries may also take place. In the northern part, input from the Nubian Sandstone aquifer and Tibesti may exist to the saline Yoa lake (NE of Faya Largeau) and Bodelé depression (Eggermont et al., 2008; Grenier et al., 2009; Kröpelin et al., 2008) to date. At present, Lake Chad is an in-transit hydrologically open system lake ensuring removal of dissolved salts. Exchanges between Lake and the Quaternary aquifer are not significant and, according to isotopic data, are limited up to a distance of around 50 km from the lake's shore (Zaïri, 2008; LCBC-IRD, 2016).

The aquifer system discharge occurs via the surface water systems' inflow (gain flows) from *Q* and *CT* (in the southern basin part), and by groundwater abstraction through agricultural and drinking pumping wells, mainly from the *Q* aquifer. Groundwater discharge may occur to the Lowlands northern region at the Bodelé depression, the lowest topographic point of the basin (approx. 165 m).

3. Methodology

The adopted methodological approach to assess transboundary groundwater fluxes includes an updated understanding of the groundwater dynamics in the CAF and further development of a steady-state three-dimensional (3D) numerical model for the 2008–2011 period. The model is based on the improved conceptual model.

The quantitative data analysis includes a review, understanding and quality assessment of the following: i) daily rainfall and temperature data series from ground stations to assess natural recharge; ii) lithological logs to better define aquifer geometry; iii) spatial distribution of groundwater head observations and groundwater exploitation to define groundwater status and use*;* iv) aquifer testing to define the key hydrodynamic parameters; v) land use/land cover and soil mapping for natural recharge assessments.

3.1. Data source and tools

Soil surface elevation (2010 data, m a.s.l.) were obtained with SRTM30 DEM (https://earthexplorer.usgs.gov/) of 30 arc-seconds (resolution of about 1 km). Land use and Land cover, 20 m resolution, created from Copernicus Sentinel-2A images, the European

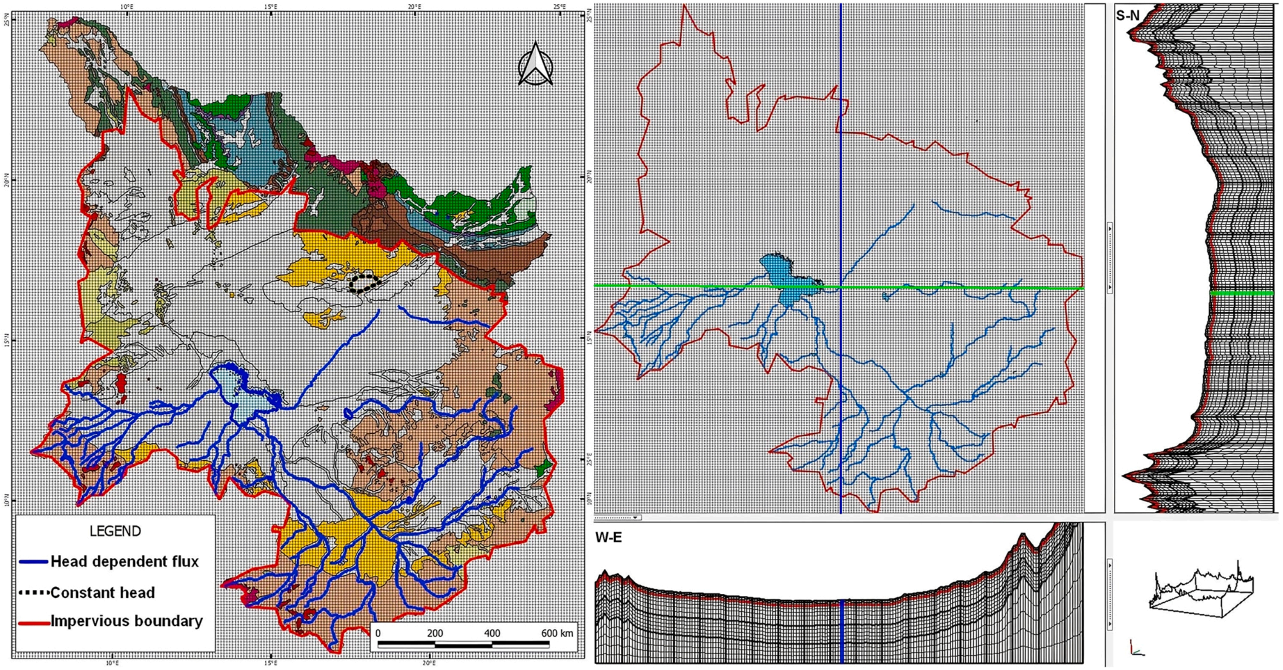

Fig. 6. Model domain, finite differences mesh and vertical layer definition cross-sections (output from MODFLOW).

Space Agency-ESA (CCI Land cover-S2 prototype map of Africa 2016; https://www.esa.int/ESA_Multimedia/Images/2017/10/African_land_cover). Soil maps were from the European Soil Data Centre (https://esdac.jrc.ec.europa.eu/content/soil-map-soil-atlas-africa#tabs-0-description=0). The geological digital mapping of the basin area is based on the GIS shapefiles from BGS (http://earthwise.bgs.ac.uk).

The geological data, retrieved and compiled from a number of scientific and technical publications, were mainly provided by LCBC, Institut de Recherche pour le Développement-IRD, ResEau and BRGM. To characterize the geometry of sedimentary formations, subsurface geological information was obtained from 430 lithological well logs datasets. Selection was based on those records considered quite precise, with measured clearly geo-localized attributes, and with observations made whenever a change in stratigraphic sequence occurred and measurements were taken. Deep drilling, generally for oil research, occurs only in a few spots.

The ground-based daily precipitation (P) and temperature (T) time series for 25 meteorological stations in the basin were compiled from the Trans-African Hydro-Meteorological Observatory-TAHMO Platform (Van de Giesen et al., 2014). Of the whole historic data record (1973–2018), the 2005–2014 period was chosen as that which presents the narrowest data gaps ($\leq$20%) in the time series.

In order to infer a groundwater level map for the 2008–2011 period, water level measurements in wells, piezometers or open wells were taken from public databases (LCBC) and reports. The final selection included a dataset of 250 (out of 9356) water points.

3.1.1. Applied tools

The basin's three-dimensional geological architecture was generated with the RockWare code (RockWorks 17). Based on the geological logs description, the top and bottom depths of hydrostratigraphical units were obtained. The model was also adjusted with existing cross-sections and geophysical information from the literature. The three-dimensional geological model constitutes the basis for the 3D numerical flow model.

Groundwater natural recharge in the CAF for the 2005–2011 period was quantified with VisualBALAN v.2.0 (Samper et al., 2005), a suitable spatially distributed computer code for long-term simulations of the daily water balance in soil, the vadose zone and the aquifer. Output was imported to the numerical flow model as model input.

3.2. Groundwater modeling

3.2.1. Regional model definition/modeling approach

The aquifer system flow model (steady-state) was performed with the MODFLOW-2005 (Harbaugh et al., 2000) under ModelMuse 3.10 interface (Winston, 2009) for the 2008–2011 baseline period.

The numerical model covers the Chad Formation Aquifer system areal extension (1900,000 km^2) based on outcropping geological materials and hydrogeological boundary conditions (Quaternary, Pliocene, Continental Terminal, Basement). The model domain extended beyond the CAF's geological-hydrogeological boundaries (Cretaceous and weathered granite basement buffer area) to reduce the impact of the assumed boundary conditions on model outcomes (Fig. 6). The top domain was set at the SRTM30 DEM topographic elevation. The model domain was discretized into 198 rows and 187 columns, with a cell size of 10 × 10 km. The resulting mesh had 37,026 cells (18,967 active ones).

The model layer structure included four horizontal layers based on defined hydro-stratigraphic units: *Q*, *Pli* (aquitard), *LPli-CT*. Vertical discretization comprised 20 horizontal numerical layers (total thickness of 530 m) with the following distribution in depth:

Layer 1: Unconfined, five sublayers, 8 m thick (40 m total thickness).
Layer 2: Confined/unconfined, five sublayers, 30 m thick (150 m total thickness).
Layer 3: Confined, five sublayers, 28 m thick (140 m total thickness).
Layer 4: Confined, five sublayers, 40 m thick (200 m total thickness).

For each model cell (379,340 active cells out of 740,520) value, hydrogeological properties or node parameters were assigned according to the existing hydrostratigraphical units of each layer.

In order to simulate the hydraulic head condition in the Chari-Baguirmi and Bornou depressions, a 40-meter deep 'drain', covering the Chari-Baguirmi and Bornou areas, was defined. Drain discharges input groundwater (from the lateral boundaries) to the northern basin part (Bodelé depression, Fig. 1). The assumption of this geological draining layer is founded on the paleostratigraphical data that result from sedimentary deposition during ancient Mega Chad Lake coastal migration.

3.2.2. The initial and boundary conditions

The initial condition, groundwater hydraulic state at the start of the model run, corresponds to the head levels from the potentiometric map (Fig. 4), with 240 m and 270 m in the Chari-Baguirmi depression and the Bornou depression, respectively.

Three types of flow boundary conditions were defined: head-dependent flux, specified flux and constant head. The boundary conditions are presented in Fig. 6.

The boundaries of the model domain were considered impervious due to the nature of the geological materials limiting the unit, which shaped the zero-flux boundary condition, and no-flow was simulated for the subsurface lower boundary model domain (aquifer bottom). Head-dependent flux conditions were considered at the Chari, Logone, Komadougou-Yobé Rivers and tributaries, and the major Chad and Fitri lakes. For the river boundary conditions, riverbed conductance values (used in MODFLOW) were based on river bed sedimentary deposit properties; riverbed bottom and head of the river were obtained from DEM. Lakes and dams were simulated by a constant head condition. On the northern basin boundary (Lowlands), the Bodelé depression was simulated using a constant head boundary. Given the uncertainty of the bedrock top location, this deep boundary was not included in the model.

The recharge and abstraction rates from wells were the specified flux conditions. The spatially distributed recharge (2008–2011), independently estimated with VisualBALAN at the daily rate and based on meteorological data records from 25 TAMOH stations, was the input set of the the upper active cells top level. The recharge values ranged from 8×10^{-10} m/s (25 mm/yr) to 8×10^{-11} m/s (2.5 mm/yr), and were zero for the northern basin part.

The groundwater abstraction rate (upper aquifer) is considered a local sink; the amount was estimated at a yearly rate according to intended agriculture use (i.e., agricultural management, crop needs, areal extension) and local water withdrawal for drinking purposes (water allocation according to the population; www.citypopulation.de/Chad.html; United Nations, 2015) Considering the scale of model, abstraction was uniformly applied to the well-fields extension and no individual wells were modeled.

3.2.3. Hydraulic parameters

The initial values of the hydraulic parameters (k_h, T, S) of aquifer formations assigned to layers and active cells were based on the field observations deriving from the collected hydraulic tests (Table 1).

Most observations corresponded to the *Q* aquifer (54 tests) and were located mainly in the Komadougou-Yobé river basin (Chad), and the Chari-Baguirmi and Hadjer-Lamis regions of Chad (near Lake Chad). As data to support a spatially distributed hydraulic conductivity were scarce, constant properties over large zones and throughout the hydrostratigraphic units were applied (Fig. 7). The assigned values are summarized in Table 2. For vertical hydraulic conductivity (k_z), the $k_x/10$ ratio was applied. A high hydraulic conductivity value (0.05 m/s) was set for the model ‘drain’ condition.

3.2.4. Model calibration and sensitivity analysis

During calibration, independently estimated natural recharge, boundary conditions and hydraulic parameter values were adjusted to better match the simulated hydraulic heads to observations.

The final estimates of the hydraulic parameter values were obtained by model calibration based on the potential head datasets from

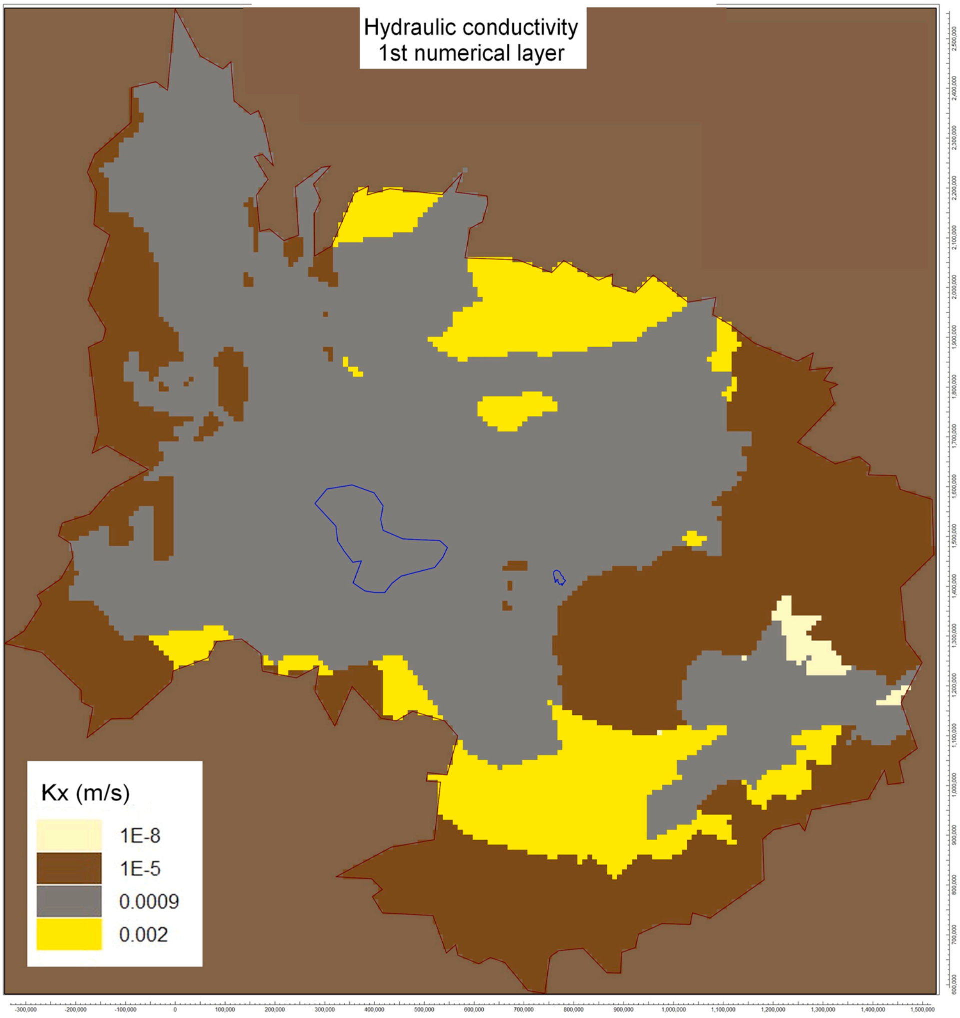

Fig. 7. Initial hydraulic conductivity values distribution (k, m/s) for the top numerical layer (unconfined top layer).

Table 2
Aquifer formations. Initial hydraulic conductivity values and values adopted after calibration.

Aquifer unit	Initial values, k (m/s)			After calibration, k (m/s)
	Min	Max	Input	
Q	1×10^{-6}	1×10^{-2}	8×10^{-3}	1×10^{-3}
Pli (aquitard)	–	9×10^{-5}	1×10^{-7}	1×10^{-8}
LPli/CT	110^{-6}	1×10^{-2}	2×10^{-3}	2×10^{-3}
Basement	–	–	1×10^{-4}	5×10^{-6}

wells (potentiometric surface for the 2008–2011 period) and qualitative criteria. Calibration by trial-and-error was carried out by modifying the hydraulic conductivity values to fit field observations. The goodness of fit between the observed and simulated groundwater levels was measured using root mean square error (RMSE, Eq. (1)) and scaled RMSE (%, Eq. (2)), which are good indicators to evaluate simulation performance. The correlation between the observed and predicted values was calculated by coefficient of determination R^2 (Eq. (3)).

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n}}{O_m} \tag{1}$$

$$RMSE\% = 100. \quad \frac{\sqrt{\sum_{i=1}^{n} (P_i - O_i)^2 / n}}{O_m} \tag{2}$$

$$R^2 = \left(\frac{\sum_{i=1}^{n} (O_i - O_m)(P_i - P_m)}{\sqrt{\sum_{i=1}^{n} (O_i - O_m)^2 \sum_{i=1}^{n} (P_i - P_m)^2}} \right)^2 \tag{3}$$

where O_i is the measured head at *n* locations, $_{Pi}$ is the predicted value and O_m is the observations mean.

The objective of the sensitivity analysis was to identify the input data and model parameters that most significantly affect the model's results. A sensitivity analysis can increase the model's confidence and its predictions by providing an understanding of how the model output variables respond to changes in inputs, the data used for calibration, the model's structure, among other factors, i.e., model-independent variables (Chen and Chen, 2003).

Recharge and abstraction were considered the most important drivers. All simulations were based on running proposed changes in the calibrated numerical model for the defined conditions (baseline). A sensitivity analysis was performed by modifying the recharge (water directly recharging the aquifer) and water abstraction values by different amounts and comparing the obtained results (groundwater level) to the baseline data. The strategy adopted for simulation involved applying a scaling factor of 10%; the percentage definition was not based on the projections made by experts and stakeholders for future trends, but is an indicator of the system response. The model runs included: *i*) 10% recharge reduction; *ii*) 10% increase in water abstractions; *iii*) 10% recharge decrease and 10% increase in water abstraction.

3.3. Transboundary simulation

Transboundary flux simulation through the international borders of CAF was performed after model calibration by running the regional numerical model with the ZoneBudget Modflow postprocessor. For a defined subregion of the modeled aquifer, the ZoneBudget computed the groundwater balance and input-output flow between adjacent areas. To this end, and following the areal extension of the Member State countries sharing the Chad Aquifer Formation, five zones in the modeled area were defined for further model runs.

4. Results and discussion

4.1. Regional model

4.1.1. Model calibration

As presented in the scatter plots of the observed and simulated groundwater levels (Fig. 8a,b), the differences between the observed and computed groundwater levels gave a final RMSE of 18.38 m and the scaled RMSE was 4.75%, which is lower than the recommended threshold value of 5% (Anderson and Woessner, 1992; Giambastiani et al., 2012). On average, the calibrated values for the unconfined aquifer varied by up to 11.9% in relation to the initial values in depressions (Chari-Baguirmi and Bornou), with 0.13% for Chari-Logone, the east lake part, the western part of the Nigeria areas and along the Guera impervious boundary.

The dispersion of the positive and negative residuals was also rather uniformly distributed in relation to 0 m (RMSE= 18.38 m). The

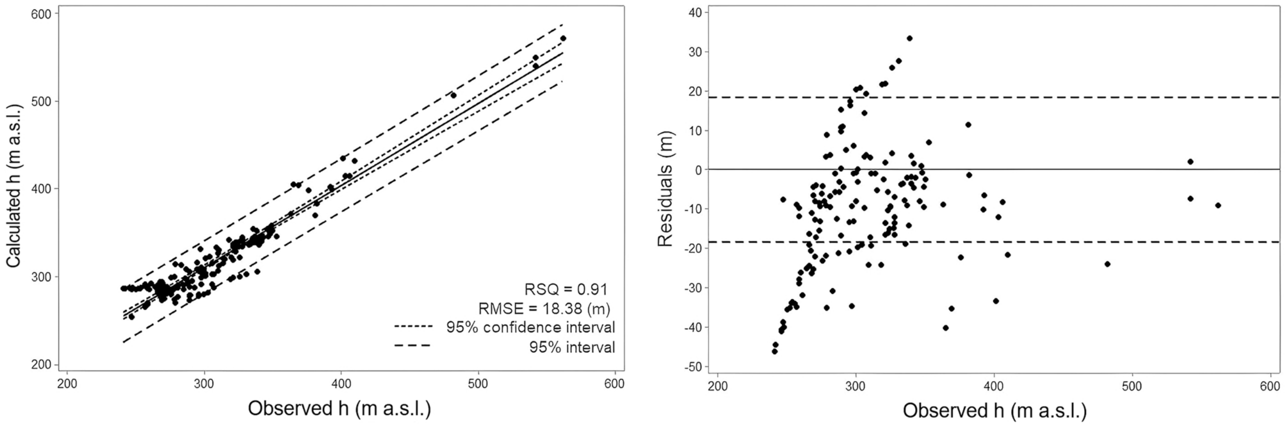

Fig. 8. Hydraulic head observations vs. the simulated values by the model (left). Residuals vs. the observed hydraulic head values (right).

best match was obtained in the Chari-Logone area, around Lake Fitri and the eastern Lake Chad part and in Kano and the Jigawa Basin (Nigeria) with residuals of + −0.5 m, which were higher in the Bornou and Chari-Baguirmi depressed areas (+- 45 m). The determination coefficient (R^2) was 0.9129.

During calibration, independently estimated natural recharge values were spatially lowered by different factors to better match the model's results. River conductance (q) was modified according to the river-bed's geological material characteristics to fit the groundwater level observations.

The initial hydraulic conductivity values and final calibration are reported in Table 2. By considering the model's dimension, the number of cells, and the amount and quality of available data, the calibration for the upper aquifer was considered to be reasonable satisfactory.

Simulated groundwater level and flow pattern (Fig. 9) with the calibrated hydraulic parameters showing reasonable agreement with field observations (Fig. 4). No field observations. North of Lake Chad (14ºN parallel) impaired the piezometric level simulation. Recharge, discharge areas and the northern sink are clearly identified.

The hydrogeological conditions in the depressed areas (Chari-Baguirmi and Komadougou-Yobé) and the eastern part (with groundwater flooding in the Guera zone) were not accurately reproduced.

4.1.2. Water balance

The modeling results indicated the major contribution of natural recharge together with existing surface water-groundwater exchanges (losing and gaining rivers), mainly with the Chari-Logone Rivers (Fig. 10). This contribution is especially important for the deep semiconfined aquifer, where most of the river basin extends (Table 3). Data are also supported by Gonçalves et al. (2020). The most important discharge is to rivers.

The water balance error from the 3D regional numerical model under simulated conditions accounted for 0.063%, which is much

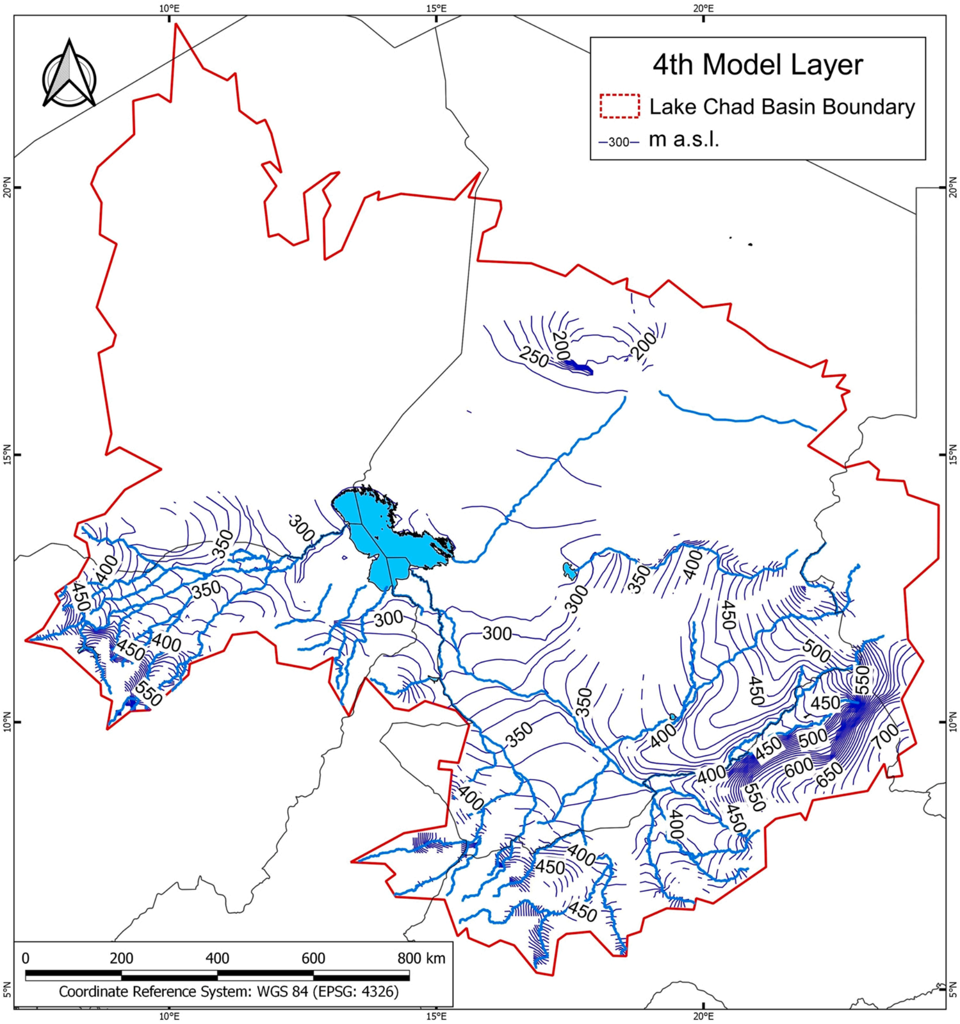

Fig. 9. Upper aquifer. Simulated piezometric level.

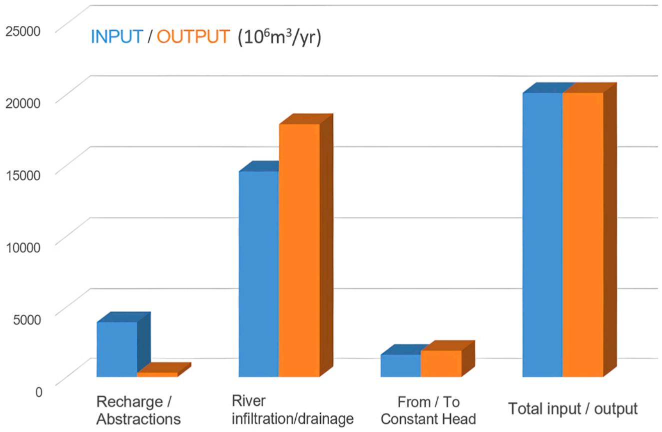

Fig. 10. Groundwater 3D model budget results (10^6 m^3).

Table 3
Groundwater balance for the upper (*Q*) and lower aquifers (*Lpli-CT*) from the calibrated model.

Aquifer system	Quaternary (10^6 m^3/yr)	LPli-CT (10^6 m^3/yr)
Input		
Recharge	1891	1356
Pli (aquitard)	1229	328
LPli/CT	960	–
Rivers and Lake	1214	12,958
Bedrock/lateral	449	457
Quaternary	–	459
Output		
Pumping	39	65
Pli (aquitard)	768	1161
LPli/CT	459	–
Rivers and Lake	4138	13,000
Lowland	4	–
Bedrock/lateral	335	371
Quaternary	–	960
In-Out	-0.368	0.602
In-Out (%)	-0.0064	0.0039

lower than the recommended threshold value (1%). The water balance error, the difference between the total predicted and the inflow and total predicted outflow, was only 0.13×10^6 m^3/yr. From the MODFLOW results, the water balance discrepancy for the two defined aquifers was $-$ 0.0064% and 0.0039%, although considerable uncertainty exists for the LPLi-CT aquifer.

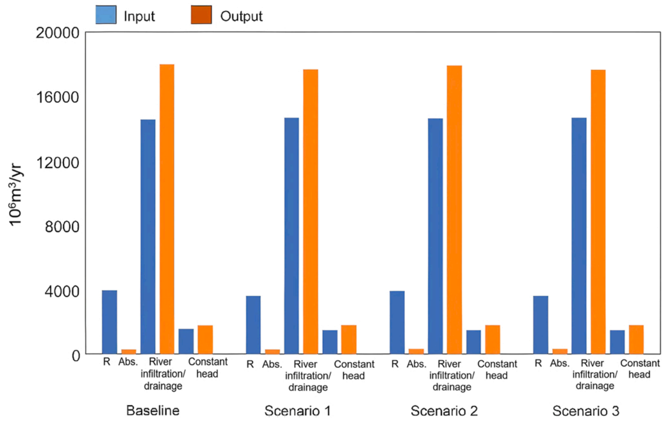

Fig. 11. Average annual water balances in each scenario (R: recharge; Abs: abstraction). Scenarios: 1) 10% recharge reduction; 2) 10% increase in water abstractions; 3) 10% recharge decrease and 10% increase in water abstraction.

4.1.3. Sensitivity analysis

The model shows the Quaternary aquifer's clear response to net natural recharge variation, where the impact of changes in water budget was very weak (0.0016%) and not very sensitive to changes in water abstraction (0.0001%), which take place locally and constitute a small part of the water budget (Fig. 11). This is a reasonable behavior considering the basin-wide scale of the work and mesh size.

The system appeared to be more sensitive to natural recharge than groundwater abstraction. Nevertheless, the results indicated that the groundwater level was not very sensitive to either the 10% reduction (drier than the baseline) in the net recharge (*i*) or (*ii*) the 10% increase in water abstraction. This finding indicated that the groundwater level was not strongly influenced by these changes. With a lowering natural recharge (*i*), the groundwater level drawdown went up to 7 m, as observed south of Kanem and in the Chari-Logone, while several cells dried out in the NE area of Lake Fitri (Batha region). The mean groundwater level lowered by around 1.5 m.

With an increase in only groundwater abstraction (for irrigation and population supply), simulations revealed a minimum impact on the groundwater level changes, which were evident only in those areas only a few kilometers away from pumping areas. As the highest withdrawal took place in the area near the western lake part due to irrigation, a shallow groundwater drop in level was observed (0.6 m in the zones close to pumping areas).

When simultaneously considering net recharge and withdrawals (10% decrease in recharge, plus 10% increased abstraction), similar values were obtained with only a decrease in natural recharge. This fact reflects that recharge is a key issue for the modeled area, and also supports the model's robustness.

4.2. Fluxes to transboundary countries

According to modeling, aquifer flux exchange (about 348 $\times 10^6$ m^3/yr) took place along all the international borders of LCBC Member States in the CAF system. Transboundary fluxes (input-output, x 10^6 m^3/yr), by considering the flow system hydrodynamics

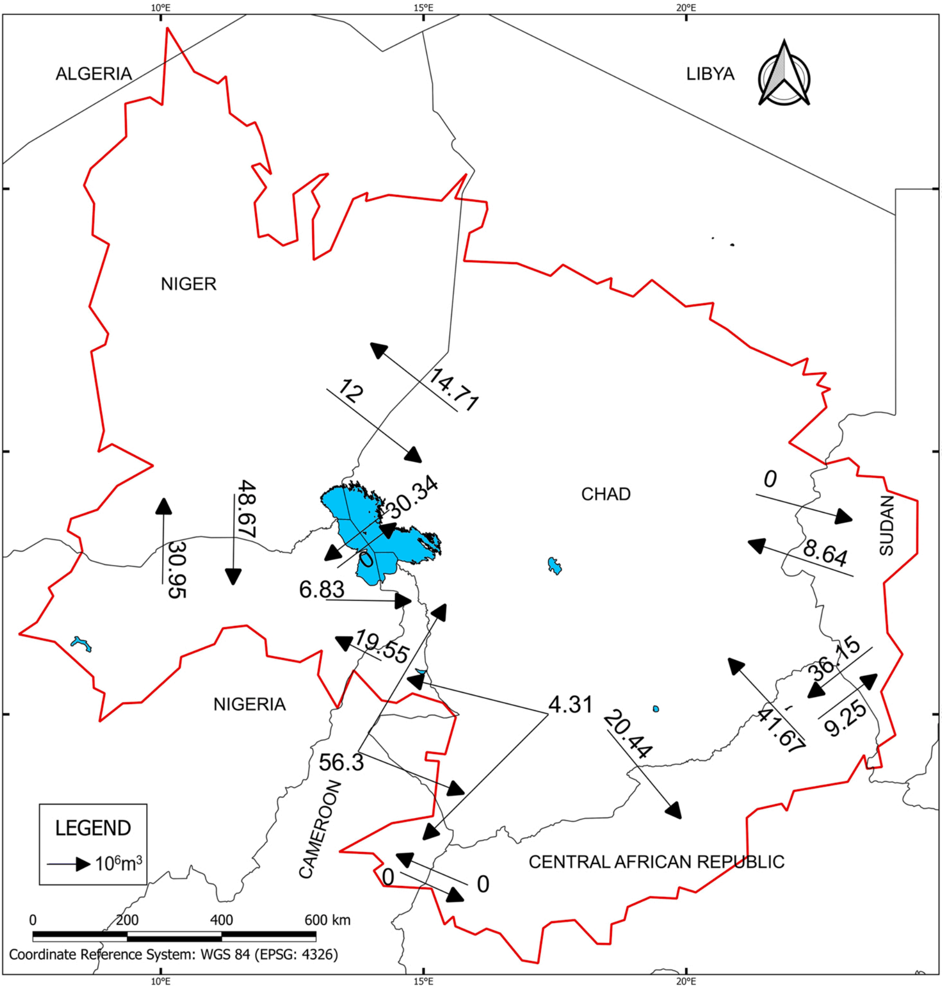

Fig. 12. Modeled groundwater fluxes (10^6 m^3/yr) between the TBA-sharing countries (average for the 2008–2011 period).

rather than aquifer boundaries as a quantitative analysis, among the countries sharing common groundwater resources of the Chad upper aquifer are found in Fig. 12.

The Chad Aquifer System in Chad shares international borders with six countries, with regional groundwater flowing to lowlands and a wide areal extension, which showed the greatest input flux (Table 4). Following the defined regional transboundary hydrodynamics of the CAF (Fig. 4), the groundwater flux is toward the upper northern basin part (according to the conceptual model output). For the groundwater flow exchanges crossing the country's international borders, all the sharing Member States showed a positive flux input as regards output, except for Sudan and CAR. For both, country estimations may denote marked uncertainties due to limited information coverage, lesser CAF extension, and their inclusion as buffer areas for modeling purposes.

Nevertheless, it is also noteworthy that the groundwater balance for the different sharing countries (not the objective of this simulation, which focuses on the CAF system) may show wide-ranging results.

Results from sensitivity analysis indicate that decrease of natural recharge, would imply changes in the groundwater level (average decrease less than 2 m), mainly in Chad (south Kanem, Lake Fitri or the Chari-Logone area with the highest drawdown), as well as further implications for transboundary fluxes among countries. In the Bornu area (Nigeria), the local groundwater level lowered due to withdrawn groundwater for agriculture (at present, most irrigation takes place using surface water), which may affect the transboundary flux to Chad. Observations and information prove too scanty to obtain more accurate results for the modeled area size.

5. Discussion

5.1. Conceptual model

The CAF conceptual model relies on the previous model developed by Schneider (1989), which was updated after extensively collecting and integrating all the available hydrogeological information to more accurately represent aquifer system behavior to date. To this end, the basin-scale hydrostratigraphical framework was developed by integrating all the available geological information.

The basis for constructing a 3D conceptual model was the lithofacies analysis from boreholes. However, geological subsurface information coverage (lithological logs) was unevenly distributed; water-bearing formations' (hydrostratigraphical units; *Q,* unconfined aquifer; *Pli,* confining layer; *LPli,* confined aquifer; *CT,* semiconfined aquifer and the basement) most accurate geometry (less uncertainty) lies in the central Lake Chad Basin part. The subsurface depth to bedrock (Cretaceous, crystalline rocks) is barely known. Sedimentary layers can show lithological variability and little continuity due to changes in sediment facies, which result in heterogeneous hydrostratigraphical units of different aquifer properties, water storage and water transmission in depth terms, and also laterally.

The conceptual model consists of two multilayer aquifers: the upper (Quaternary, unconfined) and the deeper (Lower Pliocene and the Continental Terminal, confined-unconfined). Due to scale constraints, minimum *LPli* unit thickness and data scarcity, the *LPli* and *CT* hydrostratigraphic units were grouped into a single aquifer layer. As no other natural surface outlets or natural sinks were identified, the conceptual model definition considered that substantial groundwater loss could take place in the upper northern area (Lowlands, Bodelé). However, mechanisms still remain uncertain and data to estimate the magnitude of this process are lacking.

The natural recharge zones and rates defined by a distributed model are supported by the best available information. The approach is based on a physically robust process for recharge estimations. Some associated uncertainty comes over owing to the time series of groundwater levels not being available for further calibration. However, other authors working in the area (Goni, 2008; Leblanc, 2002; Ngounou Ngatcha and Reynault, 2007) have obtained similar recharge values to those obtained by modeling.

Groundwater level observations are available mainly for the Quaternary aquifer in the central and southern basin parts, but are scarce and only exist in the southern part for the Lower Pliocene-Continental Terminal. The potentiometric surface defined for the 2008–2011 period is considered representative of a 'quasi' steady-state condition at the regional level by assuming that if groundwater levels appear more or less stable, active recharge takes place and the amount of water withdrawn in most of the area is not large. It presents similar characteristics to previous piezometric maps reported by other authors (Schneider, 1989; Leblanc, 2002 and BGR-LCBC, 2010), including the presence of natural depressed areas.

To date, several mechanisms (overexploitation, subsidence, structurally conditioned deep drainage, changes in seawater level and evapotranspiration loss) have been suggested to explain the origins of depressed areas (e.g. Aranyossy and Ndiaye, 1993; Dieng, et al., 1990; Durand, 1982, Leblanc et al., 2003). As provided by chemical and isotopic data (Abderamane, 2012), recharge in depressed areas probably took place during the last pluvial period (around 6000 yr).

Table 4
The total input-output transboundary groundwater flux (10^6 m^3/yr) in Member States (average for the 2008–2011 period).

Country	Total input Flux (10^6 m^3/yr)	Total output Flux (10^6 m^3/yr)
Chad	118.63	84.13
Nigeria	56.59	46.33
CAR	11.14	50.92
Niger	98.56	48.67
Cameroon	54.21	75.85
Sudan	9.25	44.79

Nonetheless, as the scientific community has reached no unanimous agreement, its presence has been generally explained by exfiltration processes, along with lack of recharge. For saturated porous media, when the groundwater level exceeds a depth of 10 m, the water table is generally not subject to direct evapotranspiration, except for the areas covered by acacias trees, where the net recharge may be lower than the total ET. Therefore, the exfiltration mechanism is difficult to explain naturally with a groundwater depth of about 40 m (Leblanc et al., 2007). In the conceptual model, a deep drainage mechanism to the northern zone was adopted, based on the paleostratigraphical data resulting from sedimentary depositions during ancient Mega Chad Lake coastal migration (Drake and Bristow, 2006; Griffin, 2006; Bristow et al., 2009; Maley, 2010).

5.1.1. Modeling for transboundary issues

Flow model simulation involved developing a steady-state 3D numerical model for the 2008–2011 period based on the improved conceptual model. The model domain vertical discretization into four numerical layers included three aquifer layers (*Q*, *LPli&CT*), one aquitard (*Pli*) and the basement (Cretaceous and weathered granitic rocks), which acted as a model buffer. Hydrogeological and hydrological features were simplified for model representation purposes. *LPli* and *CT* were jointly taken as a unique aquifer layer for modeling purposes. The defined model grid was quite coarse, and could not be refined beyond 10 × 10 km per cell due to computational and data limitations.

In order to reproduce existing piezometric depressions, under a steady-state model condition at basin scale, a mechanism capable of extracting groundwater from the system needs to be defined, with exfiltration is the most widely accepted process by previous authors (Eberschweiler, 1993; Gaultier, 2004; Leblanc, 2002; Schneider, 1989). For modeling purposes, the solution adopted to simulate current hydraulic head conditions involved defining a subsurface drainage layer mechanism to remove groundwater input from lateral boundaries (groundwater flow moves to the northern basin area). However, such singularity has not yet been fully validated conceptually or numerically, and more research and data are needed to reach an agreement about interpreting this phenomenon,

Model parametrization was based on data previously collected for the conceptual model definition. For the regional model flow, defining hydraulic conductivity zonation over large zones and throughout hydrostratigraphic units is a common approach; modeling requires making predictions depending on large-scale spatial averages rather than on local variability (Voss and Soliman, 2013), which also reduces computational efforts (De Caro et al., 2020).

For the aquifer-river interaction, the calculation of the flow between the river and aquifer was based mainly on streambed deposit properties (Dade and Friend, 1998) because it is assumed that all measurable aquifer-river head losses are due to the streambed itself. This approach is very useful for, and applicable to, regional studies when no information on streambed deposits is available.

Calibration proved a complex task as data relating to the spatial scale were sparse, mainly located in the central basin part basin and in wide areas, and without any available data mostly in the northern basin half. It is noteworthy that the local data calibration predicted responses only in these areas (Voss and Soliman, 2013).

A worse match between simulations and field observations was achieved in Bornou and Chari-Baguirmi, with higher and lower simulation results than the observations, respectively. The existence of drawdowns by pumping wells was not reproduced, and wells field abstraction was appropriate for regional scale modeling, but not for evaluating detailed drawdown patterns on the local scale. Being a steady-state model, model calibration was generally acceptable in the upper aquifer, which was the main modeling objective. However, head calibration in the depressed areas was not very successful (Chari-Baguirmi; Komadougou-Yobé), with a poorer match between simulated and observed heads.

The model was not very sensitive to water abstraction changes because they only took place locally. The applied sensitivity analysis indicated that the obtained results were those expected for this large-scale regional model. Changes in results were observed according to the perturbations applied to parameters, with the largest differences found in the areas where no observation points were available. However, overabstraction by pumping for irrigation and supply may constitute a local groundwater issue for the basin if future developments take place. The region has a 2.5–3% growing population rate (www.gwp.org/en/WACDEP/IMPLEMENTATION/Where/Lake-Chad/), which means that large amounts of groundwater may be required to support irrigation requirements during dry periods. Land cover changes resulting from economic development may also influence groundwater recharge rate, which makes the aquifer particularly susceptible to impacts during low rainfall periods.

The objective of developing the model was to use it as a tool to study the system's different hydrologic conditions. Of them, the assessment of aquifer regional transboundary hydrodynamics provided a quantitative understanding of the groundwater fluxes all over the sharing countries borderlines making up the Lake Chad transboundary aquifer. Rather than employing aquifer country boundaries, this approach is a key issue for common groundwater resources management along borderlines (Rivera and Candela, 2018b).

As intrinsic uncertainties emerging from model development due to lack of observations or computing issues were translated to the obtained results, the obtained quantitative values were estimations of the process taking place. However, the results of the aquifer exchanges from 14ºN parallel to further south can be considered more reliable; data are scanty in the northern lake part. The observed contributions from countries where bedrock outcrops (Sudan, CAR, Nigeria) should also be carefully considered in model outcomes, as the simulated aquifer domain extended beyond the aquifer system formation boundaries (buffer area).

6. Conclusions

The basin-wide perspective, while integrating multiple available data sources, provides a foundation to better understand and quantify basin-wide hydrogeological dynamics to date. The objectives included improving the understanding of Lake Chad Formation transboundary aquifer system behavior and identifying possible groundwater hot spots by considering the whole spatial CAF coverage. The conceptual model proposed to support a numerical model was based on the best-available preexisting hydrogeological data for the

Lake Chad Basin. Developing a model to evaluate regional behavior requires data on the regional scale, but very few quantitative data are available for defining vertical and lateral boundaries and hydrogeologic properties. Significant data and knowledge gaps can influence any uncertainty in the hydrogeological conceptualization.

This work also characterized the contributing areas where recharge originates, and where particular attention should be paid to water resources management. Water use and land use changes in these areas will directly influence aquifer recharge in the future. This is especially relevant with climate change predictions, which foresee rising temperatures, evapotranspiration potentials and intensified hydrological cycles. Watershed conservation measures and nature-based solutions are always a good no-regrets approach for climate adaptation to mitigate the effects of floods and droughts, while increasing infiltration and recharge. Moreover, impacts on the recharge of surface water developments and irrigation investments (like those in the Komadougou Yobe subbasin which led the Northern basin of Lake Chad to dry up) should be evaluated on a case-by-case basis from this basin-wide perspective.

Our modeling effort is the first basin-wide perspective of water balance in the entire Lake Chad basin to integrate all currently available data. Given the data budget, model complexity and computational limitations, the established groundwater numerical model (3D steady-state) is a first step toward providing a support tool for managing aquifers on the basin scale (water abstraction, temporal variation, changes in water recharge, etc.). The modeling scale may limit its use as a predictive tool for groundwater local effects, even though both the overall conceptual and numerical model needs to be further improved. This basin-wide modeling effort first provides estimates of transboundary groundwater fluxes across LCBC Member States' borders.

Transboundary water management poses many special challenges, ranging from common implementation strategy harmonization on information exchange to joint monitoring, among other actions toward equitable distribution. No standard approach exists for complex water resources distribution, which is generally subject to negotiations between involved parties; volume allocation according to aquifer extension or recharge fraction is a simple, but not a good solution. Identifying sensitive zones of transboundary impacts may help to determine those areas that are likely to undergo quantitative changes on groundwater level, water quality or artesian conditions. Finally, it is necessary to enhance international cooperation and shared management strategies to prevent and mitigate further cross-border conflicts, and to more efficiently allocate groundwater resources.

CRediT authorship contribution statement

Guillermo Vaquero: Investigation, Numerical modelling. **Nafiseh Salehi Siavashani** : Data preparation, Investigation, Writing – original draft, Preparation. **Daniel García-Martínez**: Data preparation, Investigation. **F. Javier Elorza**: Conceptualization, Modelling, Writing – review & editing. **Mohammed Bila**: Resources. **Lucila Candela**: Supervision, Conceptualization, Writing – review & editing. **Aleix Serrat-Capdevila**: Conceptualization, Funding.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2021.100935.

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