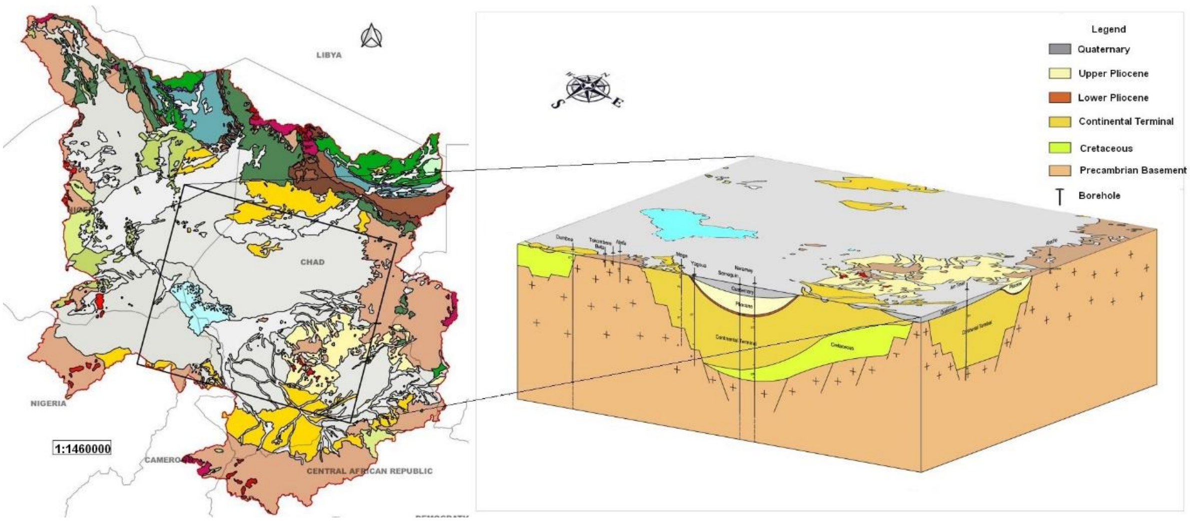
A Groundwater Model for the Lake Chad Basin

Integrating data and understanding of water resources at the basin scale.



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ACRONYMS

AFD Agence Française de Développement
AVHRR Advanced Very High Resolution Radiometer
BAD Banque Africaine de Développement
BGR Bundesanstalt für Geowissenschaften und Rohstoffe – Federal Institute for Geosciences and Natural Resources
BMZ Bundesministerium für Zusammenarbeit und Entwicklung
BRGM Bureau de Recherches Géologiques et Minières
CAR Central African Republic
CDIG Centre Documentation et Information Geographique
CHADFDM Chad flood and drought monitor
CILSS Permanent Interstate Committee for Drought control in the Sahel
CT Continental Terminal
DB Database
DEM Digital Elevation Model
DREM Direction de Ressources en Eau et Météorologie (Chad)
EDA GDG Direction du Développement et de la Coopération Suisse
ESA European Space Agency
FAO United Nations Food and Agriculture Organization
FED Fonds Européen de Développement
FFEM Fond Financier Environnement Mondiale
GEF Global Environmental Facility
GIS Geographic Information System
GRACE The Gravity Recovery And Climate Experiment
GWP Global Water Partnership
IAEA The International Atomic Energy Agency
ICCP Intergovernmental Panel on Climate Change
IRD Institut de Recherche pour le Développement (French Research Institute for Development)
IWRM Integrated Water Resources management
LaCBO Lake Chad Basin Observatory
LCBC Lake Chad Basin Commission
LPli Lower Pliocene
MEA Ministère de l'Eau et de l'Assainissement du Tchad
MEH Ministère de l'Elevage et l'Hydraulique (Tchad)
MODELMUSE. USGS Graphical User Interface for Modflow
MODFLOW the USGS's modular hydrologic model
MODIS Moderate Resolution Imaging Spectroradiometer
MSWEP Multi-Source Weighted-Ensemble Precipitation
NHS Nigerian Hydrological Service
ORSTOM Office de la Recherche Scientifique et Technique Outre-Mer
PHPTC Programme d'Hydraulique Pastorale au Tchad Central
Pli Pliocene
Q Quaternary
QGIS Quantum Geographic Information System
ResEau Cartographie des ressources en Eau du Tchad. Government of Chad and the Swiss Agency for Development and Cooperation (SDC)
SAP Strategic Action Plan

SIEREM Système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation
SIRE Water Resources Information System
SRTM90 USGS Shuttle Radar Topography Mission
STRM Shuttle Radar Topography Mission
TAHMO The Trans-African HydroMeteorological Observatory
UNECA United Nations Economic Commission for Africa
UNESCO United Nations Educational, Scientific and Cultural Organization
UNHCR United Nations Refugee Agency
UNIRES US-Nigeria International Research Experiences for Students
UNITAR The United Nations Institute for Training and Research
UNOSAT UNITAR Operational Satellite Applications Programme
USGS United States Geological Survey
WB World Bank

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EXECUTIVE SUMMARY

This report is part of the Water Global Practice efforts to support the Lake Chad Basin Commission (LCBC) and its Member States (Cameroon, the Central African Republic, Chad, Niger and Nigeria) fulfill their mandate to better monitor and understand water resources dynamics in the Lake Chad Basin. While parallel work is leveraging remote sensing to improve the monitoring of surface water resources, this report focuses on the basin's groundwater resources. Hydrologic modeling is essential for representing current understanding, putting existing data to good use, informing new data collection efforts, and supporting water resources planning and management.

The initial objectives of the efforts portrayed in this report were to (a) integrate all available groundwater data available in the Lake Chad Basin in an updated database; (b) develop an updated and integrative conceptual groundwater model of the Lake Chad Basin, including all old and new information and reflecting the best current understanding, and (c) develop the equivalent numerical groundwater model of the Lake Chad Basin, with emphasis on two focus areas: the Komadougu-Yobe and Chari-Logone river basins, given their relevance for groundwater recharge and use. Even though the overall conceptual model and the numerical model need to be further improved, the basin-wide perspective presented in this work, integrating multiple sources of available data, provides a foundation to better understand and quantify basin-wide hydrogeological dynamics. This enables future efforts to assess potential impacts of future investments and climate futures.

The tasks of this activity started with the extensive collection and integration of all available information and data from national and regional databases, previous studies, projects and partners, to provide the data basis for an updated conceptual understanding of groundwater in the Lake Chad Basin. The integration of information and knowledge enabled the preparation of an improved basin-wide numerical groundwater model. Thus, this database and model represent the best available understanding of groundwater resources in the Lake Chad Basin to date.

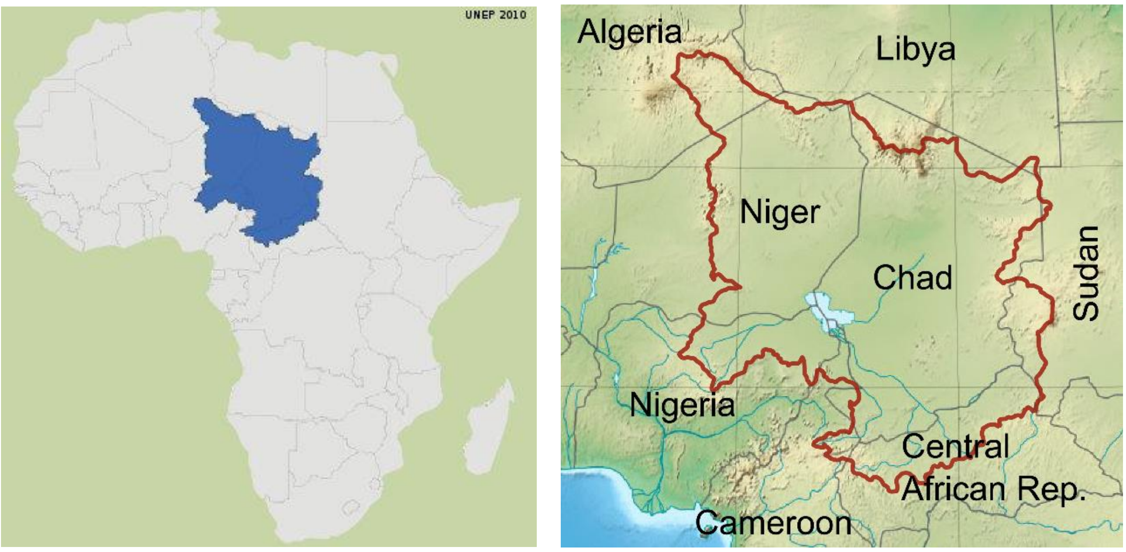
This model is expected to be a foundation for further regional numerical modelling efforts. Due to limited availability and lack of time-series data, as well as the complexity of the aquifer systems and the large geographical area, the conceptual model was tentatively validated through a steady-state numerical model only. A steady-state model considers that the piezometric level has reached a position of equilibrium, and its outputs represent a snapshot of the groundwater system. Once sufficient data is available, the conversion to a transient model would allow the analysis of future investment and climate scenarios to inform decision-making and water resources management.

This report has four chapters: first, a brief introduction of context and goals; second, a review of the geology, hydrology and hydrogeology data and information in the Lake Chad Basin; third, a description of the numerical model and simulations; and fourth, a conclusions chapter. This report also contains 7 annexes (A to G) providing information and background on a range of variables and topics. A digital database of information, probably the most complete compilation of available groundwater data in the Lake Chad Basin is also available, with a subset database including all the data used win the numerical model and simulations.

The Lake Chad Groundwater System

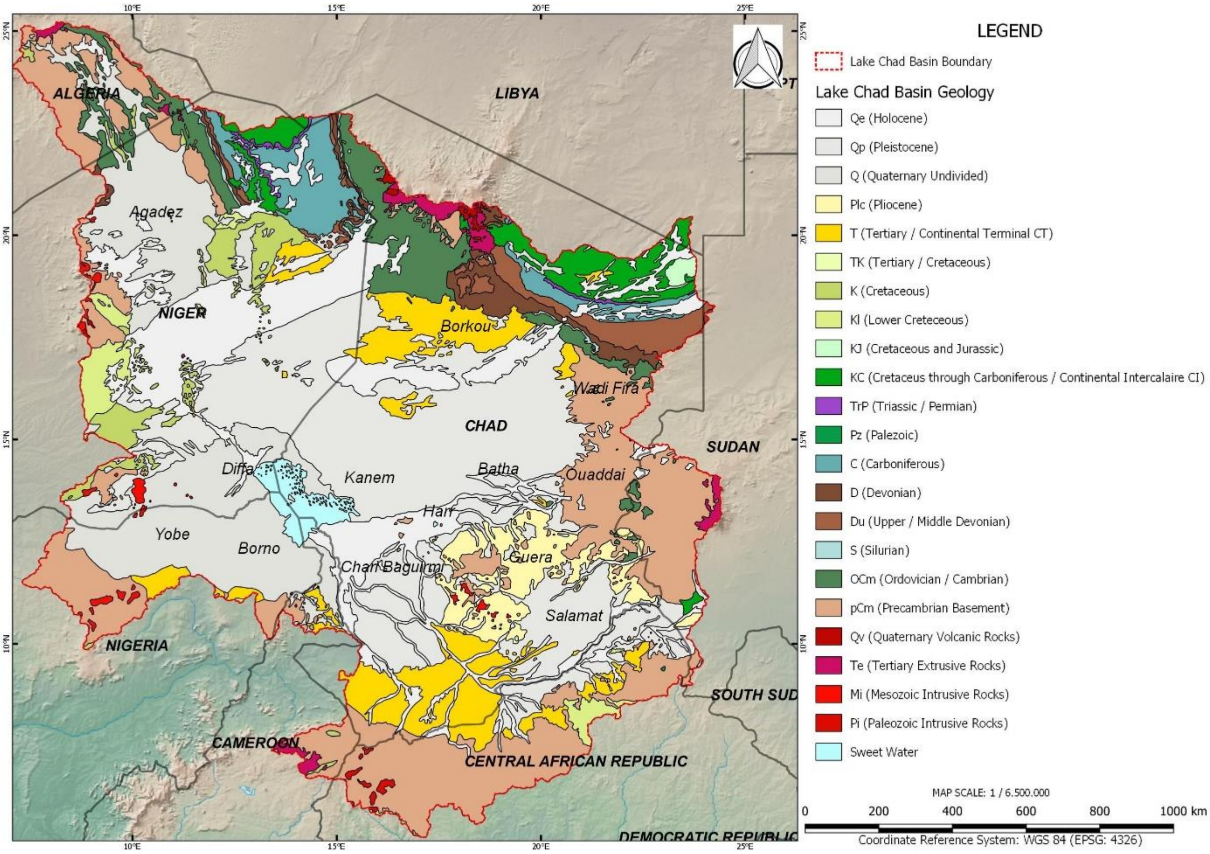
The Lake Chad Basin is an inland drainage system covering an area of about 2,355,000 km^2 in the eastern part of the Sahel region of Africa that is shared by Algeria, Cameroon, the Central African Republic, Chad, Libya, Niger, Nigeria and Sudan, to a larger or lesser extent. It spans a wide range of climates from Saharian in the North to tropical in the south. The Lake Chad itself, mainly fed from the Chari-Logone System Rivers, is highly variable across seasons and years. It is currently greater than 10,000 km^2. It provides a source of livelihood for about 2 million people along its shore and contributes to food security for about 50 million people in its hydrographic basin.

The Lake Chad Hydrologic Basin



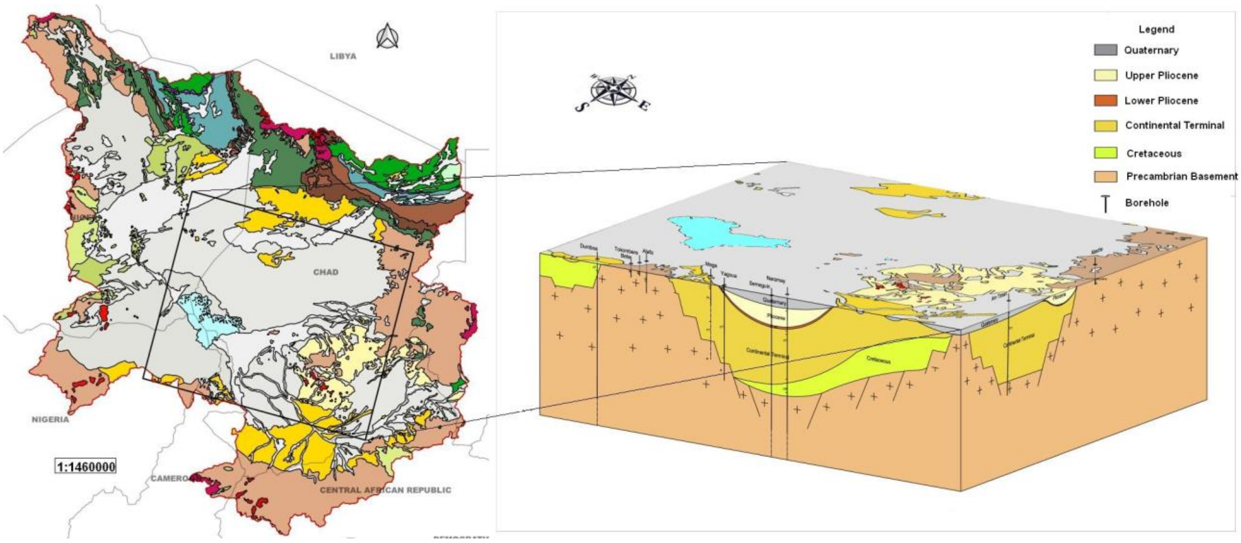
Several aquifers have been identified in the Lake Chad Basin, and the sedimentary Chad Formation is of special interest. The Chad Formation, a recent geologic formation, is an aquifer system that extends along the entire basin, and is composed of the following hydrostratigraphical units or water-bearing formations (FAO, 1973): Quaternary (unconfined aquifer), Pliocene (aquitard, impervious), Lower Pliocene (confined aquifer) and Continental Terminal (semiconfined aquifer). The Quaternary aquifer, composed of aeolian sands and fluviodeltaic deposits, outcrops in the whole basin area, and the Continental Terminal (CT) to the south of the basin is mainly confined. Hydraulic connectivity exists between different aquifers, and also between surface water (lakes and rivers) and groundwater. Groundwater recharge takes place directly from precipitation and irrigation return flow, where aquifers are unconfined, and by surface water from river systems. Groundwater exploitation takes place mainly in the Quaternary aquifer or the CT in southern areas where it outcrops. Only deep boreholes in cities (i.e.: N'Djamena) exploit deep aquifers. In general, the groundwater level in the basin has lowered because of increased abstractions and decreased recharge.

Geology of the basin area. The red line shows the area of the Lake Chad Hydrologic Basin, modeled in this hydrogeologic study.



To date, a limited number of groundwater models for the Quaternary aquifer have been developed at the basin level, based on different tools and numerical methods, and with various goals (Eberschweiler, 1993a; Leblanc, 2002; Boronina and Ramillien, 2008). Locally, groundwater models have been developed for different objectives for the Kazdell, Lake Chad vicinity, Chari Logone and Chari-Baguirmi. Although these efforts are most valuable, no existing model covers the entire hydrogeologic basin and hydrostratigraphical units of the Chad Formation Aquifer System.

The Chad Formation water-bearing formations (hydrostratigraphical units) schema: Quaternary (gray), Upper Pliocene (yellow), Lower Pliocene (brown), Continental Terminal (dark yellow) and bedrock (cretaceous and crystalline rocks)



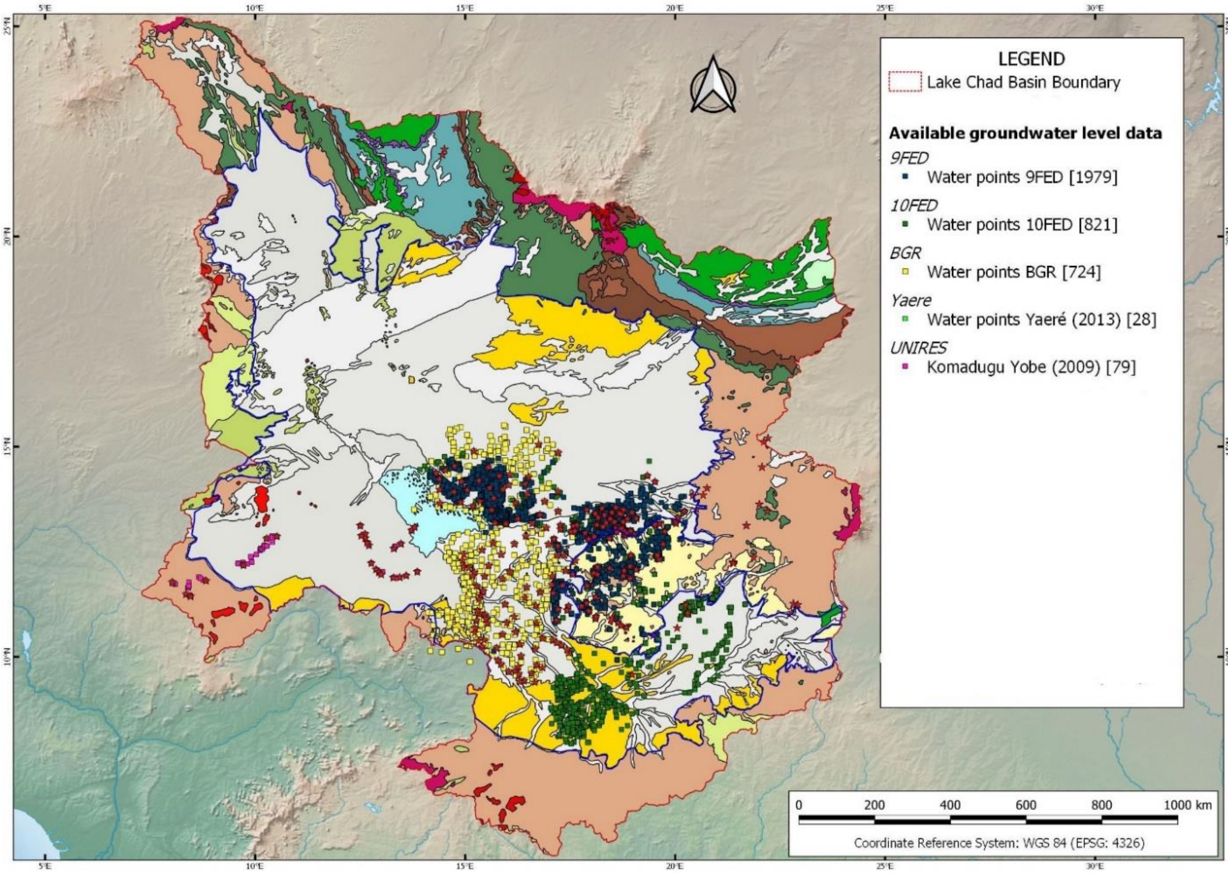
Integrating Data from Diverse Actors

The first half of the report provides an updated picture of the current knowledge of the Lake Chad Basin groundwater resources. The data analysis is the product of direct interactions with a range of institutions and actors that have worked on topics that are relevant for groundwater resources in the region. It also summarizes the hydrologic research outcomes for groundwater studies conducted by a range of different international and national organizations involved in the Lake Chad Basin. A significant amount of the collected data was provided by CDIG-ResEau and LCBC.

To date, the most quantitative data in repositories (basically at the LCBC, and Member State's national organizations) are available for the basin area in the Republic of Chad. For the other LCBC Member States, information is limited. Reports or research studies and quantitative data (climate, hydrological, hydrogeological, groundwater, groundwater exploitation and geological) that relate mainly to the projects undertaken with a domestic water supply objective focus mostly on the central part of the Lake Chad Basin and the Quaternary aquifer (shallow unconfined aquifer). Scarce information has been found for deep aquifers. Groundwater information is lacking for the Northern part of the Chad Formation Aquifer System (N. Chad and Niger), the Sudan area and Nigeria. This aspect also applies to the Komadougou-Yobé area (mostly in Nigeria), one of the model focus areas, where major agricultural developments take place, and where surface-groundwater interactions need to be assessed.

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

Spatial distribution of all the water points used to exploit the aquifer system in the area (from the RESOPIEZ, SUIVPIEZ and SITEAU databases). UNIRES: (year) and [number of data] for the UNIRES campaign



The spatio-temporal coverage of ground-based hydrological and meteorological data (measurement stations, gaps and time periods) is very variable. Limited ground-based weather stations with accurate daily datasets of precipitation and temperature for the 2008-2011 period are available for estimating natural recharge. The geological subsurface information coverage (lithological logs) of the sedimentary package provided a highly accurate hydrostratigraphical description (aquifer layers) of sedimentary thickness in the central part of the Lake Chad Basin. Reliable groundwater abstraction, from spatially distributed wells, does not exist. Groundwater abstractions were estimated from population data and irrigated areas identified from remote sensing products (satellite photos). Finally, hydrodynamic parameters to define hydraulic properties of aquifer media and groundwater level measurements are mainly available for the Quaternary aquifer and in the central part of the basin. There was very scarce data for the Lower Pliocene and CT aquifers. Lack of data limited seriously the basin-scale hydrogeological assessment.

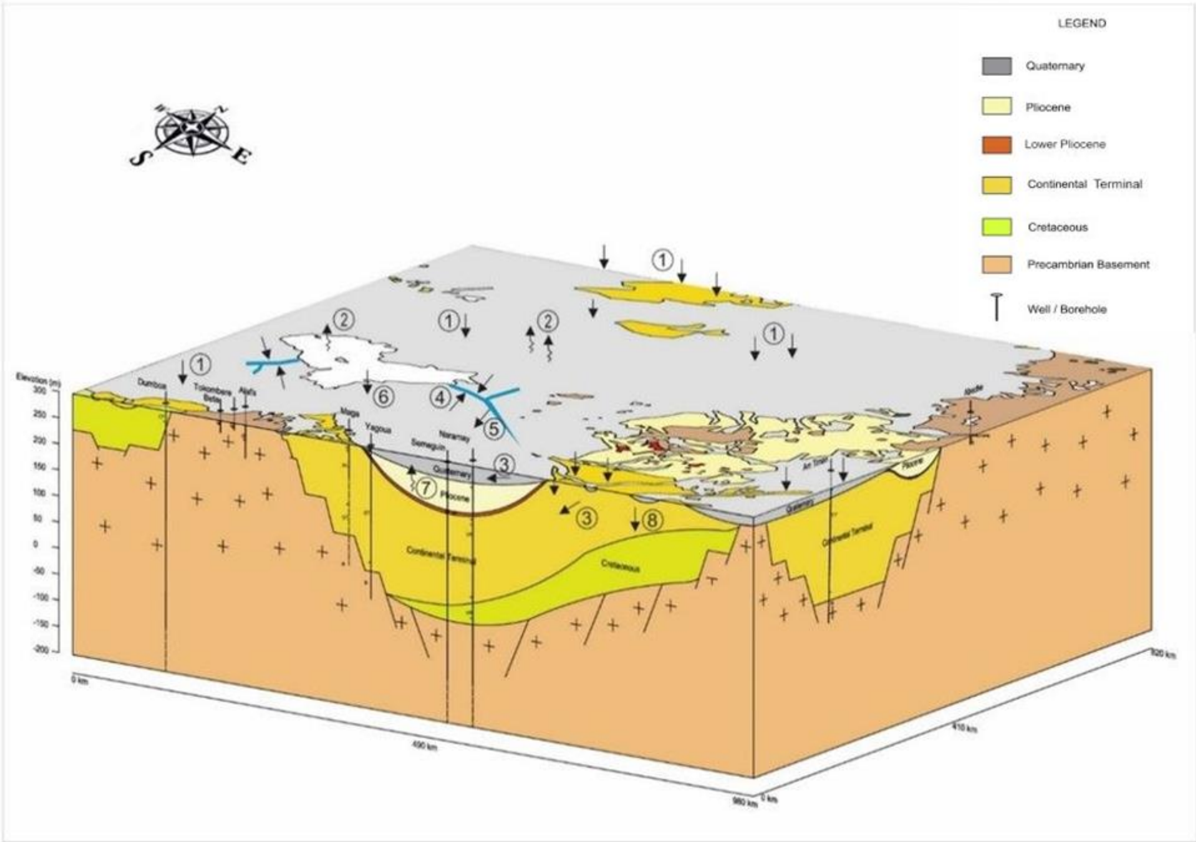
An updated understanding of the groundwater dynamics in the basin

The existing conceptual model of the Chad Formation Aquifer System (Quaternary, Lower Pliocene and CT) has been assessed and improved with the new information to more accurately represent aquifer system behavior on the basin scale to account for all the available data today.

The following improvements to the previous regional hydrogeological conceptual model were made:

- At the basin level: the three-dimensional conceptual model of the groundwater system was updated based on the additional data obtained from current hydrostratigraphical and hydrodynamic parameters and groundwater levels (i.e. water-bearing formations, recharge-discharge processes, etc.).
- Revising and expanding the aquifer geometry definition of the Chad Formation Aquifer System (Quaternary and Lower Pliocene/Continental Terminal) to the basin's boundaries, as presented in the previous figures.
- Natural recharge distribution and amount (2008-2011) independently estimated with a soil-plant-water distributed model. It is based on a review of crop irrigation dose, the distribution of agricultural areas and the daily precipitation data series from the meteorological ground stations provided by the TAMOH platform.
- Updated Quaternary aquifer groundwater level mapping for the 2008-2011 period.

Input-output processes in the 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. Lateral recharge from the weathered crystalline bedrock also takes place



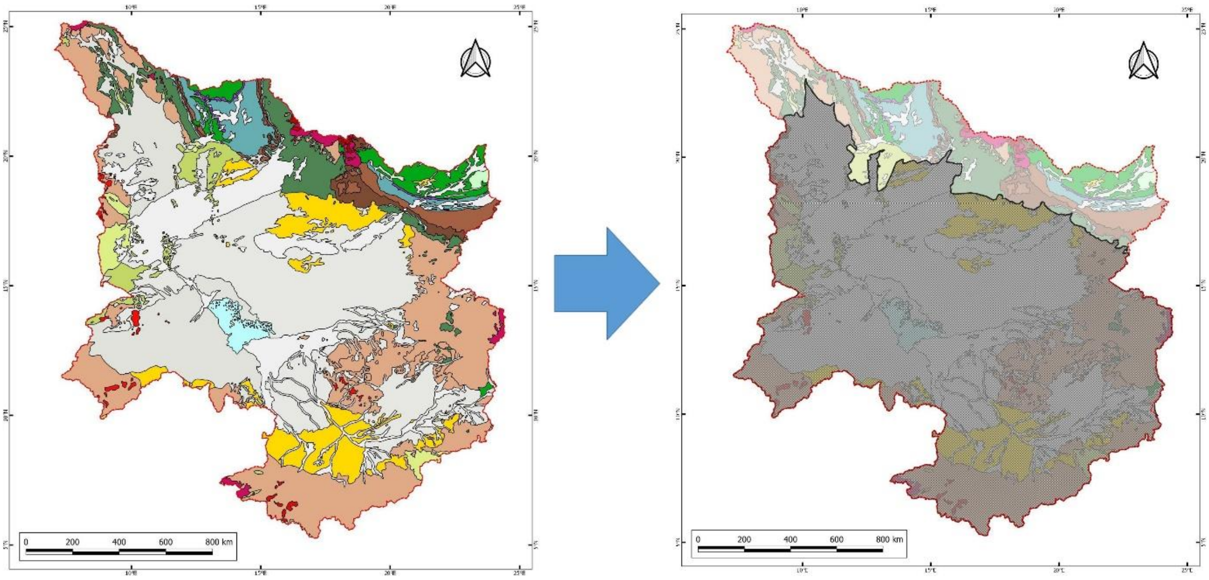
A numerical model to simulate the entire basin

Thesecond half of the report presents the development of three-dimensional (3D) hydrogeological numerical flow model of the Chad Formation Aquifer System. It involves developing a steady-state numerical model for the 2008-2011 period based on the improved conceptual model.

The modeling approach followed reflects the discussions held during two participatory workshops with the LCBC and regional stakeholders, which took place when this activity began. An agreement was met on the need to: determine the basin's boundary in relation to groundwater; model the entire basin, and also focus in more detail on specific key areas in a multiresolution approach. In particular, the need for a model that can support operational water resources management was discussed, as well as the creation of a 3D conceptual model to capture all the data, including quantity parameters for any new abstractions, in the model's database.

The Lake Chad formation aquifer system flow model has been numerically programmed with the open-source MODFLOW 2005 code with the ModelMuse 3.10 graphical user interface. The steady-state model is used to understand the Lake Chad Formation aquifer system behavior and to identify possible groundwater depletion hot spots.

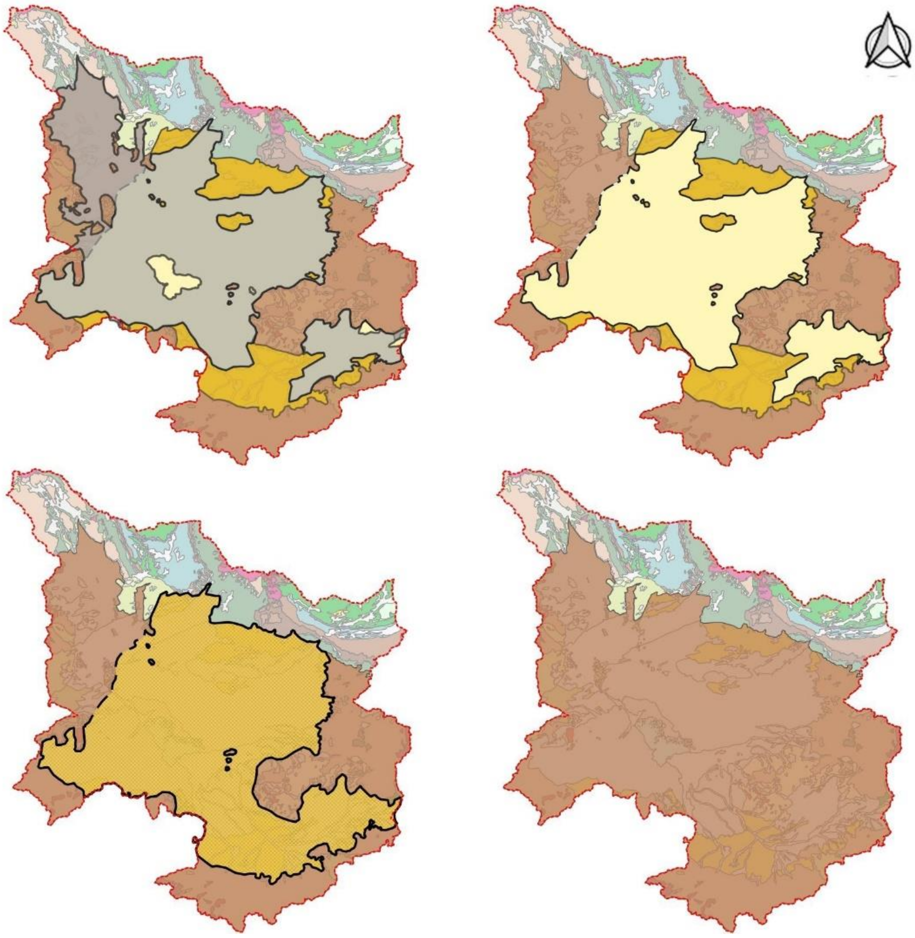
Groundwater Model Domain.



The spatial coverage (1,900,000 km^2 of the model domain) and four layers (Quaternary, Pliocene, Lower Pliocene/CT and Bedrock) were defined based on existing hydrostratigraphic units. Model layers are a numerical tool defined for modeling water fluxes in confined or unconfined conditions, including confining layers and by simulating the vertical structure of the aquifer and flow paths. The model was run in a 10x10 km grid over the entire flow domain.

The model performance was validated by evaluating simulated to observed groundwater head (piezometric map with a reference to sea level for the 2008-2011 period) and by relative error. Apart from overall basin calibration, the model performance was also assessed in the Chari-Logone and Komadougou-Yobé areas, also by evaluating the piezometric head.

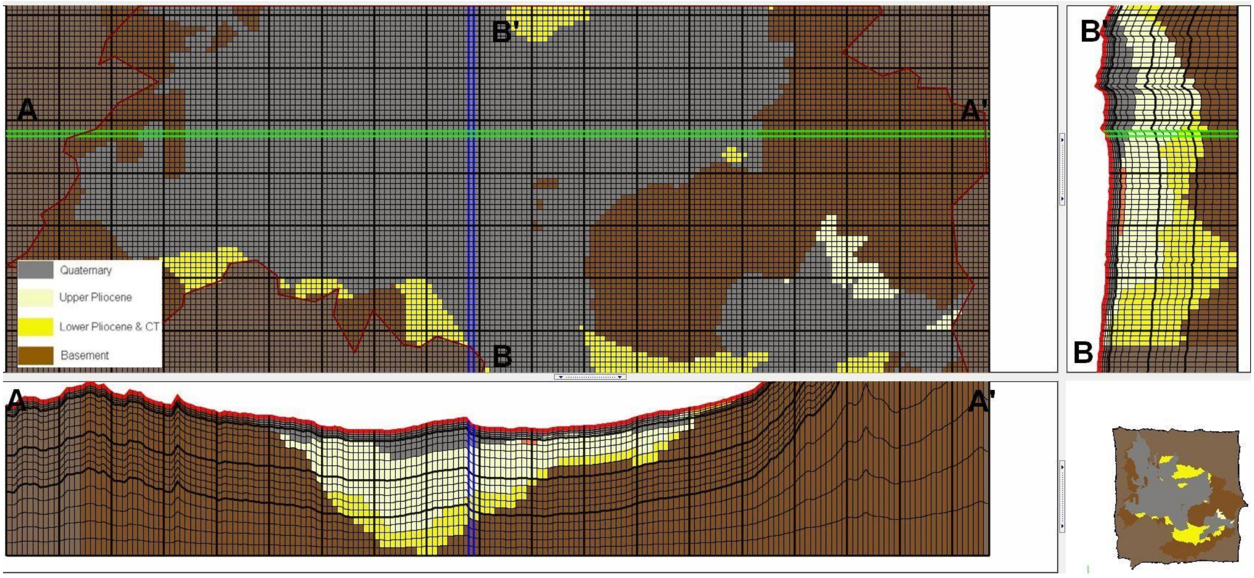
Conceptual Model layers extent. Gray: Quaternary; pale yellow: Upper Pliocene; yellow: CT and Lower Pliocene; brown: Basement.



Parametrization was based on the previously collected data on lithology, aquifer thickness, transmissivity and permeability. The initial parameters set on the larger catchment scale were obtained through estimations based on collected data from databases and in literature research. The calibration procedure was based on adjusting estimated recharge, transmissivity and river influence.

The spatial distribution of recharge from precipitation and irrigation return flow (independently calculated) was directly applied to the top level of the modeled area as initial input for further recharge assessment by the numerical model. Groundwater-surface water interactions (water flux among groundwater, rivers and lakes) were estimated based on groundwater head (piezometric level), river water level and literature research estimates. River levels generally interact with the top model layer as a river boundary condition. Groundwater abstraction, estimated following the water demand for the population's supply and agricultural irrigation, takes place mainly in the shallow wells of the Quaternary aquifer. For modeling, abstraction (as well fields) was spatially distributed and the pumped amounts were allocated to the corresponding aquifer layer and cell.

Cross-section across the central part of the basin showing the different layers (vertical scale enhanced by 500). Gray: Quaternary; pale yellow: Upper Pliocene; yellow: CT and Lower Pliocene; brown: basement.

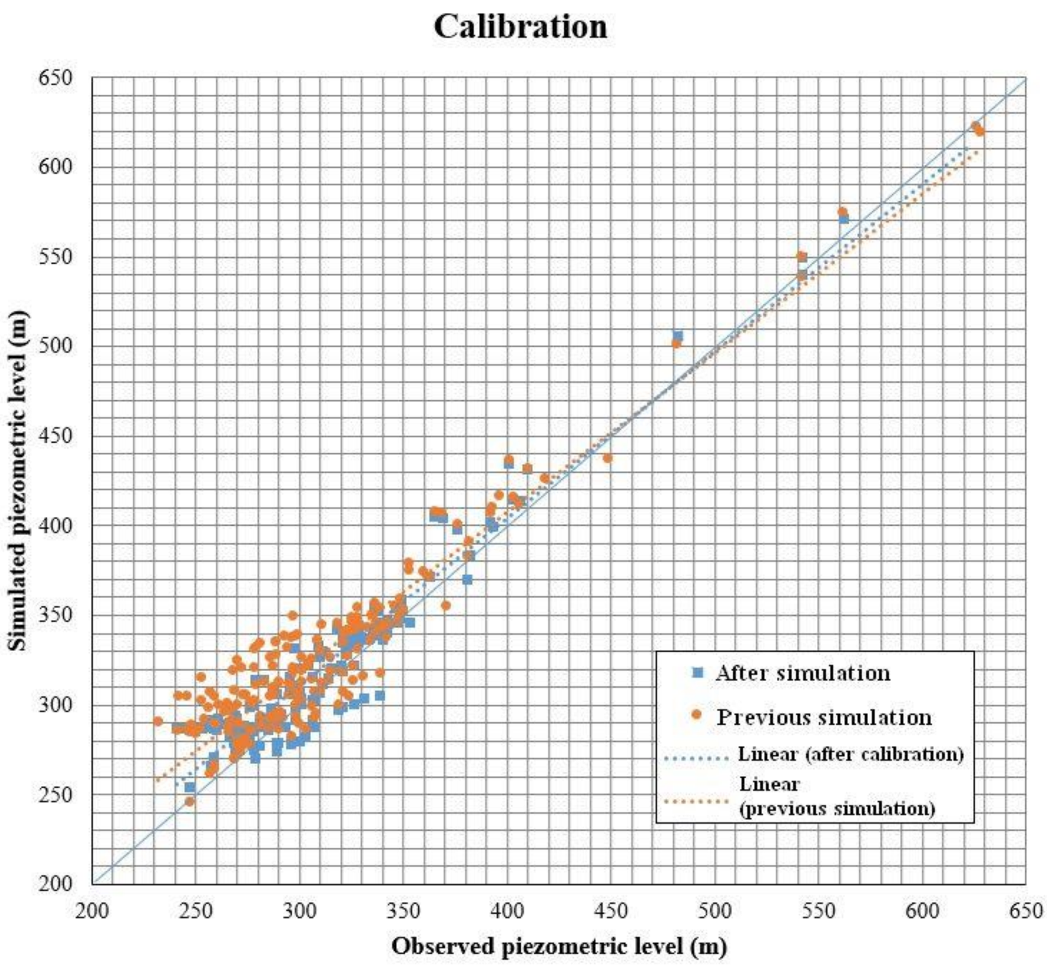


Model results

The system outputs, i.e. flows of water leaving the groundwater system, are: groundwater discharge to surface water (water is drained from the aquifer if the groundwater head lies above the river head); evapotranspiration (already considered in the net recharge estimation); and groundwater abstraction from pumping wells for domestic supply and agriculture.

Model calibration to fit the groundwater level simulations to field observations, is work in progress for the upper aquifer, mostly impacted by the poor match between simulations and field observations in the depressed areas of Komadougou-Yobé and Chari-Barguirmi. Given the steady-state simulation conditions, the groundwater heads at the Chari-Baguirmi and in the SW part of the lake were not well captured by the model and are overestimated. The simulated groundwater levels are higher than the measured ones. Improved adjustment to the conceptual model and to boundary conditions might also be proposed in the next modeling step.

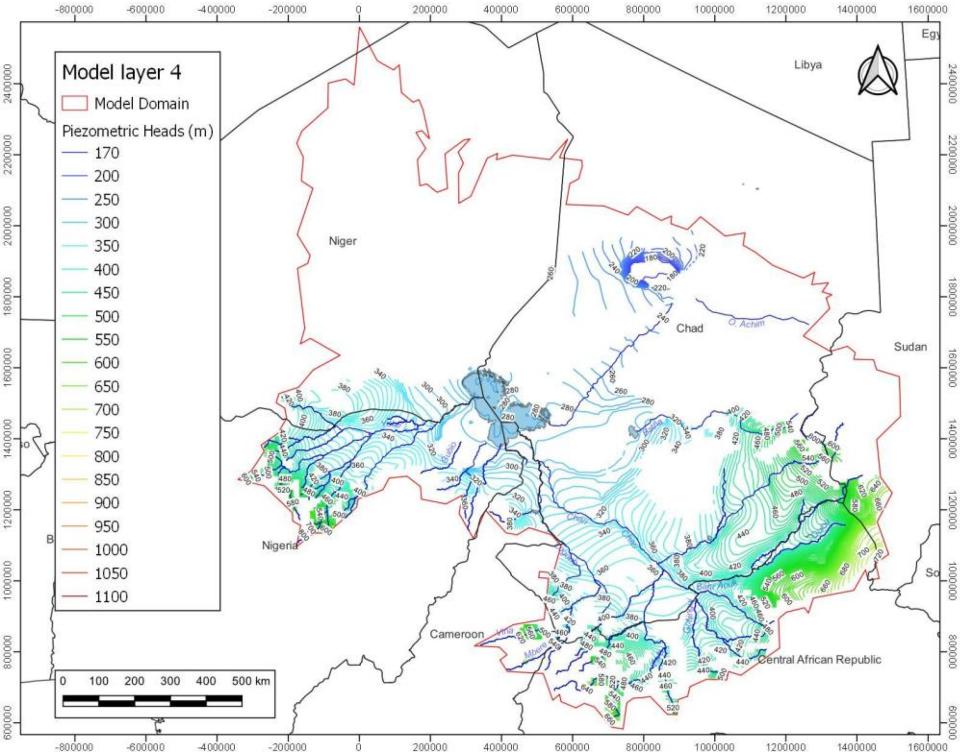
Overall in the superficial aquifer, the model is able to capture the amplitude of the observed heads. The general flow pattern agrees with field observations for the baseline period. Modeling the water balance error shows a good numerical accuracy, differences between the simulated input and output results account for 0.0025%. The observations made for the deep aquifer are scarce, which limits further comparisons with the simulated results.



Model sensitivity analysis

The sensitivity analysis revealed that the developed model was not very sensitive to the changes in water abstraction that have taken place locally, but a clear response to natural recharge variation was observed, as recharge is the main process to control groundwater balance. This is reasonable behavior when considering the work's basin-wide scale.

Simulated piezometric level for the unconfined aquifer (output of layer at 40 m depth)



Results of this Work. Key Findings

The newly developed 3D steady-state groundwater flow model of the Lake Chad Basin allows groundwater dynamics to be simulated on a basin scale. In particular, the groundwater volume and associated head are simulated and the model can be used to identify groundwater depletion hot spots at the basin level and in the Chari-Logone and Komadougou-Yobé areas. It also provides the necessary boundary conditions for further numerical model developments in selected areas at local level.

However, the current model cannot be used as a reliable Decision Support System (DSS) tool for water management or planning. Nevertheless, once the conceptual model will be adjusted and the steady-state calibration will be adjusted, this model will be able to provide detailed water balances in defined areas and can also identify unknown hot spot areas in the Lake Chad Basin.

The obtained results refer mainly to the superficial aquifer (unconfined), as scarce data are available for modeling the deep semi-confined aquifer. The net recharge in the basin (from precipitation and irrigation return flow, recorded on a daily basis) has been independently estimated as model input. It also includes the new parameterization of unconfined and confined water-bearing formations and upgraded geometry and simulates lateral flows and groundwater-surface water interactions.

The developed steady-state model constitutes a snapshot of the groundwater dynamics in the basin. This modeling study is the first step toward a transient flow model at the basin scale for modeling time-dependent stresses and/or conditions when water enters or is released from the groundwater system.

Further development of a transient model would require monitoring the groundwater level, along with time series datasets, for the spatially distributed data. A transient model can only be developed if the groundwater level historical data are available for model input. Improving the data in the hydrogeological database would be the first step.

The model is an important tool for a properly designed monitoring network across the basin to provide considerable spatial coverage monitoring by incorporating: number of observation wells and locations and spatio-temporal coverage of measurements frequency, and new monitoring wells design to assess groundwater level at varying depths in focus areas.

The model's results must only be taken as an indication of the system response due to the sources of uncertainty related to the scale of the work done:

- Local piezometric level changes may be slighter than the adopted mesh resolution. A 10 kmx10 km model grid is too coarse to identify small-scale local impacts
- Adopted assumptions for modeling, such as computational and data limitations, or hydrogeological and hydrological simplifications of groundwater-surface water interactions, to reflect the model need to be set according to Modflow2005.

Recommendations and Future Work

Insights from this modeling exercise help point towards future work to improve the basin-wide understanding of groundwater dynamics and for overall model improvements. The recommended investments to collect additional observations related to groundwater and new analytical efforts, are as follows:

- It is highly recommended that further investments should focus on the unconfined aquifer which constitutes the major groundwater supply contributor. The Lower Pliocene and CT aquifers are also an important water resource potential, and research efforts should be targeted to improve current knowledge in the southern part of the basin (with special focus on Chari Logon and Komadougou-Yobé areas) where exploitation is increasing and main natural recharge takes place.
- A better aquifer system geometry definition on the northern and eastern boundaries of the basin where geologic information is lacking, and is important for defining the aquifer system boundaries. Mapping of aquifer unit thickness would require geologic information from oil and gas and new drilled wells for subsurface exploration purposes.
- Hydrogeological studies in the Upper aquifer of the basin should be addressed to: conduct aquifer tests to estimate hydraulic properties (hydraulic conductivity,

porosity), to collect new groundwater level time-series data with time in targeted monitoring zones (the Chari-Logone, Komadougou-Yobé basins, Salamat, NE, SW and central part of basin area) and to place monitoring wells throughout the basin
- Establishing a groundwater monitoring network and a groundwater monitoring plan based as much as possible on existing and new drilled wells. The primary purpose is to monitor groundwater levels and groundwater fluctuations (and groundwater quality in a further step) to define the aquifer's background, to support estimated groundwater flows and to detect changes in aquifer status These data are critical to decisions concerning water management.
- Research addressing the assessment of connectivity between aquifers in the basin's southern part (CT-Q), and surface-groundwater interactions (Komadougou-Yobé, Chari-Baguirmi) will help to improve the current conceptual model interpretation. Surface geophysical surveys, e.g. electric resistivity transects, should be conducted to delineate aquifers contacts in depth.
- Accurate data provision on the irrigation practices, crops and spatial distribution of existing and newly proposed agricultural developments. Good agricultural management is a key issue to protect water resources. Future works need to include exact quantitative data on groundwater exploitation and the location of pumping wells, type of crops, irrigated volume, and timing.
- Collecting and storing data from detailed hydrogeological research and quantitative fieldwork by the hydrologic agencies involved in the basin's management (Member States and LCBC).

In order to manage groundwater use effectively, the basin's water balance assessment requires additional data. The information that is particularly required includes:
- Groundwater and surface water extraction data based on real estimations of demand across the whole basin
- Placing water level monitoring wells at properly designed hydrogeological sites in river basins to assess surface water–groundwater connectivity, and to understand and quantify recharge/discharge processes
- The amount of water supplied from dams and other water storage facilities for irrigation purposes and the specific locations where transfers take place
- Placing gauges at specific monitoring sites in river basins to provide streamflow data. A hydrograph analysis to support conjunctive surface water–groundwater management practices

In addition, a regular reassessment of the conceptual model is required to increase the level of confidence in model predictions and to answer the defined questions based on the modeling objectives:

- Introducing new datasets with geologic data for geometry improvement, specifically an in-depth geological description. Updating temporal data coverage as regards climate, pumping, the riverbed longitudinal profile, drainage or land use change data for the most recent period

- Introducing new aquifer stresses (new groundwater exploitation areas, river water transfers) not previously considered, but represent anticipated changes for assessing inflow and outflow in the aquifer system because of the hydrologic changes made in the region

1. INTRODUCTION

Context

The Lake Chad Basin is an inland drainage system covering an area of about 2,355,000 km^2 in the eastern part of the Sahel region of Africa, whose active basin, which includes Lake Chad, is an important freshwater resource for neighboring countries.

Lake Chad is a tropical lake with related wetlands that is shared by Cameroon, Chad, Niger and Nigeria. Parts of the Central African Republic fall in its active hydrological basin. Over the past 100 years, the lake's area has significantly varied in size from over 22,000 km^2 in 1960 to about 1,700 km^2 in January 1985 but has since then increased again to an average area measuring approximately 8,000 km^2 during the 2000-2015 period. This lake's variability in size is explained by rainfall variations over its basin, which lead to a wide variability in river flows and lake input, particularly over the Chari-Logone River Basin, which may account for about 95% of the water inflows to the lake. Although climate change is often mentioned to explain Lake Chad's current state and its possible disappearance, current models that assess climate changes forecast rising temperatures, but have not assessed the rainfall regime changes in the Lake Chad Basin (2050 and the 2100 time period; LCBC, 2015).

Lake Chad, its banks and its islands are a source of livelihood for nearly 2 million people. They are also a food-exporting hub that plays a key food security role of a hinterland with nearly 13 million inhabitants and two metropolitan centers, N'Djamena, the capital of Chad, and Maiduguri, the capital of the State of Borno in Nigeria. The entire basin is home to about 50 million people as of 2015. The lake's rich biodiversity has enabled riparian communities to perform productive activities based on fishing, agriculture and livestock farming. The area's dynamism is based mainly on a complex system that has adapted to environmental variability and is characterized by mobility, multi-activity, and multifunctionality. Mobility refers to people responding to changing natural resources. Multi-activity means that a dominant proportion of the lake's population practices several activities, such as fishing, livestock, agriculture, and also trade and crafts, to secure revenue. Multifunctionality refers to the successive use of the same space for fishing, agriculture and livestock by following the rhythm of annual floods and flood recessions. In its watershed, Lake Chad is a large productive socio-ecosystem, but one with much poverty, demographic pressure and security threats. Lake Chad's value, therefore, lies in the ecosystem services that it provides, which are particularly precious in its Sahelo-Saharan regional environment, characterized by aridity and erratic water resources availability.

However, it is also a vulnerable socio-ecological system that faces numerous risks: climate variability and hydrological shifts, risks of pollution (pesticides, oil industry, sewage, industrial and mining effluents), a low human development index and basic services, one of the highest population growth rates worldwide and insecurity.

In 2012, the Heads of States of LCBC Member Countries adopted the Water Charter for the Lake Chad Basin as a binding framework to promote sustainable development there through the integrated, equitable and coordinated management of natural resources, particularly the basin's water resources (www.cblt.org/en/themes/ lake-chad-water-charter-vehicle-sub-regional-integration-and-security). The Water Charter is ratified by Cameroon, Chad and Niger.

The Water Charter observes that: *i)* precipitation and hydraulic flow conditions in the Lake Chad tributaries are extremely variable and likely to be affected by climate change; *ii)* the total water use in the Lake Chad Basin (2.5 km^3/year) currently represents about 10% of the lake's water inflow and, to date, variations in its water level are caused by variability in rainfall and related river flows. However, an uncontrolled increase in abstractions could cause significant effects on the water level and extent of Lake Chad; *iii)* groundwater resources are currently managed inadequately; *iv)* the basin's ecosystems are sensitive to variations in inflows and pollutant discharge; at *v)* insufficient availability and exchange of information limit knowledge of water resources and aquatic ecosystems, and restrict the possibility of their transboundary management.

Some Water Charter objectives aim to enhance the quantitative management of surface water resources, including the establishment of: *i)* principles and management rules for water resources by limiting abstractions from the lake and its tributaries (State Parties agreed in the Charter to limit total abstractions to 6 km^3/year and establish procedures for recording abstractions); *ii)* the environmental flows to be maintained in watercourses during low flow and high flow periods. However, the total abstraction limit of 6 km^3/year is not based on a rigorous scientific and evidence-based analysis, but on an approximate value that does not account for either climate shifts/drought periods or the spatial allocation of abstraction limits.

Surface water and groundwater in the Lake Chad area are interconnected. While surface runoff-rainfall models, lake models and groundwater models separately exist, no comprehensive understanding of the dynamics among surface water, groundwater and abstractions exists. Hence, there is no understanding of how a sustainable or "balanced" basin would be in terms of abstractions and sustainability.

Thus, an overview of the system must be produced to fully understand the hydrologic dynamics of groundwater and surface water. An updated groundwater model, which includes all the information available to date, is a useful representation of the current understanding, and allows analytical work to be done on hydrological and water use scenarios. The results of such hydrologic modeling and analyses can inform about the domains for future investments and the sustainability of new water use abstractions. An updated model (or set of models: groundwater, surface water) can also be used for continuous near-real-time monitoring and to understand the Lake Chad system.

In the field of hydrology and water resources, specifically in groundwater hydrology, the basin has been subject to considerable research by national and international agencies. Groundwater numerical models for the basin have existed since 2004, but they cover most of the basin at a very low resolution or certain areas of interest, and do not include up-to-date information and linkage to surface water models.

Current modeling at the Lake Chad Basin

Since the previous regional works by Schneider and Eberschweiler (1993b), a number of hydrogeological models have been or are being developed, as presented in the modeling chapter. Previous modeling efforts and initiatives focus on very specific local objectives and areas, which cover mainly the central-southern part of the basin and the Quaternary aquifer (Abderamane, 2012; Hassan, 2002; Gaultier, 2004; Massuel, 2001; Zairi, 2008). Only a few are on a regional scale (Leblanc, 2007; Boronina and Ramilien, 2008) but they do not cover the entire hydrogeologic basin and hydrostratigraphical units of the Chad Formation.

The current modeling exercise, and the development of a three-dimensional (3D) flow model of the Chad Formation for the 2008-2011 period, include updating and upgrading the last documented regional models based on additional data collected since 2005. As time-dependent hydrologic parameters (i.e. groundwater level measurements over time) do not exist, only steady-state modeling is performed. Therefore, the principal objective is to represent the groundwater system more realistically by including updated information to adequately simulate groundwater head dynamics and groundwater depletion affected by climate changes and human water use.

It strictly focuses on groundwater, and the conclusions herein provided do not address any ecological or human health toxicological issues that may be associated with the site or potential issues associated with constituents in surface water or soil. Chemical and isotopic information is used only to support the groundwater system (recharge, discharge, mixing waters, flow direction, circulation depth) in order to understand the assessment of hydraulic connections, and the establishment of the boundary conditions of the conceptual model for formulating and updating the mathematical model.

The following changes to the conceptual model of the Chad Aquifer Formation and its numerical representation are included:

- Updating the boundaries of the regional aquifer, its geometry and the new model layers structural contours at basin level
- Updating the groundwater level contour map for the 2008-2011 period
- Updating recharge zones and rates (from precipitation and irrigation return) for the 2008-2011 period
- Updating the understanding of the basin’s groundwater dynamics

Objectives of this report

This report describes the Lake Chad groundwater flow model (steady-state, 2008-2011 period), its conceptualization and model development at the basin level, the calibration procedures carried out, the principal results and findings of the calibration process, and the predictive analysis results.

Hence the report provides:

- An updated baseline of the groundwater conditions in the Lake Chad Basin. It points out current data gaps and data quality for the intended objectives
- A conceptualization of the basin's hydrological status and hydrologic system dynamics (precipitation, groundwater and surface water, abstractions, environmental status, vegetation cover) to date
- A numerical groundwater flow by integrating all the new available data and information

The report includes detailed information on model inputs (natural recharge) and outputs of groundwater flux arranged in two main chapters:

Chapter 2: Geology, Hydrology and Hydrogeology Of The Study Area. This section presents current knowledge and summarizes previous hydrological works for groundwater studies in the Lake Chad Basin aquifer system, including: study approach, data sources and review; conceptualization of the groundwater system; an approach to the basin's water balance.

Chapter 3: Groundwater Modeling. This section introduces groundwater numerical model definition, calibration procedures and results. It describes how the conceptual model is translated to the numerical model's grid. It includes the definition of boundary conditions and layers, spatial discretization, parameters, predictive results and also model limitations.

There are seven appendices with background information: Appendix A on reservoirs and gauge stations; Appendix B on the lithological logs and geometry of the basin; Appendix C lists information available on aquifer system hydraulic parameters; Appendix D on groundwater flow mapping, and the groundwater level data available for the 2008-2011 period; Appendix E on the natural recharge estimation for the study period. Appendix F on the data archiving of collected information. Finally, Appendix G includes model layers information.

2. GEOLOGY, HYDROLOGY AND HYDROGEOLOGY OF THE STUDY AREA

2.1. The Lake Chad Basin. An Overview

Extending between 6°N and 24°N latitude, and between 8°E and 24°E longitude, the study area, otherwise known as the Lake Chad Hydrologic Basin (Fig. 1), covers some 2,381,000 km^2 (www.cblt.org/en). It extends as far as Algeria and Sudan, and even to a small area of Libya, as well as to five LCBC Member States (Cameroon, Central African Republic, Chad, Niger and Nigeria). A large part of the area (around 44%) lies in the Chad Republic.

The Conventional Basin (Fig. 2) is the intervention zone of the Lake Chad Basin Commission (LCBC) among Cameroon, Chad, Niger, Nigeria and the Central African Republic. In 2012, it covered an area of 967000 km^2.

Figure 1. The Lake Chad Hydrologic Basin (BGR-LCBC, 2009). The hydrographic network, wetlands and swamps are also shown.

It is characterized by wide spatial climate variability, an arid climate north of N'Djamena, a sub-humid climate in the central part and a humid climate in the south. Most rainfall occurs between April and October. 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. Intensive agriculture takes place in areas of Nigeria and Cameroon.

Figure 2. The Conventional Basin (from 1954 to the present-day, LCBC).

The basin is an extended plain covered mostly by medium-to fine-grained sand. Surface height varies from above 3,000 m in the north, NW and the SW to 165 m in the center. The basin's central part is characterized by two different landscapes subdivided by the 14°N parallel. Sand dunes and lack of surface water sources are typical in the northern part. The south is composed of sandy and clay rich soil with a channel network made up of the two main rivers that discharge into the lake.

The Conventional Basin's is heterogeneously spread, and population is estimated at about 44 million distributed as so: 3,090,000 in Cameroon, 1,080,000 in the Central African Republic, 10,670,000 in Chad 3,200,000 in Niger, and about 26,090,000 in Nigeria (LCBC-GIZ, 2016). The annual population growth rate is estimated to be 2.5-3.0% (UN Population Division, 2015). The population's water supply is covered mainly by a number of shallow wells and by exploiting the upper aquifer. Around 20,000 wells have been identified (BGR, 2010).

Agriculture remains the most important activity for over 60% of the basin's population, and irrigated agriculture is the main water user. The water supply source for agricultural irrigation, livestock and market gardens irrigation is generally rain-fed and based on flood-recession, or is provided by existing dams and also from groundwater in the Chari-Logone (Chad, Cameroon, CAR), the Komadougou-Yobé (Nigeria) basins and Niger. In most schemes, surface water is conveyed from existing dams by a main distribution canal to existing irrigation zones. Generally, no account is taken of the amount of volume used from dams, the applied dose or the timing involved. Groundwater is increasingly employed for irrigation, especially during the dry season (GWPO, 2013) and in areas where precipitation is irregular (marginal lands; BGR-LCBC, 2012).

2.2. Hydroclimatic conditions

The area extends over three climate zones (Fig. 3): the desert regime characterized by a wide variability of spatial climate conditions (rainfall and temperature); the humid tropical (south); the Sahel semi-arid area and the arid Sahara (north). The Lake Chad Basin's climate is classified into three subtypes (from north to south, according to the Köppen–Geiger climate classification system):

- Hot desert climate (BWh), characterized by less than 180 mm of rainfall per year
- Hot semi-arid climate (BSh) with an average annual rainfall of between 300 mm and 1,100 mm
- Tropical wet and dry or savanna climate (Aw) with an average annual rainfall exceeding 1,300 mm

Only the information and availability of the hydroclimatic parameters providing useful information (physical quantity) on groundwater conditions are discussed here.

Across the basin, the mean annual rainfall ranges between 10 mm and 1,900 mm, with temperatures north to south varying from 41ºC to 18ºC. In the central-southern part, minimum temperatures are reached in December and January, with maximum values in March and April, after which temperature lowers during the rainy season. The annual mean temperature depends on the climate zone and can reach up to 29ºC at the 15ºN parallel, with 27ºC in the south.

Potential evapotranspiration-ETP (Penman) has maximum values of 230 mm/month in March (N'Djamena). ETP values of 2,000-3,000 mm are common.

The range of changes in rainfall, as regards the mean precipitation for the long-term average (197-2017) at the Faya, N'Djamena and Pala ground-based stations is plotted in figure 4. From the visual analysis, it appears that changes are more evident for the ground-based stations in southern and middle parts of LCB (Pala and Ndjamena, respectively), and there is no evidence for a precipitation trend. However, wide periodical variability is observed in the south (Pala).

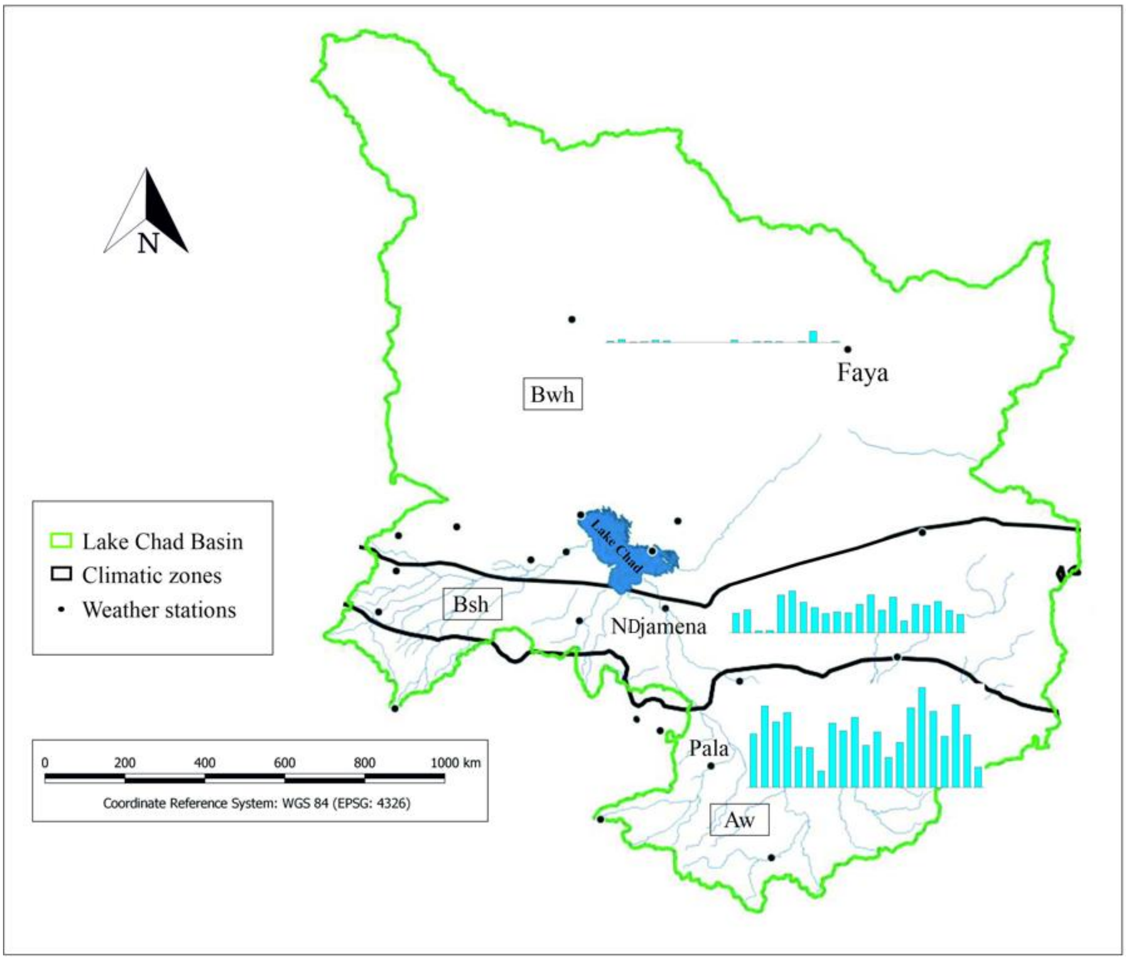


Figure 3. Climate zones inside LCB. BWh: hot desert; BSh: hot semiarid; Aw: wet and savanna (Köppen-Geiger, 1961). Annual precipitation (mm), as recorded at the Faya, N'Djamena and Pala meteorological stations for the 1994-2014 period, is also presented.

In the Lake Chad Basin, ground-based climatic data, mainly precipitation and temperature, are recorded by a network of some 680 meteorological stations (Fig. 5) with a wide spatial distribution, time span coverage, maintenance of regular observations, limited number of daily datasets and relevant gaps. For the ground-based weather stations and existing records, the main spatial coverage lies in the basin's central part. A few stations are located in the inhabited areas lying north of Lake Chad.

Reasonably good meteorological data (ground data) are available from a number of platforms (e-tools) of hydro-meteorological datasets from existing weather stations, with stored information provided by corresponding countries. E-platforms are the most important quantitative data repositories of Precipitation-P and Temperature-T (i.e. TAMOH: http://tahmo.org/african-climate-data/; https://en.tutiempo.net/climate/africa.html; SIEREM: http://www.hydrosciences.fr/sierem/, Boyer et al., 2006). The use of remote sensing data merged with ground-based data is an important source of datasets (CHADFDM; Sheffield et al., 2018).

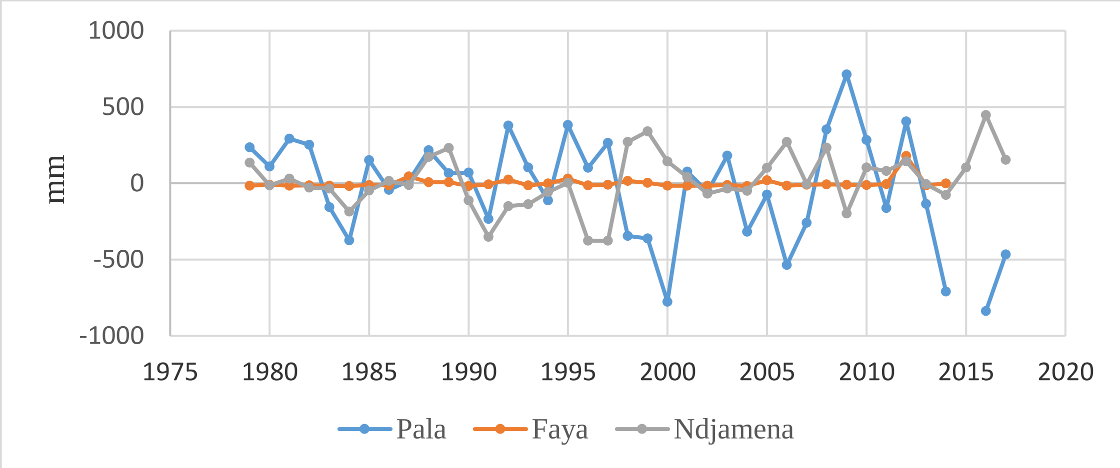


Figure 4. Precipitation variability as regards the mean for Faya, N'Djamena and Pala from 1975 to 2017 (see also Fig. 3 for spatial location).

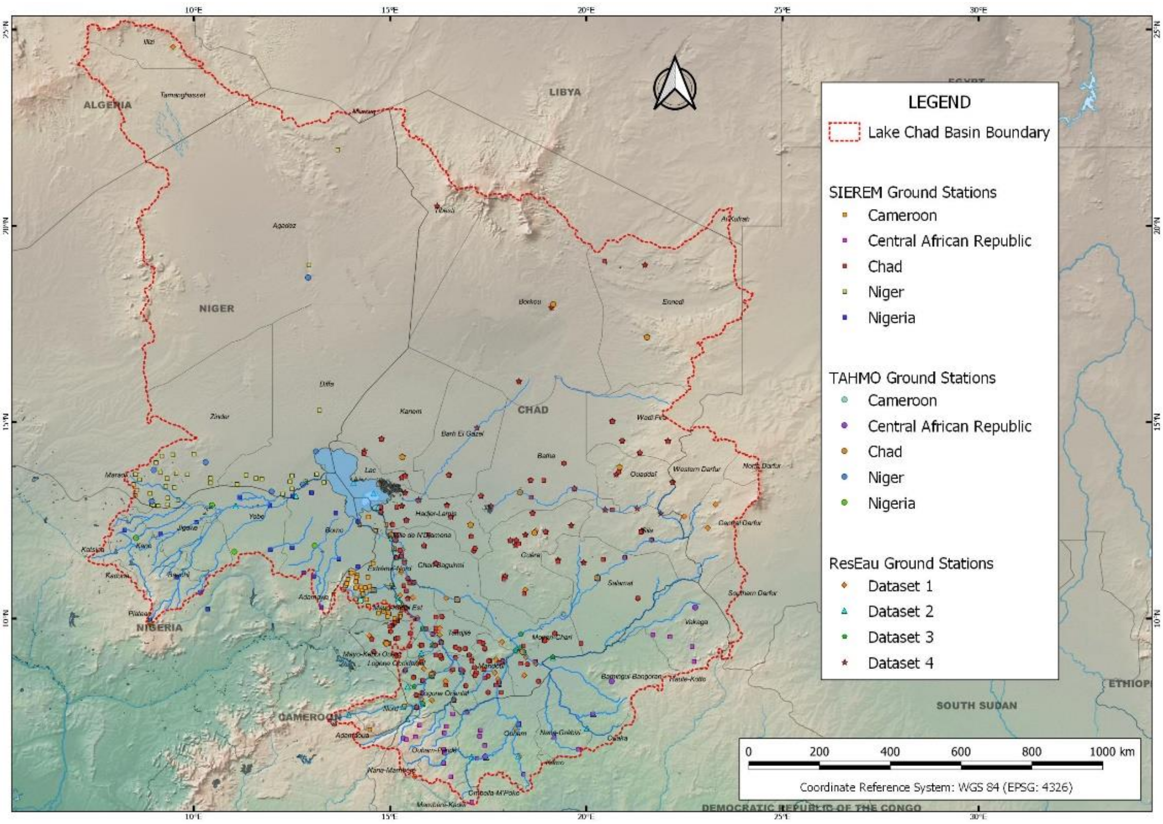


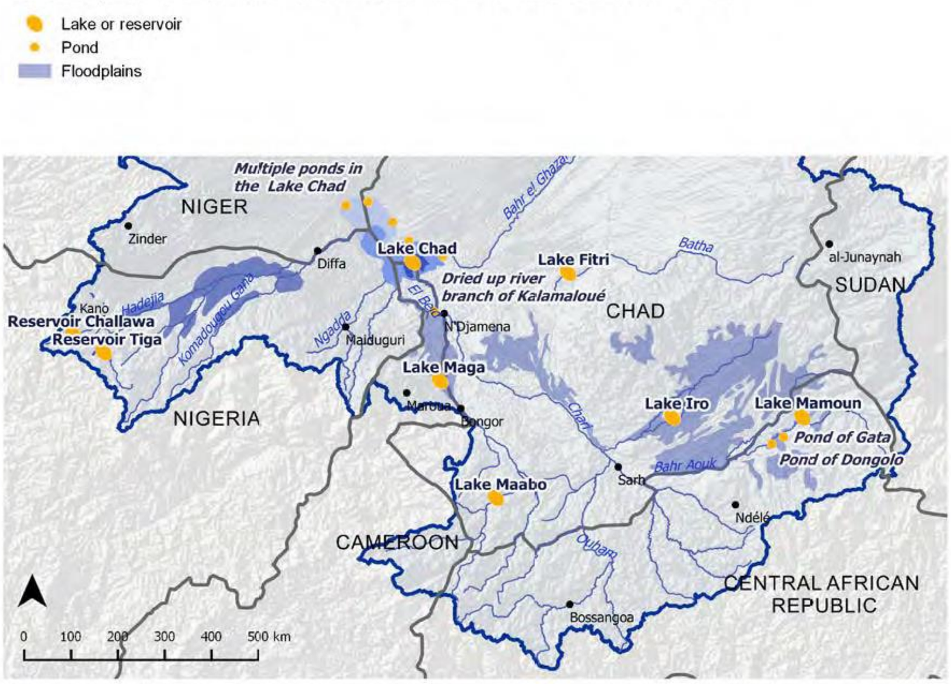
Figure 5. Ground-based meteorological stations in the LCB (various sources).

2.3. Surface waters. Hydrology

The study area is a closed (endorheic) basin that drains into Lake Chad and extends mainly in Chad, NE parts of Nigeria, southern Niger, northern Cameroon and, to a lesser extent, in NW parts of the Central African Republic and western Sudan (Fig. 2). Regionally, updated published information is found in the BGR-LCBC project (regional groundwater management project for 2008-2019). The thorough report of Shaofeng et al. (2017) focuses on monitoring (and modeling) surface flows, including Lake Chad. Locally, a number of studies and reports also exist and are included in the References section.

a)

b)



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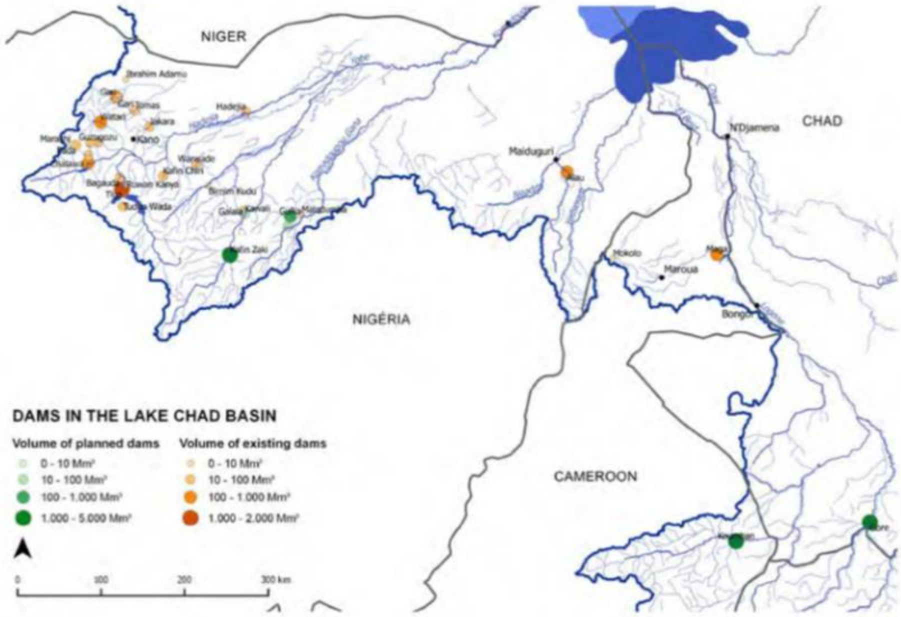


Figure 6. Surface hydrology in the Lake Chad Basin; a) delimitations and rivers; b) lakes, reservoirs and ponds; c) dams (LCBC-GIZ, 2016).

The principal permanent rivers are Chari and Logone (in the basin's southern part), and Komadougou and Yobé in the western part (Fig. 6a). Less important basins (average area covering less than 15,000 km²) include Yedseram, and Ngadda in Nigeria and El Beid on the border between Nigeria and Cameroon, all of which drain into Lake Chad. The remaining hydrographic network is made up mainly of a number of intermittent watercourses.

The two main river basins occupy the area below the 15th southern parallel (Fig. 7). The Chari and Logone river system, with headwaters in the Central African Republic and the Cameroon, and an area covering 690,000 km² in southern Chad, is responsible for 95% of the inflow to Lake Chad. Both rivers converge at N'Djamena.

Komadougou-Yobé, which descend from the Bauchi plateau, and River Yedseram from the Biu plateau, extend over approximately 148,000 km² with 57% of its basin lying in Nigeria and the rest in Niger, provide about 3% of the annual inflow to Lake Chad (RAF/7/011). It has a generally low streamflow and marked seasonal irregularity, undergoes long periods with low water levels and even completely dries up.

From July to December in flat topographic areas, the formation of floodplains takes place principally in rainy months; the numerous plains (Yaéré, Dérésia, Massenya, Salamat, Komadougou-Yobé) are periodically flooded (after FAO and LCBC-GIZ, 2016). The Logone feeds the Yaéré floodplains in Cameroon which, in turn, are drained by the El Beid river toward Lake Chad when Logone exceeds a flow rate of 1,500m^3/s (UNESCO-BMZ-LCBC, 2002). In the Komadougou-Yobé Basin, the Hadejia-Jama'are floodplain (also named Hadejia-N'Guru) is located upstream of the confluence of both the Komadougou Gana and Yobé rivers. The Hadejia-Jama'are floodplain covers an area of over 2,000 km^2 at peak floods. Floods begin in July and the maximum flood peak is reached in August-September (Acharya, 1998).

The national hydrological services in the basin are in charge of collecting, monitoring, storing and managing of hydrologic data and of maintaining a network of hydrological stations (gauge stations) made available to the LCBC (Table 1; LCBC-GIZ, 2016).

Table 1. The gauge stations that formed part of the national networks of LCBC countries in 2012 (LCBC-GIZ, 2016).

Country	Stations recorded in the basin	Stations operating in 2012
Cameroon	9	0
Libya	0	0
Niger	1	1
Nigeria	40	-
Central African Republic	9	0
Chad	52	36

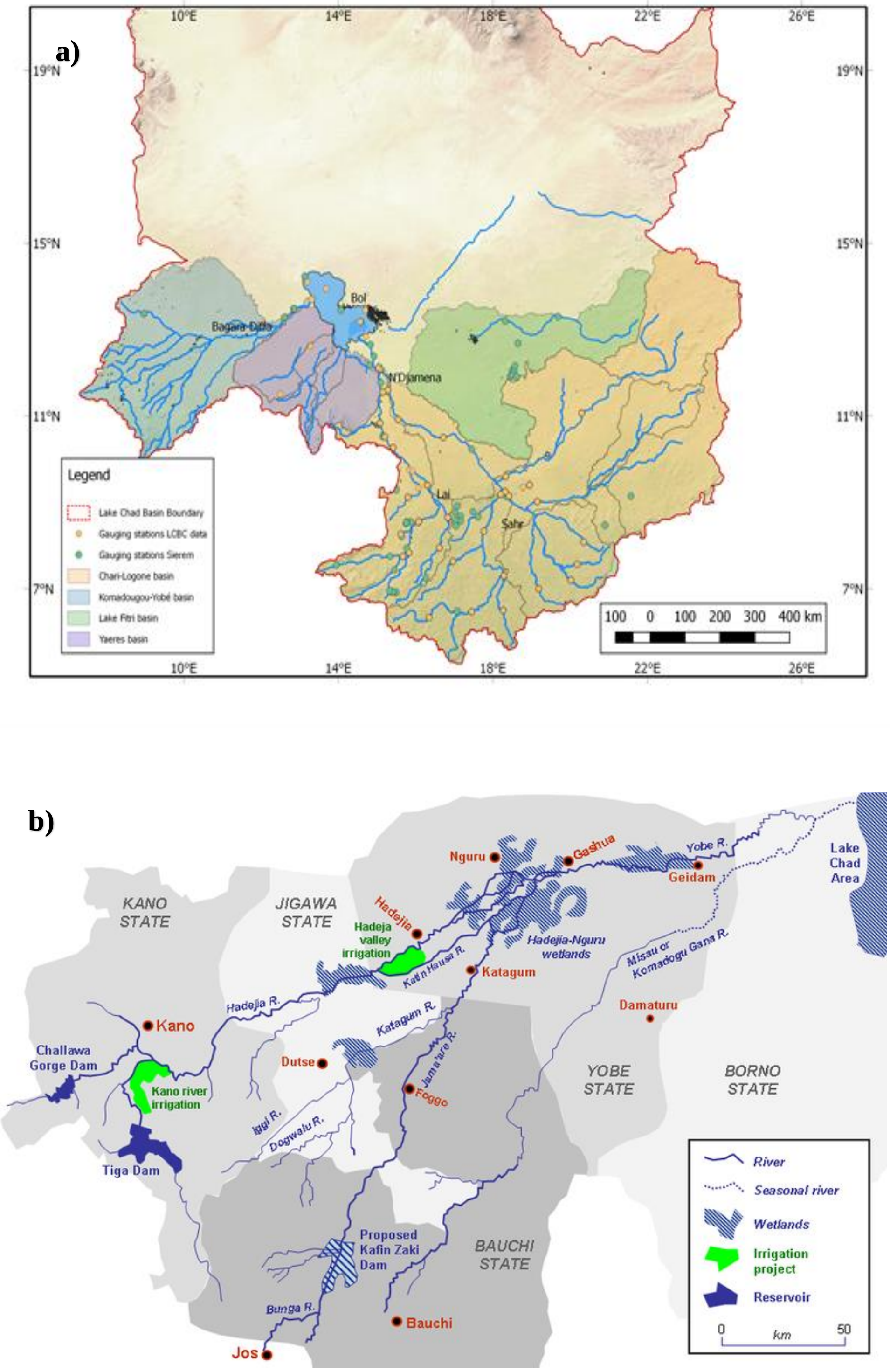


Figure 7. Delimitation of the: a) Chari-Logone, Komadoudgou-Yobé, Yaérés and Lake Fitri River Basins; location of gauging stations; b) Komadoudgou-Yobé (https://fr.wikipedia.org/wiki/Fichier:Yobe_river_catchment_area.png).

The surface water data (streamflow and lake surface level) provided by the LCBC (files from CDIG-ResEau) include daily values of the streamflow at different gauge stations in the two main river basins. Existing records (cm or m^3/s obtained from rating curves) are available from

1933 to 2018, but with widely variable time series length and quality at different hydrometric stations.

Although streamflow information is usually stored on a daily basis, a number of gauge stations have not been operational due to lack of resources since the mid-1990s. Appendix A presents the collected information of groundwater interest from the gauging stations in the Chari-Logone and Komadougou-Yobé Basins, and that obtained from different sources. Table 2 includes existing information on the SIEREM platform.

Table 2. The SIEREM platform. Existing data in the LCBC-DB and time period length. Gauge stations in Member States.

Country	Gauge Stations	Gauge Stations with data	Daily data (m^3/s)		monthly data (m^3/s)		daily data (cm)		monthly data (cm)	
			Period	Data series	Period	Data series	Period	Data series	Period	Data series
Chad	169	66	1936-2008	gaps	1936-2009	gaps				
Nigeria	17	7	1955-2000	gaps	1946-2008	gaps				
Niger	174	34	1956-2003	gaps			1956-1977	few gaps		
Cameroon	196	79	1940-2007	gaps	1951-1980	gaps				
CAR	108	62	1911-2000	gaps	1911-2010	complete			1911-1994	complete

For the Komadougou-Yobé (Fig. 8), streamflow ranges from 498 Mm^3 (2009-2010; 2011-2012) to a maximum of 894 Mm^3 (2012-2013). Runoff events start at the end of June and may finish early in March at the latest. Hydrograph peaks generally occur in November, and the decreasing slope of recession (segment of the hydrograph) generally starts at the end of December. The hydrographs for the period (2008-2012) show runoff duration periods (streamflow from precipitation) lasting between 184 and 222 days.

Figure 9 shows the annual discharge of the Chari and Logone Rivers after joining at N'Djamena. High streamflow volumes occur from September to November, and floods generally occur in November (Chari), with low values observed as of April.

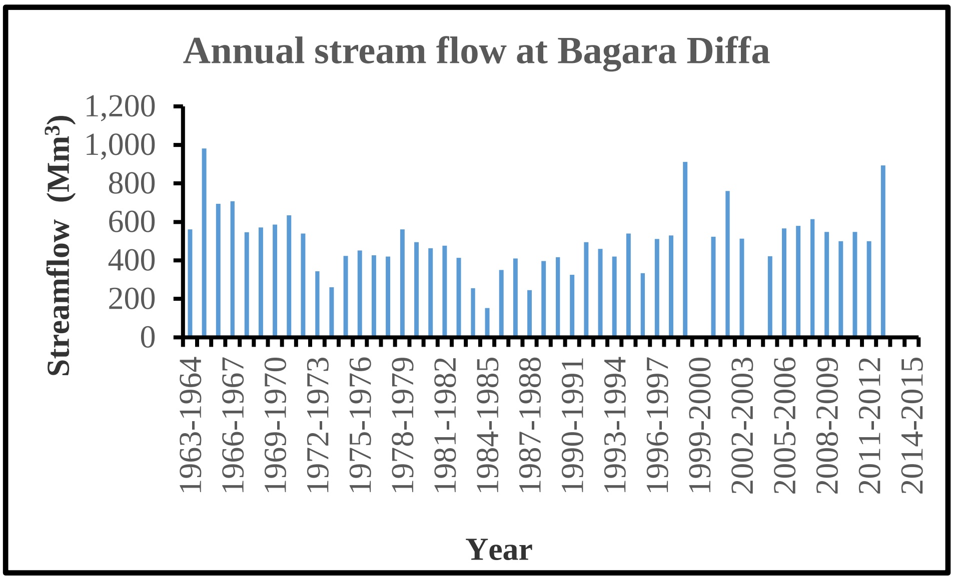


Figure 8. The Komadougou-Yobé annual streamflow (Mm^3) at the Bagara-Diffa gauge station (LCBC data). See the location in Figure 7a.

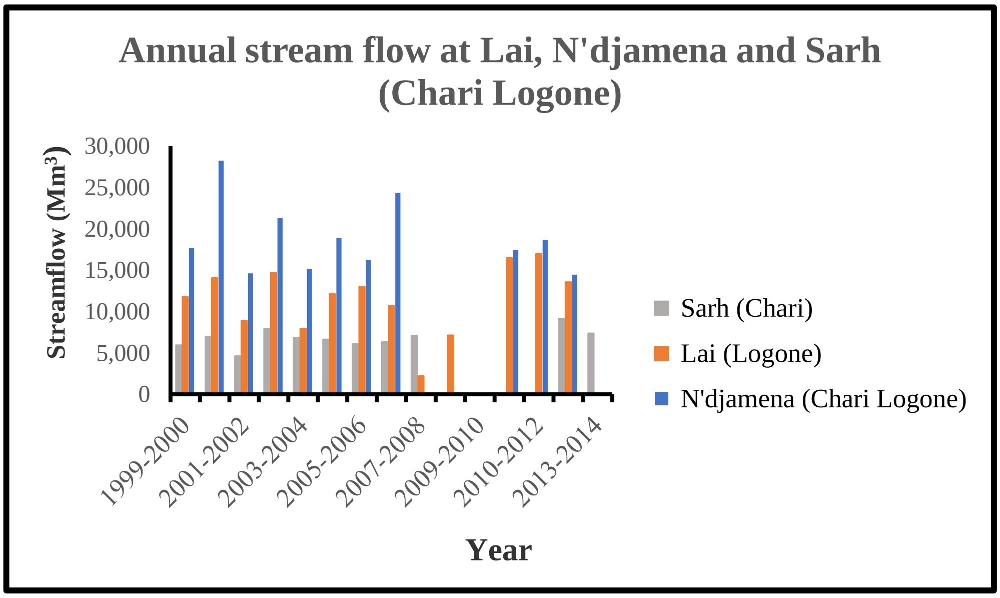


Figure 9. The Chari-Logone annual streamflow (Mm^3) at gauge stations N'Djamena, Lai and Sarh (LCBC data). See also Figure 7a for the streamflow gauge location.

Lake Chad, in its current 'small Lake Chad' state (around 2,000 km^2), is an endorheic system supplied mainly by the Chari-Logone River system (up to 95% of total inputs), and is also supplemented by inflow from other tributaries (Komadougou-Yobé, El Beid and Yedseram (up to 3.6%), and from direct rainfall (between 7% and 14%). Rainfall on the Chari catchment is the primary lake size factor. When rainfall in the basin varies by 10%, Chari's discharge varies by approximately 30%. The precise relation between the lake and groundwater is still poorly understood (LCBC, 2015). Losses occur mainly through evaporation (95% of losses).

Lakes Iro and Fitri (Fig. 6b) belong to two different subcatchments in the central Lake Chad Basin part, and are located in two different climates: Sahelo-Sudanian for Iro and Sahelian for Fitri. Close to the Bahr Salamat watershed outlet, Lake Iro is a subcatchment of the Chari-Logone system (Fig 7a). Both are hydrologically controlled by the rainy season from June to September, followed by a dry season. In the northeast, the Ounianga-Kebir Lake system corresponds to the Nubian Sandstone Aquifer System outflow, which is also fed by a seasonal streamflow from the Ennedi Mountains during August rainfall.

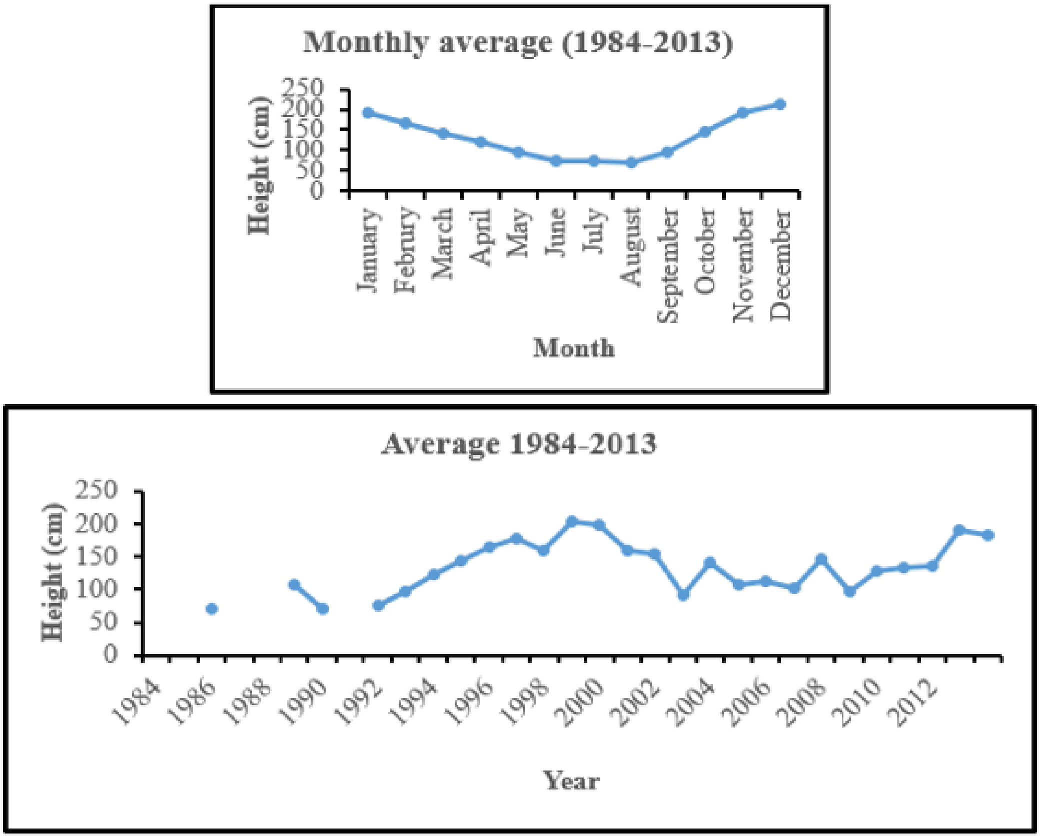


Figure 10. The Lake Chad annual and monthly average heights (cm) at the Bol gauge station (LCBC data).

Apart from Lakes Chad, Fitri and Iro, perennial or seasonal natural or artificial lakes and ponds exist, generally of a fluviatile origin and associated mainly with floods during rainy seasons. Existing reservoirs and water capacity are included in Appendix A and locations can be found in Fig. 6c. New dams are planned for further use in the Nigerian and Chadian areas.

The Lake Chad water level along time at Bol (Fig. 7a) is plotted in figure 10. While the precipitation period takes place in June-October, its maximum is recorded in August. The maximum values are recorded in the lake in December. The effect of the contribution of the two main river basins is clearly observed in the lake's level.

2.4. Geology. Regional setting

From a geological standpoint, the Lake Chad Basin is composed mainly of Late Cretaceous, Tertiary and Quaternary sandy or sandstone formations, which have built up an average 300-metre elevation plain, underlain by a Precambrian crystalline basement (Fig. 11). A lowland depression area located north of the lake (SW of Borkou) is the lowest area in the basin (120 m below the mean Lake Chad water level).

Existing data on the regional geology, obtained mainly from the works of Wolff (1964), Servant (1973), Schneider (1989), Schneider and Wolff (1992) and Eberschweiler (1993a,b), are available in the BRGM and LCBC repositories, and constitute the core of the geological knowledge herein presented, along with information collected on lithological logs from compiled reports (Table 3). Geological bore logs are available, but do not provide adequate coverage throughout the study area, as presented in Appendix B. They concentrate mainly in the basin's central part.

Additional updated information for the northern/eastern parts of Chad from the first ResEau Project phase (ResEAU, 2017) and peer review comments are included. To date, very few newly published regional data on the study area (e.g. Moussa, 2013) that are relevant for modeling have been found.

Maps as GIS shapefiles can be downloaded from various platforms on different working scales from IRD (http://sphaera.cartographie.ird.fr/pays.php), the BGS platform (http://earthwise.bgs.ac.uk/index.php?title=File:Cameroon_Geology2.png&filetimestamp=20150908085241) or the Nigerian Geological Survey Agency (https://www.ngsa.gov.ng/. Geological maps with a digital support have been developed as part of the BGR-LCBC project.

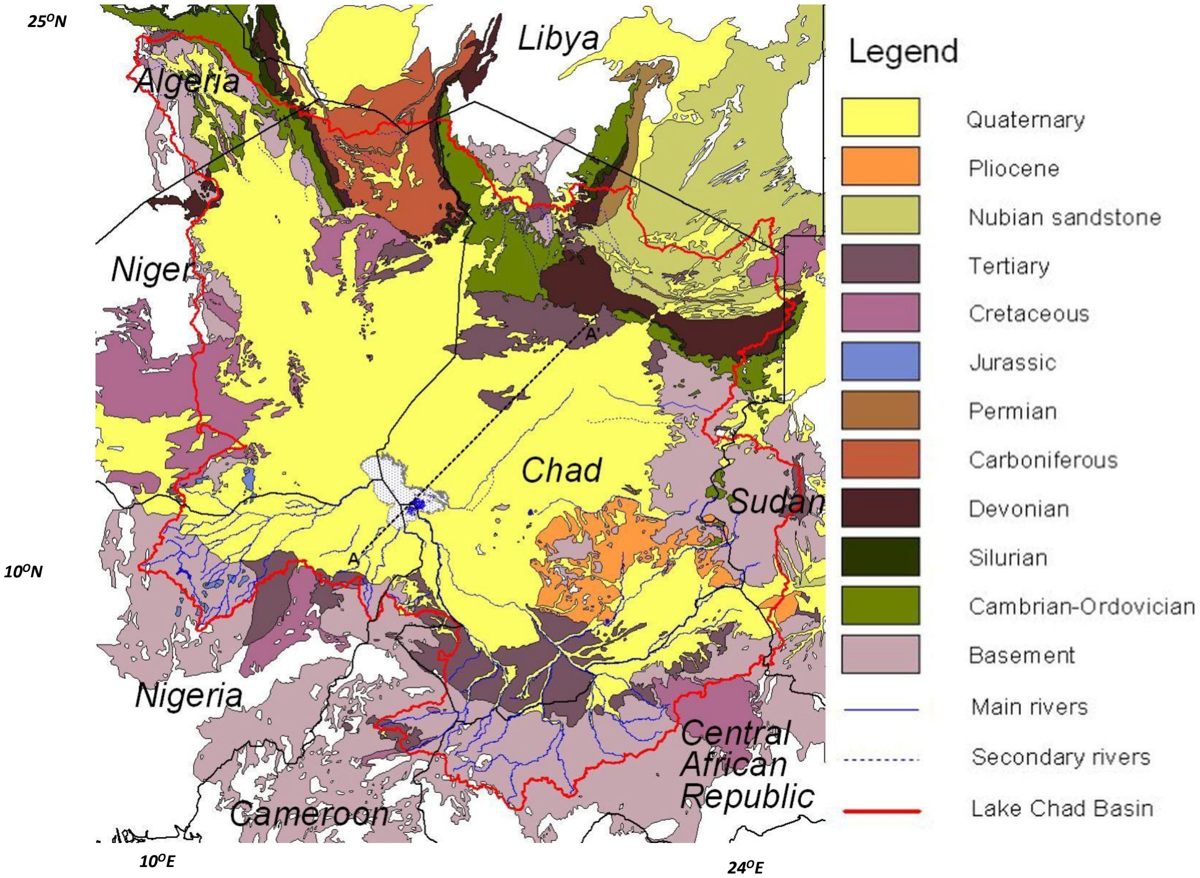


Figure 11. Geology of the basin area, geological formations and age. The red line indicates the Lake Chad Hydrologic Basin limits. The black dotted line (A-A') denotes the Figure 13 cross-section location (according to Schneider, 1989).

From the geological standpoint, in the basin's southern and northern parts, the Precambrian/Paleozoic basement presents abrupt changes (rises or falls) due to important faults that have resulted in deep basins (Termit, Niger-Lake Chad, Bongor-Bousso, Doba-Salamat). They date back to Cretaceous times and were filled by sandy and sandstone formations from the Cretaceous and Paleogene periods (Vicat et al., 2002; Ganwa et al., 2009). The maximum sediment thickness reaches 13,000 m in Termit and goes from 6,000 to 7,000 m in the Bongor, Doba and Salamat basins.

During Neogene times, the central and northern parts of the Lake Chad Basin received more important sedimentation for a longer period than in the basin's southern part, which has resulted in a greater accumulation of Neogene and Quaternary sediments in the basin's central and northern parts.

Table 3. Data source, number of water points and geological logs in the Lake Chad Basin after data set screening from the compiled information (files).

Number of water points (wells, piezometers, boreholes)	Number of lithological logs
3767 (LCBC file)	50 (Schneider, 1989)
409 (2008-2011)+226 (2013) BGR	22 (USGS-Nigeria, 1965); some in the Schneider thesis
404 (RESOPIEZ) SUIVIPIEZ	129 (BRGM, 1992; from the 1960-70s). Compilation of many existing works. A number of deep boreholes from oil explorations (>1000 m deep)
171 (UNESCO-2000)	31 (Koweit-Niger; ResEau: Forages Koweit, 2006)
148 (5-FED, 1987-1988)	5 (ACF-19xx, Musoro)
232 (6 FED,1981-1991)	37 (Almy Al Afia II, 2013-2014)
656 (7 FED, 1994-1998)	52 (Hydraulique Pastoral, Al Afia, 2004-2008)
70 (8 FED, 1990-1998, PRS)*	296 (9-FED, 2005-2014)
43 (8 FED, 2001-2009, PRS)*	22 (Alkali, 1995)
312 (2001-2008) Almi Nadif (OuaddaÏ-Biltine)**	
2000 (9 FED, 2005-2014)	
750 (10 FED, 2010-2013)	
84 (UNIRES, 2009)	
154 (UNESCO, 1966-1968)	
156 Yaéré complet (19xx)	
TOTAL 9356	**TOTAL 644**

**Programme Régional Solaire (I and II); **CE, Agence Française de Développement (AFD) and Coopération Allemande (KFW). xx: unknown*

Fractured Precambrian materials (Gear and Schroeter, 1973) comprise sandstone, together with granite. According to exploratory drilling outcomes, the depth to the basement varies from 60 m to one of about 600 m in the basin's centre (Mbwou et al., 2012).

Sedimentary formations

The oldest Lake Chad Basin sediments are composed of early Cretaceous terrigenous clastics, as well as shallow marine shales, sands, silts and minor carbonates from the late Cretaceous (Genik, 1992). Sediments seem considerably thicker toward the northeast. From the bottom to the top, the following formations are distinguished:

The Continental terminal-CT. The Tertiary era is marked by marine regression from the basin and the deposition of sandstone and clay series, generally in discordance with Cretaceous rocks. The upper parts of this formation are usually lateritized intensely, particularly in the basin's border areas. The CT is the major part of the sedimentary formation that overlies the basement complex. It mostly outcrops in the southern and northern fringes of the study area. In the basin's central part, the CT is encountered at a depth exceeding 100-300 m (Schneider and Wolff, 1992).

The Pliocene-Pli. Pliocene formations are made up of several sedimentary units whose thickness ranges from ~850 m to ~4,000 m. The Lower Pliocene formation *(LPli)* consists of fluvial sands of a thickness from 10 m to 40 m, overlain by lacustrine clays with a thickness of ~300 m (the Upper Pliocene formation, Schneider and Wolff, 1992). The clay deposits containing diatomite layers mark the end of the Tertiary era.

The limit between the Pliocene and Quaternary is not very sharp due to lateral changes of facies, and perhaps variations in the lake's level have already affected the top of the Pliocene.

The Quaternary-Q. The Quaternary constitutes the uppermost layer and is made up of sands and clay with different subformations as follows (BGR-LCBC, 2012):

- The Moji Series (from the early Pleistocene), which is a fluvio-lacustrine clayey series with evaporites (gypsum)
- The aeolian sand dunes from the "Ogolien" age (lying over the Moji Series) that correspond to the dunes formed from 20,000 to 13,000 yr BP (Swezey, 2001). These dunes appear mainly north of Lake Chad and are composed essentially of quartz sands.

The interdunal valleys, up to a distance of 30 km from the ancient lake shore, are often occupied by sodium-carbonate evaporite minerals, such as natron (Na_2CO_3, $10H_2O$), and are still exploited. To the south of the lake, Quaternary deposits are overlaid by alternating sandy layers, an indicator of past arid conditions, and by clayey layers that are either lacustrine or fluvial, and result from more humid periods when the lake size increased, and the Logone and Chari riverbeds were much wider. In CAR, and on the basin's southern border, quaternary deposits can also be found lying over *CT* deposits.

The stratigraphic sequence ends with formations composed mainly of aeolian sand and fluvio-deltaic deposits. Its thickness varies from ~15 m to ~100 m (Lopez et al., 2016). From the beginning of the Quaternary to recent times, the sedimentary deposits in the Lake Chad Basin are related to rivers and lake fluctuations.

A schematic diagram of the layout of the different geological units (Quaternary, Pliocene, Lower Pliocene, Continental Terminal) and the basement (Cretaceous and Precambrian) of the study area is presented in figure 12.

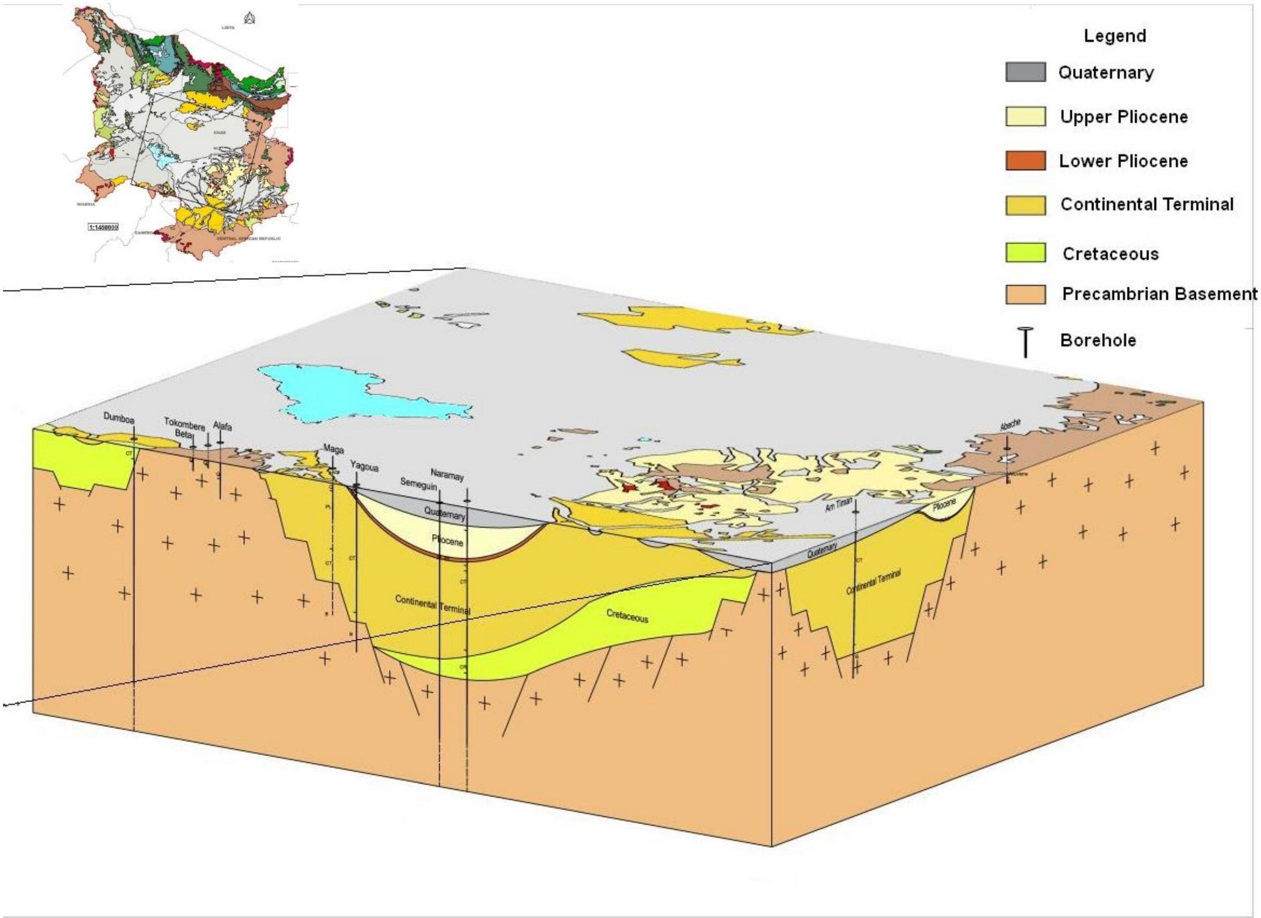


Figure 12. A 3D stratigraphic and hydrostratigraphicschema of the Lake Chad Basin showing the Quaternary (gray), Pliocene (yellow), Lower Pliocene (brown) Continental Terminal (dark yellow) and bedrock (Cretaceous and crystalline rocks). Several lithological logs with a stratigraphic description along with the depth of the lithology succession are plotted. The inset map shows the location of the schema in the basin.

2.5. Hydrogeology

Three sedimentary aquifers of interest are defined for the Lake Chad Basin: the Chad Aquifer Formation (Quaternary-Pliocene-Miocene age), the confined Continental Hammadien (Middle Cretaceous-Maestrichtian age) and the Continental Intercalaire (Diantien-Lower Cretaceous age). Precambrian crystalline rocks (schists, granite, etc.) outcrop on the basin's southern edge, the southern edge of Lake Chad (Hadjer el Khamis), the eastern area of the basin (Moyto in the sedimentary basin, Guera, Biltine, Ouaddaï), Mayo-Kebbi and the Baïbokoum areas to the south.

Following FAO (1973) recommendations, on the regional scale and for the Chad Aquifer Formation, the three sedimentary aquifers of interest are defined by the terms Quaternary (*Q*), Lower Pliocene (*LPli*) and Continental Terminal (*CT*) and are herein used from this point onward. However on local and intermediate scales, units are heterogeneous and can contain a mixture of sands and clays, present wide lateral variability in sediment type and facies distribution with different aquifer levels and varying hydraulic conductivities (laterally and depth). Alluvial aquifers, associated with riverbeds and local perched aquifers of limited extensions, also develop in some areas after heavy rain.

The main features of aquifers (or water-bearing formation) in the different countries sharing the hydrogeological basin are also discussed briefly in this section. It is worth mentioning that the terminology adopted for different hydrogeological formations may vary from one region to another. For example, the terms “Chad Formation” and “Continental Terminal" are recognized on both sides of the Niger-Nigerian border, and maybe the geological formations assigned to them are not the same (UNESCO, 2004).

Most regional hydrogeological information relies on the reports and research studies carried out mainly by Schneider (1989), Eberschweiler (1993a,b), Alkali (1995), Bonnet and Murville (1995), PNUD (2003), Massuel (2001), Leblanc (1997, 2002 and 2007), Zaïri (2008) and ANTEA/EGIS/BCEOM/CIAT (2012). Many local studies (reports and research) have been conducted in the area by different institutions (e.g. FED, LCBC, Member States and international agencies, and academic institutions).

2.5.1. The aquifers in Chad

In Chad, the aquifers herein considered are contained in recent geological formations (Quaternary and Tertiary), and correspond to the following groundwater-bearing layers:

i) the Ogolian sands aquifer (in Kanem in the NW); *ii*) the Moji series aquifer (also located in Kanem); *iii*) the Lower Pleistocene aquifer (Kanem and Batha); *iv*) the Lower Pliocene aquifer (Kanem and Batha); *v*) the Continental Terminal aquifer (Borkou, Kanem, and Batha in the north, and Koros and Salamat areas in the south). A SW–NE geological cross-section of the regional aquifer system is shown in figure 13.

2.5.1.1. Quaternary aquifers

Quaternary aquifers, including Pleistocene aquifers, are essentially composed of aeolian siliceous sands, with lower levels of clay and fluvio-deltaic deposits. Their thickness varies from 15 m to 100 m (Lopez et al., 2016). In Chad, they constitute the uppermost groundwater-bearing layer. Quaternary aquifers are made up of the following geological units (PNUD, 2003).

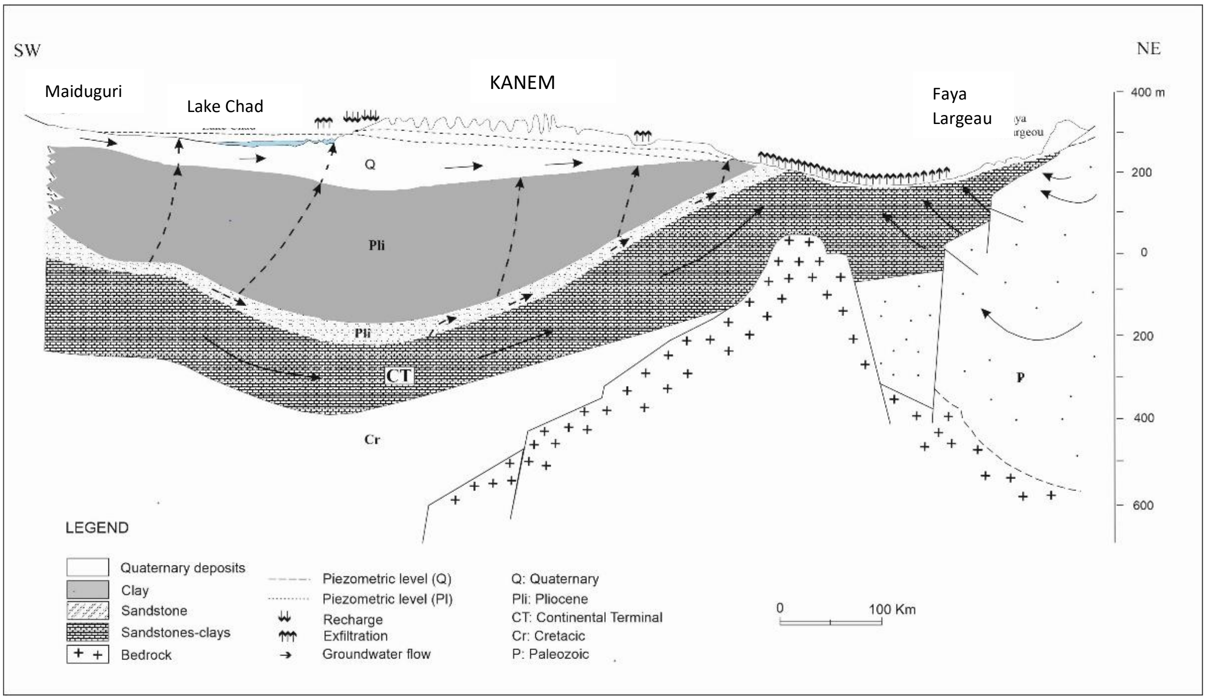


Figure 13. Cross-section of the study area (according to Schneider, 1989). See the location in Fig. 11.

The Upper Pleistocene.

- The « Ogolian » aeolian sands aquifer

Ogolian sands correspond to the unconfined aquifer located in the northern part of Lake Chad, to the west and south of Kanem. It is constituted by fine to medium-sized sands (0.1-0.5 mm) of aeolian origin (from 20,000 to 13,000 yr BP; Swezey, 2001). Thickness ranges from 20 to 70 m. It overlies either the Moji Series aquifer (especially in the Bol and Rig Rig areas) or the Lower Pleistocene sands aquifer (in Keliganga and Ngouri). Aquifer boundaries are:

- To the north, up to 16^0 of latitude (further up, the Moji Series aquifer becomes a unconfined aquifer);
- Eastwardly, up to 17^0 of longitude (further east, the Middle Pleistocene becomes the aquifer);
- Southwardly, down to 13^0 of latitude (more to the south, the Middle Pleistocene also becomes the aquifer).

The aquifer is recharged by precipitation at a rate between 10-15 mm/year, which leads to piezometric domes in recharge areas (Kimi Kimi, Harr areas).

This aquifer generally presents transmissivities above 1,000 m^2/day (around 1 x 10^{-2} m^2/s) and specific yields (e.g. discharge/drawdown), often over 10 m^3/h/m, but wells slightly penetrate the aquifer.

Except in the dune-system depressions, where evaporitic deposits are found, it is suitable for both human consumption and irrigation thanks to low mineralization (150 mg/L to 400 mg/L). This aquifer's high permeability, together with its very shallow water table, means that it is very vulnerable to pollution.

- The Moji Series aquifer (Upper Pleistocene)

The Moji Series aquifer is an unconfined/confined aquifer made up of calcareous cemented sandstone, with interlayered marls and clays (fluvio-lacustrine clayey series) and some evaporitic rocks, mainly gypsum. It covers more than 20,000 km^2 in approximately northern Kanem (Egueï and Moji areas), in Soulia (Kanem and Batha areas) and in several areas of Chari Baguirmi to the south. Aquifer thickness ranges between 10 and 20 m. The high water salinity, which often goes above 5 g/L, and even 8 g/L, impairs its further use.

The Middle and Lower Pleistocene Aquifer

It has the largest extension in central Chad, covering over 235,000 km^2 and constitutes the main unconfined aquifer in Chari Baguirmi, in northern and western Kanem, and in the southern Batha areas.

It is composed of siliceous sands, with clay being more or less present, and with rather good hydraulic characteristics and high spatial heterogeneity, depending on clay content and the grain size of sediments. Transmissivity (T) varies from 100 to 600 m^2/day (corresponding to 1.5×10^{-4} to 7×10^{-3} m^2/s), and permeability (K) ranges from 3 to 60 m/day (3.5×10^{-5} to 7×10^{-4} m/s). The storage coefficient (S) is estimated from 4×10^{-4} to 1×10^{-3}. Yields in wells present wide variability, with flow from 7 to 40 m^3/h. In some wells, high discharge rates are recorded (80 to 360 m^3/h in N'Djamena).

Recharge occurs through precipitation, and also by the surface water from the Chari-Logone river systems. This recharge takes place mainly during flood events. In the Kanem area, recharges through the Ogolian sandy aquifer overlying the Lower Pleistocene aquifer can take place.

The wide piezometric depressions (Chari-Baguirmi, extending from Massaguet to Bokoro), with a deeper groundwater level between 40 and 60 m than expected, are associated with a very high clay content in the aquifer that acts as a groundwater flow barrier. Their specific yield is generally low.

Water quality is generally good or acceptable with wide variations from 250 mg/L to values over 1,500 mg/L (i.e., in the vicinity of the Moji Series aquifer due to sulfate content) and even 5,500 mg/L north of Lake Fitri).

2.5.1.2**.** The Pliocene Aquifers

The Lower Pliocene aquifer, with highly permeable fluviatile sands, is overlaid by Middle and Upper Pliocene lacustrine clays, and its thickness is up to 300 m. It is generally considered an aquitard (Schneider and Wolff, 1992). The clayey layer confines the underlying sandy aquifer (i.e., by the *CT* clayey sandstone itself and the sandy *LPli* aquifer). In Chad, the Pliocene Formation's total thickness ranges from approximately 850 m to 4,000 m.

Lower Pliocene

The sandy Lower Pliocene aquifer (confined and often artesian) extends in Kanem, Lake, Batha, Chari Baguirmi, and also in the northern part of Mayo Kebbi in the south. This aquifer is found in deep wells at depths of about 250 m in surrounding Lake Chad areas, and at depths of more than 450 m in the basin's central part. Thickness increases from the basin's boundaries (from 30 to 70 m) to its center, where it may exceed 150 m.

Depending on local conditions, it may be considered a single aquifer system with the underlying *CT* aquifer. Productive layers may present clay content and thickness often ranges from 5 m to 10 m. The grain size fraction becomes finer in the north (Kanem and Batha) and aquifer permeability decreases accordingly. The aquifer presents good transmissivity values (100-500 m^2/day).

The hydrochemical concentration is variable from 500 mg/L to some 1500 mg/L.

Middle-Upper Pliocene Aquitard

This geological level is composed of a 200 meter-thick clay layer, sometimes up to 300 m, and acts mainly as an aquitard. However, sandy layers can be found locally with rather high transmissivity values (around 350 m^2/day) and good water quality, as found in Chari Baguirmi at depths from 145 to 215 m.

Upper Pliocene aquitard contribution to the Quaternary aquifer can be produced by vertical flows through the overlying clay.

2.5.1.3. The Continental Terminal

The *CT* period, a regression in which the sea level fell in relation to land, led to continental sediments being deposited from the Upper Cretaceous to the Pliocene period. In Chad and the whole basin, *CT* is one of the sedimentary formations attributed to the Miocene period. It discordantly overlies the marine sandstone and clay cretaceous series and the basement complex (Upper Cretaceous and Precambrian). In the southern and western fringes of the study area, it outcrops the Koros zone, with Pala sandstones and Kelo sands (also found in Cameroon) (Fig. 11). It appears to also outcrop the basin's northern part (Lowlands) and its SE part (the Batha and Ouaddaï foothills).

It underlies the Quaternary aquifer layers in the basin's central part, where it is encountered at a depth beyond 100-300 m (Schneider and Wolff, 1992).

Northern Continental Terminal
Covering 210,000 km^2 in the Chari Baguirmi, Lake and Kanem, the aquifer is still not well-known. From a hydraulic point of view, it is generally confined to the basin's northern part, sometimes artesian, but is not confined to boundaries. Composed of a sandy or clayey sandy formation that is 100-130 m thick, with moderate hydraulic characteristics and yields, values generally lower in the east toward Batha. The flow direction is toward the Lowlands (north).

Southern Continental Terminal
Covering over 145,000 km^2, it outcrops in the western and eastern Logone, Tandjile, Mayo Kebbi, Moyen Chari and Salamat areas. It constitutes the most important aquifer in this part of Chad. As a confined or unconfined aquifer, it presents important lithological heterogeneity. When the aquifer is superficial and is not confined, it is composed generally of sandy lenses, when the aquifer is confined by deep sandstone and clayey sandstone.

Thickness is variable and ranges from 70 m to 250 m, but from 150 m to 900 m in Doba/Salamat, and from 150 m to 300 m in the Bousso basins. Its hydraulic characteristics are acceptable (specific yield is around 4 m^3/h/m).

Water quality is good (salinity is generally lower than 100 mg/L), but presents high Fe concentrations and an acidic pH. Flow is northward and is drained by rivers (mainly Logone and Chari). The aquifer is recharged by precipitations and rivers during floods.

2.5.2. The aquifers in Niger

In Niger, the Quaternary and Pliocene aquifers present similar characteristics to those found in Chad, especially around the lake, with fine siliceous sands that are generally quite productive. However in the known "Manga area", to the west far from the lake's shore, the sandy quaternary aquifer thickness is probably very thin. The Quaternary and Pliocene aquifers are separated by a very thick impervious clayey formation (green clays).

In the northern part of Niger, the Chad Formation limits are the Ounissoui aquifer (Continental Intercalarie), which is probably connected hydraulically to the Manga aquifer, composed mainly of sands and gravel of Plio-Quaternary origin and Agadem sandstones (Cretaceous). The sandstones of Koutous and Termit (Cretaceous) constitute the NW limit (PNUD, 1991; Sabljak, 1994; Zaïri, 2008). (PNUD, 1991; Sabljak, 1994; Zaïri, 2008).

The Manga Quaternary Aquifer. Mainly in Niger (also west of the Chadian Kanem), it lies in the whole Diffa region and covers more than 150,000 km^2. This aquifer is similar to the Ogolian in Chad, and sand dune formation corresponds to the same time period. On a regional scale, it is made up of a number of sand dunes with topographic depressions that are 15-20 m deep in central dune part (Carter, 1994). The aquifer is made up of alternating decimetric to metric sand and clay layers. In the Manga arid area, the aquifer outcrops at the bottom of the depressions that originate between dune ridges due to weathering.

Groundwater flows to the lake and presents a very low gradient. In endorheic depressions, the groundwater level is very shallow, ranging from the top soil surface to a maximum of 15 m. It presents low water salinity, between 100 mg/L and 300 mg/L, except near the lake where a very high total dissolved solids content may occur.

The Manga Pliocene Aquifer. It extends to the south and west towards Nigeria, with the aquifer boundaries to the west of the Mounio crystalline rocks, the Termit basin to the NW and the Agadem basin to the NE. In the central part of Manga, the top of the Pliocene aquifer stands at a depth of around 300 m. It overlies the Quaternary aquifer and is generally confined (artesian). Recharge may probably take place only in upper relief areas where the Quaternary and Pliocene aquifers could merge.

In the southern part of Manga, the higher hydraulic head of the Pliocene aquifer (confined within an area of roughly 20,000 km^2), compared to the Quaternary, leads to vertical flows to the Quaternary aquifer (artesian).

Water quality is rather poor, even though it is an important groundwater resource. The Agadem and Nigeria oil fields probably place this aquifer at risk.

The Kadzell Aquifer. It covers the rather arid Quaternary Kadzell area between N'guigmi and Mainé Soroa, south of Manga and north of the Komadougou Yobe alluvial valley (the boundary between Niger and Nigeria).

It is around 80 m thick, and its composition is mostly clayey. It is a less productive aquifer. It overlies the clayey Upper Pliocene layer and the Pliocene aquifer (below 300 m, Descloîtres et al., 2013). Groundwater depth varies from very shallow in the Komadougou area to 40 m in the centre of the Kadzell depression, which are similar values to those found in other Lake Chad Basin areas. Aquifer recharge is produced mainly by rivers during floods. According to isotopic data, a limited contribution from Lake Chad and from precipitation exists (Zaïri, 2008).

Groundwater quality is poor (usually from 700 to 3600 µS/cm), except in the vecinity of the Komadougou-Yobé rivers.

The *Korama Aquifer* covers more than some 12,000 km^2 in the Korama basin (southern part of Niger) and is limited by crystalline rocks on eastern and northern boundaries, and with Nigeria on the southern border, but with a very limited extension (Sabljak, 1994 ; Sandao, 2013; UNESCO, 2004). It is composed of sandy-clay layers and alluvial sands from *CT* and *Q* deposited on bedrock (also forming part of Korama aquifer units). An apparently limited hydraulic connection exists with Chad Formation sedimentary materials.

2.5.3. The aquifers in Nigeria.

In East Nigeria and on the boundary with hydrogeological formations in Niger, three superimposed aquifers exist (Fig. 14), corresponding to Quaternary, Pliocene and Continental Terminal (Leblanc, 2002; Offodile, 2002**;** UNESCO, 2004).

To the south of Kadzell on the Nigerian side, the Komadougou River Basin and the Quaternary aquifer in the river valley present similar characteristics to those encountered in Niger. To the south of Komadougou, down to the 11th parallel in the eastern part of Nigeria, near Mora town (Cameroon), the Quaternary–Pleistocene aquifer extends, named "Chad Group" in Nigeria. Close to the lake, the Quaternary-Pleistocene aquifer has very similar characteristics to those in Chad. On the border with Cameroon, Quaternary sands are usually very fine, which makes water well construction rather difficult. At the Quaternary aquifer groundwater level, concave contours are observed south of Komadougou, known as the "Bornu piezometric depression", with poor hydraulic characteristics.

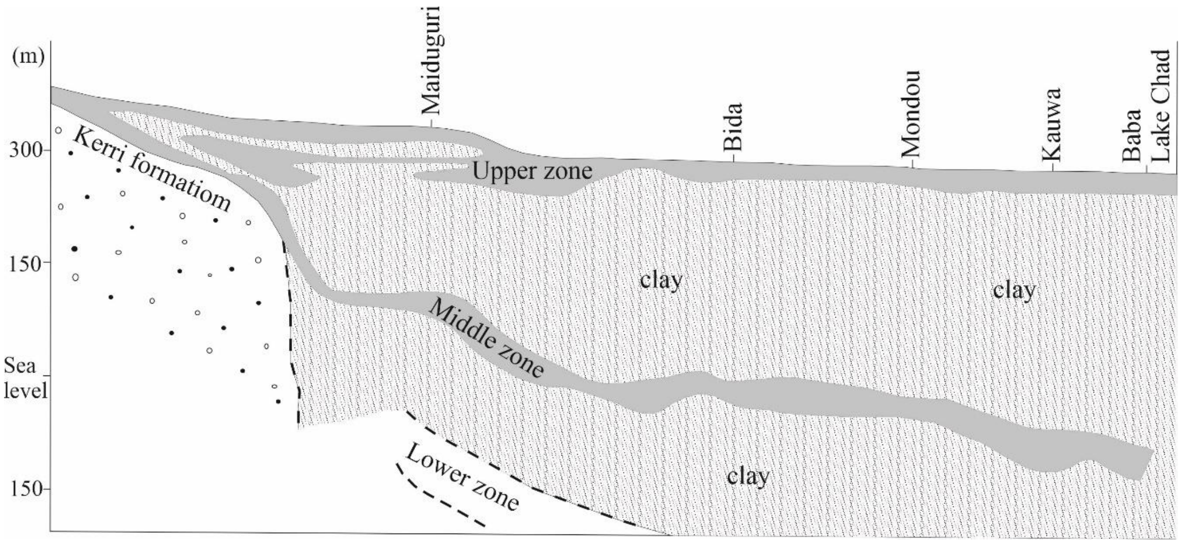


Figure 14. Cross-section of the aquifers in eastern Nigeria from the north of Bama to Lake Chad (after Miller, 1968 and Offodile, 2002). See the location in Fig. 11.

The sandy Lower Pliocene aquifer (known as the Middle aquifer in the Nigerian sector, UNESCO, 2004) overlaid by the Quaternary, has similar characteristics to those in Chad, and is found in the Maiduguri area.

The only Continental Terminal formation, which also contains the *CT* aquifer, referred to as the Lower Aquifer in Nigeria (UNESCO, 2004), outcrops the Lake Chad Basin and is the "Kerri-Kerri" cross-bedded sandstone formation (the Paleocene to the Miocene). From a stratigraphical point of view, it underlies the Chad Group in Nigeria in a local area that lies south of the Bornu basin. It is limited to the west by the Bauchi crystalline basement complex, by the Gombe Sandstone Cretaceous rocks to the east, and by the Pleistocene lacustrine clays of Chad formation to the north (Miller, 1968; Offodile, 2002). The Kerri-Kerri aquifer, which is generally not confined (Fig. 14), has a water table depth from 5 m to 20 m.

2.5.4. The aquifers in Cameroon.

In Northern Cameroon, between 13° and 10° N, the Lake Chad aquifer formation extends over 19,800 km^2.

The Quaternary aquifer area is from the border of Chad in the South (in the "Bec de Canard", South West of Bongor) and to the Lake Chad shore in the north. The aquifer is limited to its western part by the crystalline rocks of the Mandara Mountains and the foothill deposits. The Quaternary aquifer thickness increases from the south to the north, and from the west to the east. At the northernmost point, by the village of Makary and the Lake Chad shore, the upper Quaternary aquifer thickness is around 30 m, with blue or green clays at the bottom of the aquifer. In this area, the groundwater level shows a piezometric depression.

Underlying the Quaternary, a 10-250 meter-thick Upper Pliocene clayey deposit is found to overlie the 40-80 meter-thick Lower Pliocene aquifer which extends some 14,800 km^2.

The deeper *CT* clayey sandstone aquifer covers around 15,000 km^2 (BRGM-CIEH, 1979). Both aquifers are still somewhat exploited in Cameroon.

At a depth of around 2,000 m, the Cretaceous sandstone aquifer, which originates from a rifting process, covers an area of about 1,000 km^2. There is no hydraulic connection with other aquifers.

2.5.5. The aquifers in the Central African Republic (CAR).

Between the 19th and 23th degrees of longitude, within the Vataga and Bamingui-Bangoran prefectures, sandy and clayey Quaternary and Tertiary sediments are present and lie on much deeper Mesozoic layers, constituting a sediment deposit whose thickness can reach 4,000 m. For this area, very scarce information is available (Boulvert, 1983, 1995; Global Water Partnership, 2010; USGS, 2010). Quaternary deposits can be found in the NE part on the SE border of the Lake Chad Basin lying on *CT* deposits.

The geologic formations probably contain three superimposed aquifers: *i)* the superficial Quaternary sands, which probably merge at a depth with the Tertiary "*Paleo-tchadian sands aquifer"* from the *CT* to possibly form a single aquifer overlying; *ii)* a sandy Maestrichtian aquifer; *iii)* a deeper Albo-Aptian sandstone aquifer.

According to (Mestraud, BRGM, pers. Comm.), the surficial Quaternary sands would include both recent alluvial formations and older "neotchadian" lacustrine formations.

The two deep cretaceous aquifers have been found only in oil exploratory drilling areas, mainly in the Doseo and Salamat grabens located on the border with Chad in the Bahr Aouk valley area. The two deep aquifers are separated by an impervious Albian marl layer.

2.6. The Aquifer System of the Chad Formation. Basin Level

The geology, the stratigraphical sequence of formations, the aquifers and their relation with their associated geological formations in different LCBC countries have been outlined in a previous chapter. This paragraph is only concerned about the sedimentary aquifers extending in the Lake Chad Basin.

Data Collection Sources

The datasets for this study originate from scientific publications and from water supply campaigns carried out over time, compiled by LCBC, BRGM (reports of Eberschweiler, 1993 and Schneider 1989), the US-Geological Survey of Nigeria, FED, BAD, Hydraulique Pastorale, ResEeau project and a number of PhD theses cited in the references. Reports are available in the repositories of the LCBC and CDIG-Reseau, both institutions are the main providers of the information herein presented.

Most collected information corresponds to the Quaternary aquifer and covers Chad, with limited data for the north. Hydrologic information from neighboring countries is scarce, hard to collect and only a very limited number of local studies have been found.

The information obtained from databases RESOPIEZ and SUIVPIEZ, presently included in SITEAU, provides data on exploited water points (boreholes and wells with different characteristics and associated information). The sources of the employed information (raw data) are included in the text and the references section. Available data, information and time coverage are found in Appendices B, C and D.

2.6.1. Hydrostratigraphical units and aquifers

The basin stratigraphic sequence consists mainly of detrital layers sand, clay and silt of lacustrine, fluvial and aeolian of continental origins that correspond to the sedimentation of the Continental Intercalaire (*CI*) overlying the end of Carboniferous during the middle Cretaceous, the *CT* during the Tertiary (ANTEA-EGIS/BCEOM/CIAT, 2012) and the Quaternary.

The sedimentary basin limits are characterized by the relations between the sedimentary infill on the basin boundaries (controlled mainly by faults and basal and lateral unconformities) with the crystalline rocks (granite, schists), outcropping in the eastern (Guéra and Bhata) and southern parts of the Chad and Nigeria border, and mainly by sandstones (Tibesti and Nubian aquifer system) in the north (Fig. 11).

The basin sedimentary infill presents several structural horst and graben features that develop on the geologic formations of the basement and local depocentres with a thickness of more than 1,000 m (e.g. Doba, Lake Chad, Bahr el Gazal with recent tectonic activity) that pinch out to the basin’s boundaries. The infill is composed mainly of low-permeability sediments (clay, silts) with interlayered high-permeability material (sands) of different hydraulic interconnections. Layers can show lithological variability and low continuity due to changes in sediment facies that result in heterogeneous hydrostratigraphic units of different aquifer properties, water storage and water transmission both in depth and laterally.

The development of a basin-scale hydrostratigraphical framework for the Chad Formation is an important objective of this project. The basis for constructing 3D conceptual geological model data and sources of lithologic logs appears in Appendix B. Knowledge of the basin's hydrostratigraphy derives from previous groundwater studies that centered mainly on the Quaternary aquifer due to both high yield and good water quality, and from the new hydrogeological analysis based on new collected information.

Previous existing hydrogeological research has been conducted on a regional scale by Schneider (1989) and Leblanc (2002). Research has also focused on local-scale aspects, and has provided important detailed contributions about the characterization of existing aquifers. For the Nigerian side, such work has been done by Alkali (1995), Hassan (2002), Le Coz (2010), and Zaïri (2008); by Ibrahim (2013) and Gaultier (2004) in SE Niger; in the Chari-Logone Basin by Bouchez (2015), Djoret (2000) and Hamit (2012); Massuel (2001) in the Chari Baguirmi; and Ngounou Ngatcha (1993) in the Yaérés (Cameroun), among others (e.g. reports) as included in the references paragraph. Currently, new hydrogeological research by the Swiss cooperation is taking place mainly in Chad.

The Chad Formation, which is generally exploited throughout the basin, comprises the following hydrostratigraphical units from top to bottom: *i)* the upper phreatic aquifer, present throughout the basin and made up of Quaternary (*Q*) deposits; *ii)* the Upper Pliocene aquitard of clay deposits; *iii)* the Lower Pliocene (*LPli*) material, which is the intermediate confined aquifer, and is some areas artesian (flowing); *iv)* a deep confined or unconfined aquifer made up of *CT* deposits (Oligocene-Miocene). Therefore, the hydrogeologic system is constituted by deep confined-unconfined aquifers (Upper Pliocene, and *CT*, of Tertiary age) and a Quaternary unconfined shallow aquifer. For the water-bearing formations (Quaternary, Pliocene and Tertiary-*CT*) outcropping geology, a SW-NE hydrogeological cross-section in the Chad area and a hydrostratigraphical diagram are shown in Figs. 11, 12 and 13, respectively. A summary of aquifers characteristics is found in Table 4.

Aquifers are exploited by 18,964 water points (Fig. 15), of which around 11,395 are in the Quaternary aquifer (LCBC inventory, source: RESOPIEZ, SUIVPIEZ and SITEAU databases; BGR, 2010). Data from 1990 (BRGM/LCBC, 1993) on groundwater exploitation estimate 252 Mm^3/yr, which represents more than 90% of the water supply, and only 28% of the groundwater for domestic supply comes from *CT*. For the present period, the detailed water management in the area and the amount of employed water of groundwater origin are barely known.

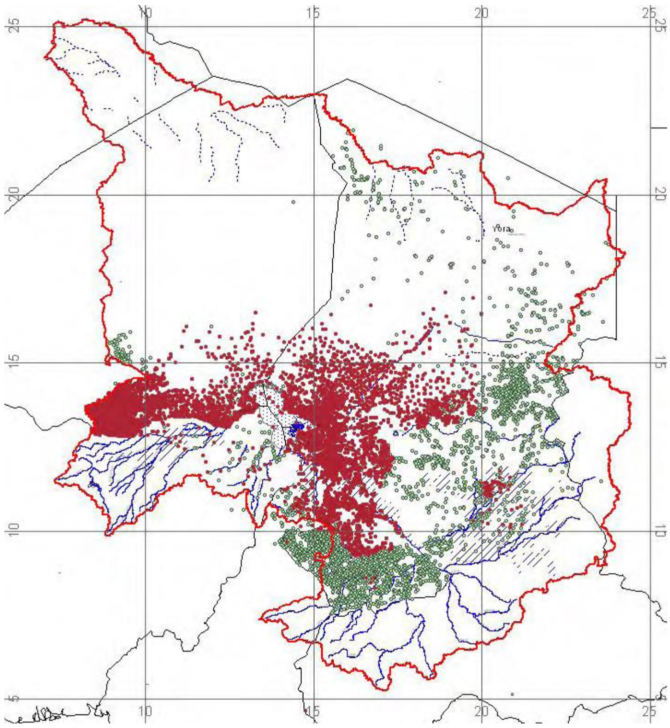


Figure 15. Location of boreholes that exploit the aquifers in the study area. Red: Quaternary aquifer; green: Lower Pliocene, Continental Terminal or basement (BGR, 2010).

Three main aquifer units are found in the basin and are presented below from the youngest at the top to the oldest at the bottom. They contain varying quantities and qualities of groundwater, and present different depths and spatial distributions.

The Quaternary unconfined aquifer includes deposits of Holocene and Pleistocene ages and covers most of the surface area geology (Fig. 16). The aquifer, considered to be continuous on the LCB scale, is heterogeneous with considerable lateral variability in sediment type and facies distribution.

The basin's boundaries on the northern limit outcrop Paleozoic and crystalline rocks in the Termit basin and SW (Djajiri) and Koutous (Continental Intercalaire) in Niger and NE Chad (Guera, Ouaddaï), the Cretaceous sandstones (Agadem) and the *CT* (also present south of the basin). The aquifer southern limit is constituted by the presence of crystalline rocks that are the basin bedrock. Boundaries are delineated based on unconformity surfaces with underlying geologic formations (Tertiary. Cretaceous and crystalline rocks). Over most of the area overlies the Upper Pliocene clays (aquitard); lies down over the Lower Pliocene, Continental Terminal (Bongor area in the southern part of the Basin, Chad), or Precambrian Basement (piedmont plain of Cameroon at the southern border of Lake Chad, Niger. The northern part are the limits of the sedimentary basin.

The main aquifer units identified in the area (see also paragraph 2.5) correspond to the *i)* Ogolian sands aquifer (Manga sand dunes north of Lake Chad, and west and south of Kanem) and calcareous cemented sandstone with interlayered fluvio-lacustrine clayey series and evaporitic rocks of the Moji series (northern Kanem and Bhata) corresponding to the Upper Pleistocene; *ii*) the middle and upper Pleistocene aquifer that extends over most of the basin, including the Nigerian part of the Chari-Baguirmi and Kadzell plains, composed of sands with a variable amounts of clay. In the Yaérés (northern Cameroon), the upper and lower Pleistocene are separated by a compact clay layer that is about 2 m thick, but can be as much as 5 m thick (Ngounou Ngatcha, 1993).

The Ounissoui aquifer of Plio-Quaternary sands and gravels, which lies north of Manga, appears to be hydraulically connected. To the north of Niger, according to Liu et al. (2017), the Holocene and Pleistocene material of the Termit basin outcrops, but information on hydrogeological characteristics has not been found.

The Quaternary aquifer predominantly consists of alternating unconsolidated or loosely consolidated interbedded sand and clay layers of continental origin, and thickness (ANTEA-EGIS/BCEOM/CIAT, 2012; PNUD, 1991) varies from 15 m to more than 100 m to the North of the basin (e.g. 190 m at Kosaki, 80 m at Kanem, Chad; 200 m at Araga, Niger). Two sand types are described (Schneider, 1989): one of fluvial origin associated with riverbeds (Lower Pleistocene); another of aeolian origin (Upper Pleistocene) that constitutes the phreatic aquifer in Kanem (Chad) and Manga (Chad and Niger). Locally, sandy layers can be confined by clays to form a multilayered aquifer that can be artesian.

Therefore, the hydraulic parameters within the aquifer significantly differ. In hydraulic terms, it behaves like a multilayer aquifer with considerable variability both vertically and horizontally. A hydraulic connection with the *CT* exists in the Bongor area (Chari-Logone), where the *CT* outcrops and also constitutes the upper aquifer.

Recharge is controlled primarily by rainfall, dune systems and river-groundwater interactions from seasonal or perennial surface waters. Rainfall recharges take place mainly in the mountainous areas of the basin’s southern and western parts (characterized by a humid tropical climate) from the Kanem and Harr areas located in the north, seasonal streams and the infiltration of perennial rivers or a dune system. According to isotope data (Eberschweiler, 1993a,b; among others), water exfiltration may occur at a rate of 2-4 mm/yr in the areas of Chari-Baguirmi, Lake Chad and polders, Bornu, Kadzell, NW, NE and Bar el Ghazal.

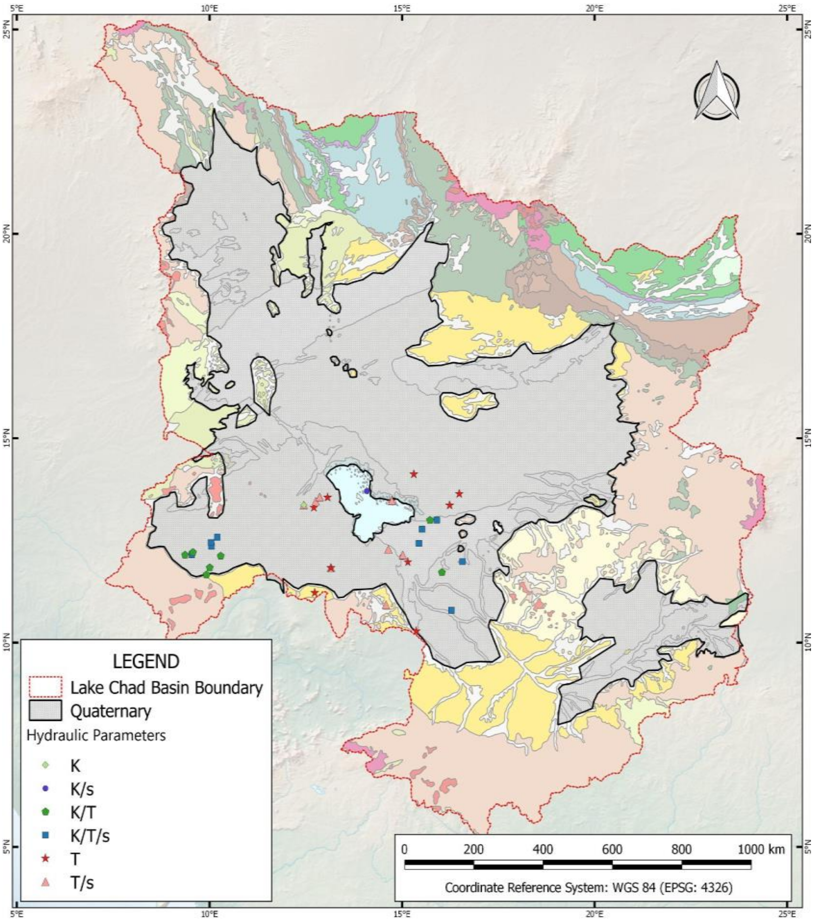


Figure 16. Contour and outcropping surface of the Quaternary hydrostratigraphical unit. Hydraulic tests, distribution and estimated parameters (K: hydraulic conductivity; T: transmissivity, S: storage coefficient) are indicated.

The Quaternary aquifer is characterized by the existence of naturally-occurring extended piezometric depressions, also called "hollow aquifers" (e.g. Durand, 1982; Leblanc et al., 2003; Boronina and Ramilien, 2008). Depressions are in Cameroon (Yaéré), Chad (Bahr El Ghazal, Chari-baguirmi), Niger (Kadzell) and Nigeria (Borno). The current piezometric level is the result of a groundwater level decline from the last pluvial Holocene period (corresponding to total aquifer replenishment). Several mechanisms to explain their origins have been suggested: aquifer overexploitation, subsidence, structurally conditioned deep drainage, changes in seawater level and evapotranspiration loss (e.g. Durand, 1982, Dieng, et al., 1990; Aranyossy and Ndiaye, 1993). However, the scientific community has reached no unanimous agreement.

Nowadays, the most accepted approach is based on insignificant recharge (natural infiltration) due to low permeability materials, along with considerable evapotranspiration (Aranyossy and Ndiaye, 1993). Deep drainage has been also proposed by Abderamane (2012), as apparently naturally groundwater levels lower with time, they are expected to move toward the basin's lowest discharge point elevation (the Lowlands, Bodelé). Crucial points of accurate stratigraphical and sedimentological aspects in the area remain mostly unresolved because a more complex hydrogeological system probably exists than that stated to explain possible deep drainage.

The Lower Pliocene confined aquifer consists of lacustrine clay layers with some alternating layers of alluvial sand at the bottom of the formation (red sand, Lower Pliocene). This is detected only in boreholes deeper than 100 m, at around 300 m and 200 m in the central part of Manga in Niger (Sabljack, 1998) and 450 m south of Lake Chad (ANTEA-EGIS/BCEOM/CIAT, 2012). With extremely variable thickness, between 30-50 m on the boundaries that may reach 150 m in the central part of Chad, it extends over most of the Chad area (Fig. 17) toward Niger (Manga) with boundaries on Mounio crystalline rocks (W), the Termit basin (NW), the Agadem basin (NE) and in the Nigerian part of the Lake Chad Basin. Lack of boreholes in the western part of Niger does not allowed to assess its subsurface presence in other areas.

It has a limited hydraulic connection with other existing aquifers (Global Water Partnership-GWP, 2013). Informative aquifer data are lacking on large-scale presence and characteristics. The conceptual aquifer behavior model is not well-known.

The *LPli* is overlaid by a thick silty-clayey impervious material (200-300 m thick) from the Upper-Medium Pliocene age (Fig. 13). So the *LPLI* acts as a confined aquifer throughout the study area and is artesian in the basin's central part (Niger) and in the south (Nigeria). In the Bhata region, given the change in depositional facies, materials are mostly composed of clay at a depth of around 60 m.

This aquifer is exploited in NE Nigeria and in the northernmost Cameroon regions and by the deep boreholes (over 200 m deep) located north of the N'Djamena city. Its artesian pressure is currently lowering, which is possibly due to pumping this aquifer.

The CT confined/unconfined aquifer is made up of sandy-clayey deposits, with the presence of laterites and iron-sand (Bhata). Thickness is around 25 m on sedimentary boundaries (Bhata, Fitri), but can reach 600 m in existing tectonic grabens, but is generally around 100 m.

It underlies Lower Pliocene deposits at a depth of more than 650 m at Madama and one of 150 m at Iaguil (Niger), it is 700 m deep in the Kanem and 450 m from the soil surface in the Lake Chad surroundings (ANTEA-EGIS/BCEOM/CIAT, 2012; PNUD, 2004). In the Kanem region (Chad), sands are directly deposited on *CT* materials and generally behave like a single aquifer system that is over 275 m thick (Eberschweiler, 1993). A narrow outcrop zone is located in the northern part of Chad and the Chari-Logone basin (southern), where it is unconfined and currently used for water supplies (Fig. 17).

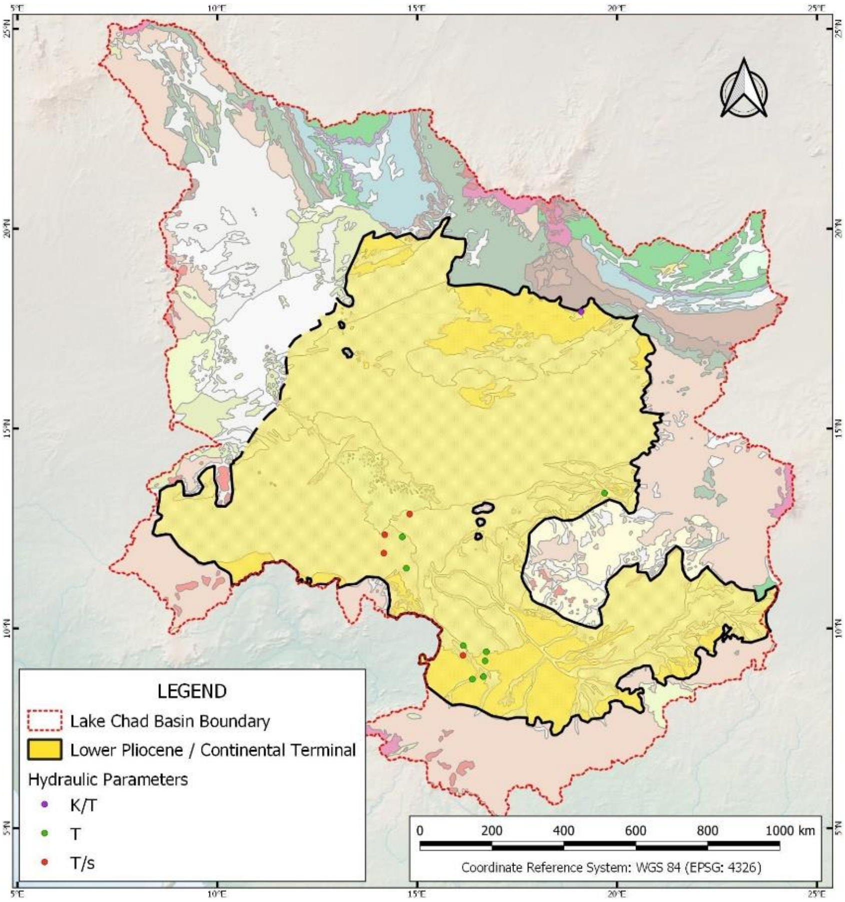


Figure 17. Contour and outcropping surface of the Lower Pliocene and Continental Terminal hydrostratigraphic unit. Hydraulic tests distribution and estimated parameters (K: hydraulic conductivity; T: transmissivity, S: storage coefficient) are indicated. CT outcrops in the areas marked dark yellow.

In the northern part, impervious Upper-Medium Pliocene layers confine the aquifer, according to data from deep boreholes. In the Bongor area (S Chad), the *CT* crops out and constitutes a phreatic aquifer that is hydraulically connected to the Quaternary aquifer. It extends to the South where recharge takes place, with a water level of approximately 10 m deep. The hydraulic relations with the *LPli* and the *Q* aquifer are barely known in most of the study area.

2.6.2. Hydraulic parameters

Many local studies have done field tests, which are mostly included in FED projects with water-supply aims for populations. Most existing data on hydraulic parameters correspond to the tests performed in the Quaternary. Whenever possible, original hydraulic test reports were assessed. Very few hydraulic tests have not been clearly identified in the area, most of they have been used to determine specific well yields and generally, have short test duration. These tests do not characterize aquifer parameters and do not allow storage coefficients estimations to help to quantify parameters for further groundwater modeling.

Collected information comes directly from specific reports on past pumping tests and their assessments in terms of: characteristics of past tests, spatial location (X, Y coordinates), aquifer hydraulic parameters and data source, are presented in Appendix C. The aquifer-testing data to define key parameters (*Q* and *LPli-CT*) are available at a few locations, but some present little or no useful information due to unknown test procedures or short testing periods. The spatial distribution of the hydraulic tests done in *Q* aquifer units (54 in all) and *LPli/CT* (25 in all) are shown in figures 16 and 17.

The data from the BRGM/LCBC (Eberschweiler, 1993a,b) regional simulation model indicate that the transmissivity (T) values for the Quaternary aquifer fall within the range of 10^{-2} to 10^{-4} m^2/s. The storage coefficient (S) reports variations between 10^{-3} to 10^{-5}. In Leblanc (2002), the data from the numerical model simulation done at the end of the calibration process provide a rough range of transmissivity values in different areas, from 10^{-4} to 10^{-3} m^2/s in the southern and western parts, and from 10^{-2} to 10^{-1} m^2/s in the eastern and central parts of the basin. In local areas in the basin's center (e.g. Chari Baguirmi, Manga, Kanem), the model shows lower T values.

According to locally conducted studies (Schneider and Wolff, 1992), the average permeability in the *Kanem* upper Holocene is 2.3 x 10^{-2} m/s ; for the Ogolien sands, T lies between 2.5 and 3.5 x 10^{-3} m^2/s, and in Bol a third deep aquifer level directly connected to the sand layer gives values from 1.6 to 2.2 x 10^{2} m^2/s. For the same area, and Bahr el Ghazal, the average T value from pumping tests is 3 x 10^{-3} m^2/s. The estimated K, based on Darcy by considering 15% porosity, is 6.4 x 10^{-4} m/s (ANTEA-EGIS/BCEOM/CIAT, 2012).

For the *Chari Baguirmi*, the values from the pumping tests performed in N'Djamena provide T values of between 3.2 and 6.2 x 10^{-3} m^2/s and S values lies between 4 x $10^{-4}$and 10^{-3} (Schneider and Wolff, 1992). According to Hamit (2012), the maximum transmissivity value was found at Tourba, 7.6 x 10^{-3} m^2/s and the minimum one at Goz, 1.1 x 10^{-3} m^2/s (average 4.5 x 10^{-3} m^2/s). Massuel (2001), based on previous pumping test results and model simulations, presents the spatial permeability distribution, whose highest value is 9 x 10^{-3} m/s and its lowest is 1.4 x 10^{-6} m/s.

Ngounou Ngatcha (1993) provides transmissivity and permeability values for the *Great Yaéré*, northern Cameroon, based on short test durations with limited validity. The obtained transmissivity ranges from 4.6 x 10^{-3} m^2/s to 2.1 x 10^{-6} m^2/s.

In the *Hadejia-Jama'are-Yobé* river valley flood plain (northern Nigeria), the aquifer parameters from pumping tests indicate T values from 3 x 10^{-3} to 2 x 10^{-2} m^2/s and S values between 0.05 and 0.28 for the Jama'are valley aquifer. In the Hadejia, T ranges between 1 x $10^{-3}$and 2 x 10^{-2} m^2/s and the mean S value is 6.7 x 10^{-3}, which correspond to a confined aquifer (Alkali, 1995).

Table 4. Summary of the characteristics of aquifer formations (Q, LPli, CT)

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

** data from reviewed hydraulic tests; ** from BGR-LCBC (2010)*

For the *Kazdell and Bornu* depressions after model calibrations, Zaïri (2008) obtained a range of spatially distributed permeability values from 5 x 10^{-6} to 5 x 10^{-5} m/s, and from 7 x 10^{-5} to 5 x 10^{-4} m/s; 1 x 10^{-5} m/s; 5 x 10^{-6} m/s, and 3 x 10^{-6} m/s. In Kazdell and Bornou, K was set at 3 x 10^{-6} m/s. In the work by Gaultier (2004), K from modeling shows a very homogeneous distribution, with a value in most of the plain of 2 x 10^{-6} m/s, with higher values, 6 x 10^{-6} and 10^{-5}, in the central part of the plain and close to the riverbed.

In *Manga*, with a numerical flow model Leblanc (1997) obtained K values between 4.5 x 10^{-6} and 8 x 10^{-4} m/s, with the highest values in the NE. For the same region and by numerical modeling, Zaïri (2008) estimated a K value to be between 10^{-4} and 5 x 10^{-5} m/s.

For the **Lower Pliocene-CT aquifer**, at the basin level, T values are between 10^{-2} and 10^{-5} m^2/s and S values go from 10^{-2} to 10^{-5} (Eberschweiler, 1993a,b).

In Miganan, the *Chari Baguirmi area*, T is 7 x 10^{-4} m^2/s, 9.3 x 10^{-5} m/s for permeability (K) and 10^{-3} for S (data from pumping tests). To the north of N'Djamena, T values range between 1.3 and 5.2 x 10^{-3} m^2/s (Schneider and Wolff, 1992).

For *Koros*, Schneider and Wolff (1992) provide T values of 5.5 x 10^{-2} m^2/s in Bédoko and 6 x 10^{-3} m^2/s for Beboni in southern Koros. These values are based on short time period pumping tests and cannot be considered representative of aquifer parameters.

2.6.3. Groundwater flow

For the Quaternary aquifer, at the regional basin scale, piezometric maps were drawn by Eberschweiler, (1993) using data from the 1960s, and by Leblanc (2002,) and Boronina et al (2005) based on UNESCO-PNUD-CBLT (1972) information. Updated piezometric information has been mapped as part of the BGR-LCBC (2010) framework project, based on LCBC database information and SRTM90 DEM for water points elevation estimations; the observation water points DB, field measurements and the datasets used to plot this map and the mapped period were not available.

According to the current compiled information (Table 3), the groundwater level measurements data coverage from different sources ranges from 2004 to 2017 (Fig. 18) with major gaps. Groundwater level observations are available mainly for the Quaternary aquifer (*Q*) in the central and southern parts of the area. Groundwater level/head observations for the Lower Pliocene-Continental Terminal are scarcely available.

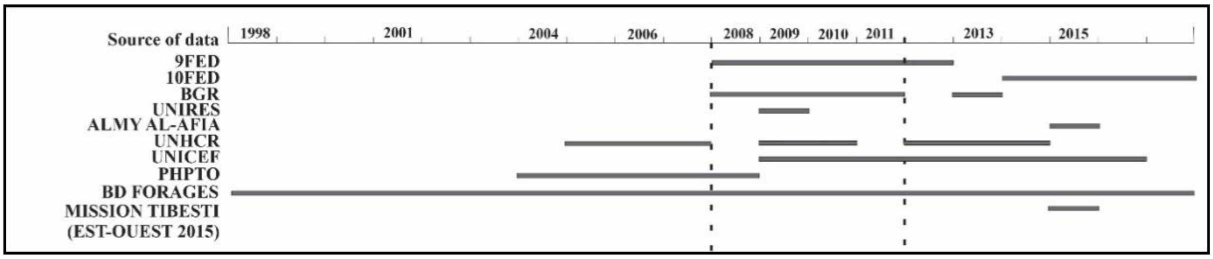


Figure 18. Existing water level measurements and period in the Chad Basin. Time span of data coverage and source of information.

In data availability and spatial distribution terms, the most complete spatial coverage with existing records was obtained from the observations for the 2008-2011 period and was, therefore, selected to draw the piezometric map and also for further modeling. Appendix D presents the total number of water points, along with their information for the 2008-2011 period. It also includes wells with the groundwater level depths and groundwater elevations (m.a.sl.) used to draw the groundwater level maps on surficial and deep aquifer.

The contour map displaying the potentiometric contour lines and the flow direction of both the water table aquifer (*Q* and *LPLi-CT* aquifers) and the semi-confined aquifer (*LPli-CT*), together with hydrogeological cross-sections, are presented in figure 19. The map is an indication of a complex regional flow pattern in a dynamic system during the considered period, but is variable with time. On the map, the contours of both aquifers are plotted; the scarce groundwater level data for the deep aquifer only allow the groundwater contours in the southern part (Koros) to be displayed. The results are consistent with previous piezometric maps (Schneider, 1989; Leblanc, 2002 and BGR, 2010).

The regional groundwater flow trend is to the basin's central part, i.e. to the Lake Chad. Low hydraulic gradients are shown in its central part. From the Kanem and Harr groundwater divide line, the hydraulic gradient moves northwardly (i.e. to the Lowlands). Two piezometric domes are present north of Lake Chad (i.e. in Kanem and Harr on both sides of Bahr El Ghazal) and are associated with the recharge areas located in dune-field sectors. Piezometric depressions exist in Bornu (Nigeria), Yaéré and Chari-Baguirmi (Chad), Kadzell (Niger) and the interfluvial zone of the Komadougou. The water level depth varies from a few meters in the lowland area of the lake to about 40-60 m below the soil surface in depressions.

Hydraulic connectivity between the two aquifers (*Q-LPli/CT*) clearly exists in the southern part of the area (Chari-Logone basin mouth), where the Continental Terminal outcrops, possibly on the aquifer boundaries near Bongor-Bousso where it is unconfined. Groundwater may also flow upwardly into the upper aquifer from lower aquifers or from the deeper aquitard. Determining the connectivity between aquifers is important to accurately assess exchanges among hydrostratigraphical units. Unfortunately, very little, or even no information, is currently available to support and assess such exchanges.

Hydraulic heads are higher along river channels and their vicinity (Komadougou-Yobé and Chari-Logone, mainly Chari) in the basin's eastern and southern parts, where the topographic gradient is relatively flat. This suggests that groundwater recharge/discharge via surface water inflow is a significant mechanism in these areas, mainly during flood periods.

Exchanges between Lake Chad and the Quaternary aquifer are not significant (IRD-LCBC, 2016) and are observed mainly up to a distance of 50 km from the lake's shore, according to isotopic data (Vassolo com.pers. 2016; Zaïri, 2008).

Groundwater level time series have been only locally described for Nigeria and for the piezometers located in Maidiguri (FIRS), Bama-Borno and Damaturu shown in figure 20 (provided by Dr. Goñi, Maidiguri University, Nigeria). During the 2008-2011 period, the groundwater level lowered in the Maidiguri area to around 2 m, which is also observed in Bama-Borno for a different shorter time span. The Damaturu data behavior may correspond to measurements taken in wells by divers during the transient calibration period and cannot be considered to be representative of aquifer trends. For the considered time period at basin area, the absence of groundwater level time series impairs assessing changes along time.

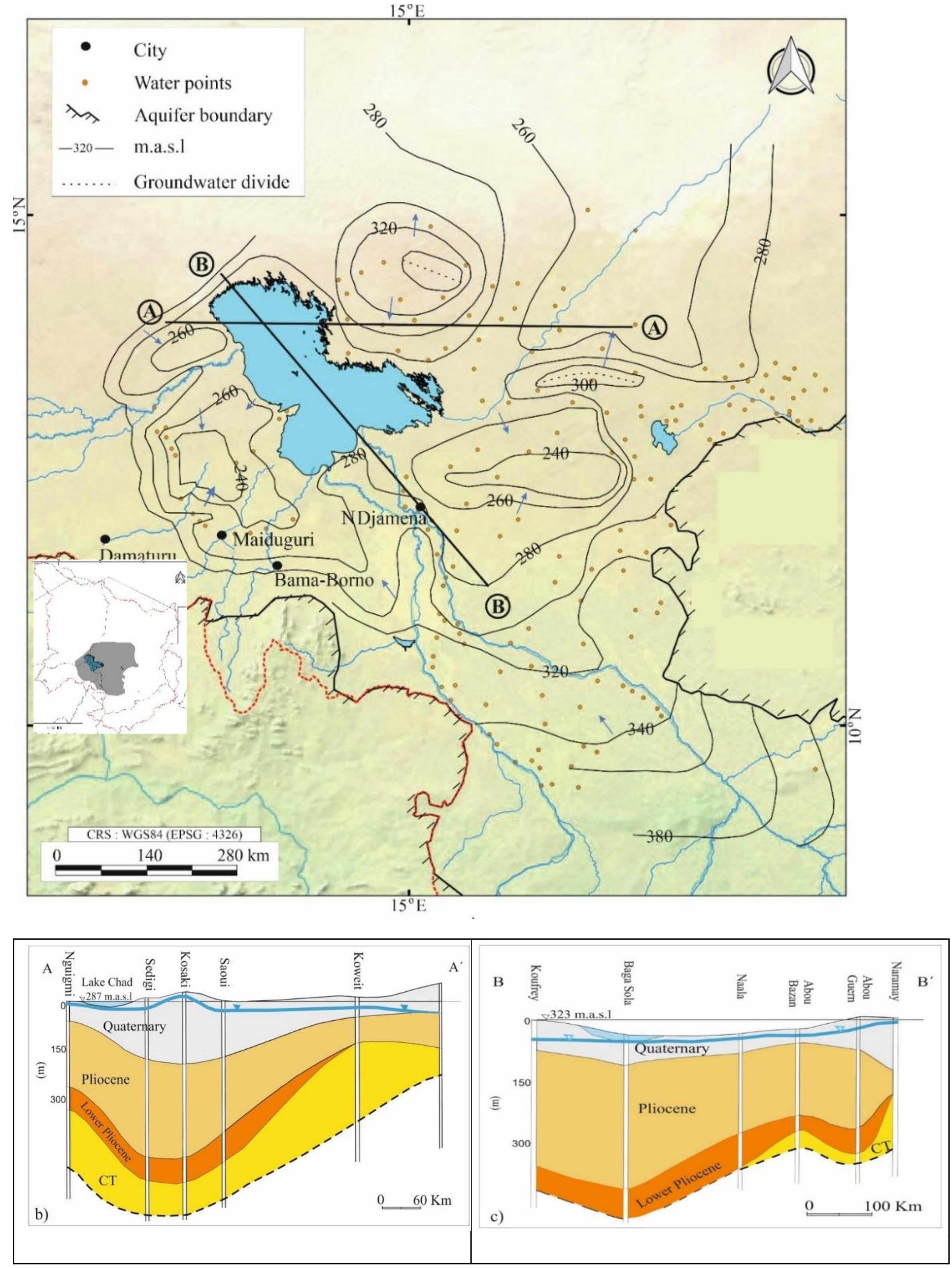


Figure 19. A) Potentiometric map of the water table aquifer (Quaternary and Lower Pliocene-Continental terminal) for the 2008-2011 period (20 m contour lines) B) and C) hydrogeological cross-sections transects and wells used for the subsurface cross-sections. The inset map shows the piezometric map location within the basin area extension.

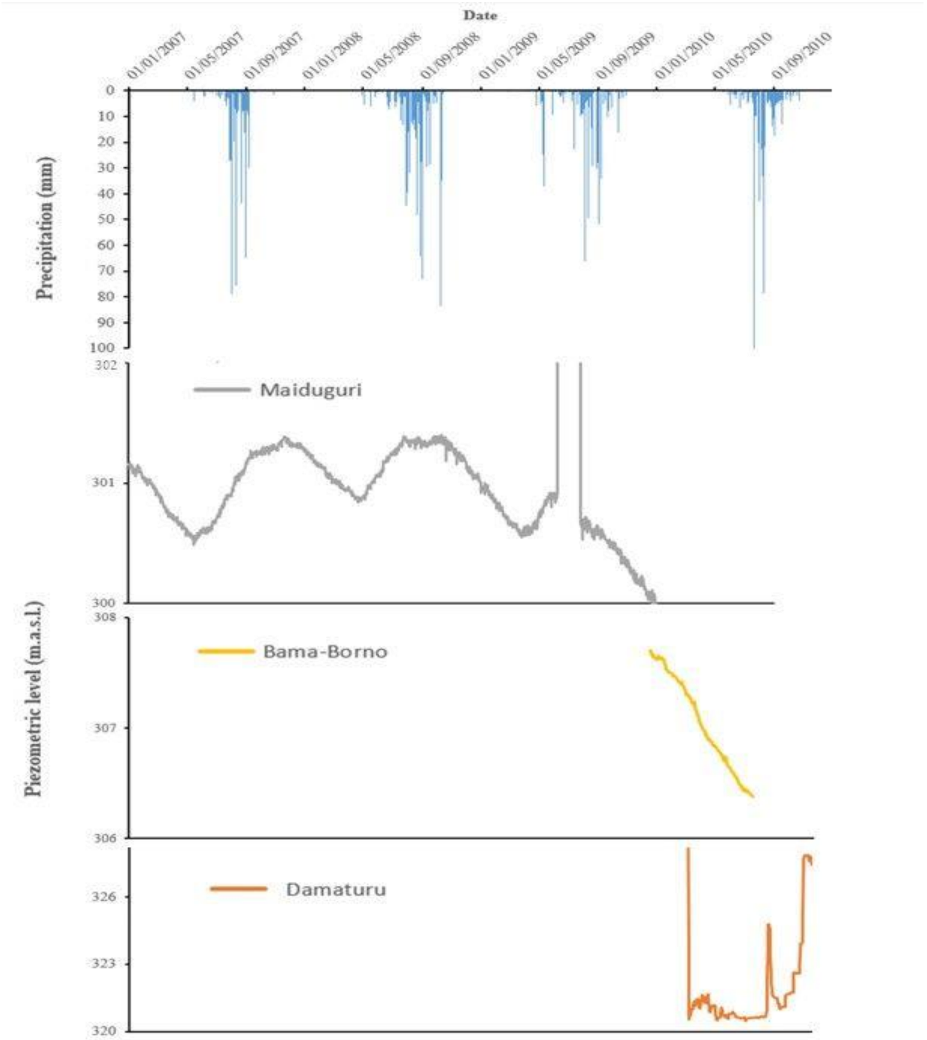


Figure 20. Piezometric level recorded at the FIRS observation borehole (Nigerian Hydrological Service). See also Fig. 19 for piezometers location.

2.6.4. Recharge and discharge

Very few studies have directly addressed recharge assessments and, if they have, they have mainly focused on the Quaternary aquifer (i.e., Leblanc, 2002; Gaultier, 2004; Goni, 2006). Although recharge mechanisms are not well understood, it seems that there are four major recharge mechanisms in the basin: *i*) direct recharge from rainfall infiltration; ii) irrigation return flow in intensely irrigated areas; *iii*) recharge via surface waters, especially during flooding periods; *iv*) vertical leakage through aquifers.

On the basin scale, recharge from rainfall predominantly occurs via infiltration directly into outcropping aquifers (unconfined) that mainly takes place on southern margins (a narrow zone for the *CT*) in the study area were high precipitation occurs, and in the Harr and Kanem areas to the north (Quaternary aquifer). This fact is observed on the enclosed piezometric map (Fig.

19). According to data from some local areas (Goni, 2008; Leblanc, 2002; Ngounou Ngatcha, 2007) natural recharge is very variable (accounting for between 0% and 13% of total precipitation).

For the 2008-2011 period, the quantification of natural groundwater recharge from precipitation was obtained by a soil-plant-water distributed model (VISUAL-BALAN V2.0), which performs daily water balances in soil, unsaturated zones and the aquifer. In areas with intense agricultural activity, the irrigation-derived recharge volume is obtained according to the irrigated surface area and water demand for cultivated crops. A description is presented in Appendix E.

Surface water systems (rivers) present the loss and gain flows for the superficial aquifer, when they are hydraulically connected according to streamflow conditions. Some previous studies have quantified the surface water–groundwater relation for Chari-Logone (Leblanc, 2002; Massuel, 2001), Komadougou-Yobé (Leblanc, 2002; Hassan, 2002; Massuel, 2001) and Lake Chad (Leblanc, 2002; Zairi, 2008; Gaultier, 2004; IRD-LCBC, 2016). For the 2008-2011 period and river basins, unit-hydrographs describing high rainfall events, streamflow and groundwater level time-series are not generally available. Therefore, a full analysis is not possible to describe and quantify groundwater contribution to rivers (base-flow separation). Also, no accurate estimate of surface water inflow into the groundwater system is available for the basin.

The lateral inflow from weathered crystalline bedrock in the southern highlands of the study area where precipitation is important also occurs.

There are currently no reliable groundwater abstraction estimates available for either domestic/industrial water supply needs or irrigation. However on the working scale, local withdrawal from domestic water wells does not apparently have a strong impact on local groundwater flow and aquifer status. Only the estimated data from previous reports exist (Leblanc, 2002; BGR, 2012), and the current abstraction is based on the population's needs and crop water demands. Regarding rural use, as no other real information is available, a 20-36 and a 75 L/person/day water quantity for rural and urban inhabitants has been respectively assumed (Leblanc, 2002). The population estimates are based on 2009 figures, collected from www.citypopulation.de/Chad.html and the World Bank (1988) and further updated according to population growth (UN Population Division, 2015). 'The water and sanitation program for the Darfur refugees' covers five camps in Chad. In some camps, like those in Djabal and Goz Beida, over 300,000 L of water are supplied daily (cf. Water for the Refugee Camps in Eastern Chad, Oxfam). It is noteworthy that the geolocation of water points (numerous wells) changes with time and abstraction was based in well-fields spatial definition.

For husbandry purposes, withdrawals for breeding are estimated by applying a rate for each animal category. It has been appraised that about 50% of cattle needs are ensured by groundwater (1990 data, Project 507/RAF/45).

2.6.4.1. Regional water balance estimations

Water balance quantitatively assesses the amount of water (inflow) that enters a system, the amount of water leaving the system (outflow) and, as a result, the change in water storage (ΔS).

$$\text{Inflows} - \text{Outflows} = \Delta S$$

A first step to assess the regional water balance in a simplified steady-state system is taken. This section summarizes the key elements of water budget estimates for both Quaternary and Lower-Pliocene/CT aquifers, and estimated inputs-outputs are provided in Tables 5 and 6. Concerning the water budget analysis, the 2008-2011 time-period and previous assumptions on recharge-discharge of the aquifer system (para. 2.6.4) are considered.

Recharge from precipitation (i.e., concerning rainfall) where the aquifer outcrops (*Q*, and *CT* in the basin's southern part) and irrigation return to aquifers in areas with agricultural cultivation, has been estimated with a water-soil-plant distributed model that computes daily water balances. The values obtained in this study by using the method described in Appendix E are similar to previously obtained values (Leblanc, 2002). However, as calibration was not possible due to lack of groundwater level time series data, recharge rates could be lower. A cross-check of the results is further carried out herein through modeling.

Inflow and outflow to Lake Chad and to aquifer systems herein considered (to and from *Q, CT/ LPli* and lateral inputs from weathered bedrock) were derived from the groundwater flow analysis of the piezometric map flow (Fig. 19) in: the Lake boundaries of Kazdell (Lake input to *Q*), Bol and Chari-Baguirmi (*Q* input to Lake); in the Chari Logone river head, Koros area *(CT* to *Q)*. Directly computed flow by unit length was based on groundwater contour map elevations, flow direction and Darcy's Law. Hydraulic parameters and thickness in the corresponding area of interest were taken from literature (2.6.2 and Appendix C,B; Table C1). Vertical leakage, upward flow from deep aquifers and downward flow to deeper aquifers are unknown.

Exchanges (input/output depending on seasonal streamflow) from the Chari-Logone river exists in the southern basin part (*Q-CT*) and with Komadougou-Yobé in the Kazdell region (*Q*). The exchange flows between the groundwater and surface waters shown in the water balance correspond mainly to the estimates and calculations from the modeling works performed by Massuel (2001) for the Chari-Logone area, and by Gaultier (2004) for the Komadougou-Yobé area (Table 5).

Table 5. Quaternary aquifer water-budget based on estimated and referenced data (average for the 2008-2011 period).

Input	Mm^3/yr	Output	Mm^3/yr
Recharge from precipitation	7×10^2	**Pumping for irrigation**	63

From irrigation return flow	22	**To Lake Chad****	4.6×10^2
From LPli/CT**	20	**To river (Chari-Logone)***	1.5
From Lake Chad**	6	**Pumping for water supply**	2.4×10^2
River (Komadougou Yobé)*	From 1.2 to 1.6	**To** LPli **/CT****	2.8
River (Chari-Logone)*	1.6		
Bedrock lateral input	?	**Bedrock lateral output**	?
Total input	¿	**Total output**	?

**Range according to the literature review: IRD-LCBC (2016); Gaultier (2004); Leblanc (2002); Massuel (2001); Zairi (2008); ** Darcy estimates*

The calculation of domestic groundwater abstractions (pumping for water supply) was obtained based on water allocation according to the population in rural and urban areas and the agricultural areas' demand. The groundwater abstraction estimate based on the number of works tapping the aquifer does not seem a reliable method because it is difficult to assess the number of existing traditional open wells. (Leblanc, 2002). For refugee settlements, well fields of abstraction were defined and abstraction was calculated for each area separately by considering the amount of water demanded and the balance time period.

The water balance assessment also relies on key assumptions, including: *i*) whether the aquifer extension is continuous over the area; *ii*) whether rivers are flowing; *iii*) areas of deeper formations encountered in the basin outcrop, and are able to provide a recharge for such deep aquifers.

A quantitative attempt of inflows/outflows into/from the system has been made and is shown in Tables 5 and 6. The discrepancy between the estimated values for input/output highlights the largely uncertain assessment due to numerous data gaps.

Table 6. Lower Pliocene and CT water-budget based on estimated and referenced data (average for the 2008-2011 period).

Input	Mm^3/yr	Output	Mm^3/yr
Recharge by precipitation	1.3×10^2	**Pumping for irrigation**	2.7×10^2
by irrigation return flow	3.7×10^1	**To Lake Chad**	-
From Quaternary**	2.8	**To river (Chari-Logone)**	-
		For water supply	**From** 3* to 0.8×10^2*
Bedrock lateral input	?	**To Q****	0.8
Total input		**Total output**	?

**From BGR (2012); ** Darcy estimates*

2.6.5. Hydrochemistry

Updated hydrochemical information has been obtained as part of the BGR/LCBC (2017) framework project (the BGR/LCBC (2017), UNESCO/LCBC (2002) and UNESCO (2004) projects). The IAEA has also been working in the basin area toward the isotopic characterization of aquifers and other contributing waters (precipitation, surface) to support the groundwater origin and age (IAEA, 2017).

In general terms, the upper aquifer water is a calcium/sodium bicarbonate water type with low mineralization, with a dry residue of less than 500 mg/L that is frequently less than 200 mg/L. The electric conductivity in the south central region is in the order of 150 µS/cm and increases northwardly to reach average values of around 350 µS/cm, which may even exceed 900 µS/cm north of N'Djamena. The existence of recharge from the Logone and Chari near river channels is reflected by increasing sodium in groundwater the further the distance from rivers.

The Lower Pliocene aquifer is characterized by a sodium bicarbonate water type with high mineralization, and by electric conductivity between 600 and 800 µS/cm, which increases with aquifer depth, (i.e. north of the region). pH varies between 6.7 and 7.4. Temperature, which is rather high, varies between 36ºC and 41ºC.

According to Eberschweiler (1993), the water from the upper level of CT deposits may show a dry residue less than 100 mg/L. As it dips beneath the Pliocene deposits, aquifer mineralization increases north of the project area, and shifts from a sodium/calcium bicarbonate water type with electrical conductivity around 150 µS/cm, to a sodium bicarbonate water type and electrical conductivity above 1200 µS/cm.

2.7. The conceptual model of the Chad aquifer system

The overall objective of a conceptual model, a schematic or simplified representation of the geohydrological system and its behavior, is to identify and evaluate the hydrogeological conditions (including the relation to surface water, wherever appropriate) of the Lake Chad Basin aquifer system over a selected time period.

It is worth mentioning that a conceptual model does not need to be able to answer or solve every hydrogeological problem, contain all the available data and be very detailed, but should be made as easy as possible for the problem to be solved, be easy to update and can acquire data from, and provide, good visualization possibilities.

The conceptual model design concerns: *i*) the definition of the aquifers' geometry and boundaries; *ii*) the thickness of the defined hydrogeological units; *iii*) how the hydraulic parameters were selected and spatial distribution; *iv*) a hydrogeological interpretation of the groundwater flow system; *v*) the groundwater and surface water relations; *vi*) external stresses (groundwater abstraction, recharge and evapotranspiration assessment and distribution).

This involves the following steps:

- Updating the existing database with new hydrological, geological, meteorological and groundwater levels information for the whole area and the complete considered time period.
- Analyzing the Lake Chad aquifer system, and aquifer dynamics (mainly groundwater flow and water balance), using existing information on natural recharge-discharge from rainwater, Lake Chad, flooded areas and rivers.
- Revising the natural recharge distribution from rainfall and irrigation return.
- Establishing the conceptual model; i.e. constructing a conceptual model for the aquifer system based on the hydrostratigraphical units, water budget and flow system definition according to the analyzed information.

It includes data collection and a critical data review to ensure lack of errors and the interpretation of a variety of existing geological and hydrological datasets, and other relevant ones such as topographic, geophysical and remotely sensed data for further modeling. One critical issue regarding hydrological interpretations refers to time-frame assessments, mainly for hydrologic processes and stresses. This requires a thorough and detailed analysis of data series availability with time for further time-period selections.

Figure 21 presents a schematic 3D hydrogeological conceptual model diagram with the stratigraphical distribution of the Chad Formation. This figure provides details of the groundwater relation between the aquifers, the broader regional groundwater flow system, the inter aquifer flow, and the local recharge and discharge mechanisms and dominant input-output processes that occur in the basin.

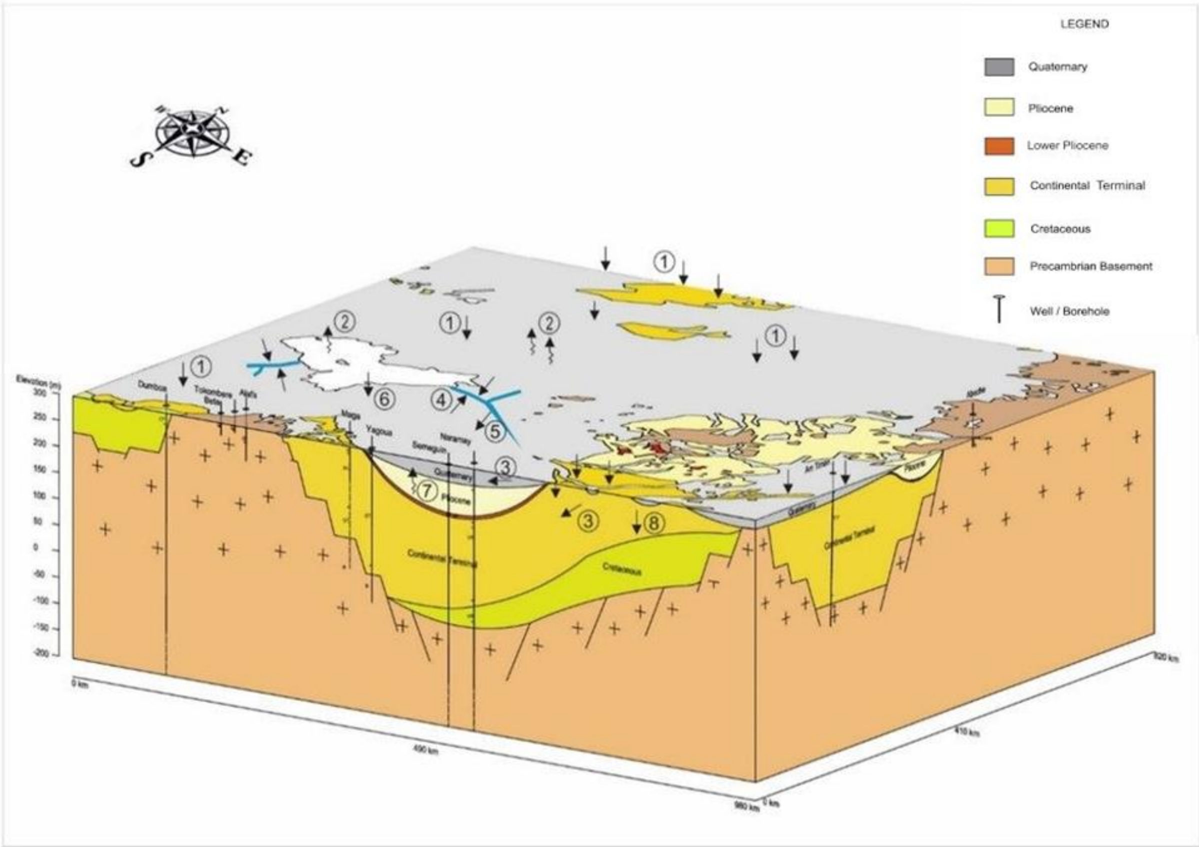


Figure 21. A schematic 3D conceptual model diagram (partial section of the study area) with the input-output processes in the basin. (1) Natural recharge, (2) evapotranspiration, (3) groundwater inflow, (4) recharge from river, (5) discharge from river, (6) recharge from lake, (7) up flow from the deeper aquifer, (8) vertical recharge from the shallower aquifer to the deeper aquifer.

The groundwater system consists of the following hydrostratigraphical layers limited by impervious rocks of the basement: *Q* (unconfined aquifer), *Pli* (confining layer), *LPli* (confined aquifer), *CT* (semi-confined aquifer) and the basement constituted by cretaceous or crystalline rocks. Only the Quaternary outcrops and extends over all the area, while the Lower Pliocene is always subsurface. The thickness of individual layers varies significantly with the greatest thickness found in the central basin part and grabens, pinching out to the basin's limits.

Figure 22 displays a graphic output of the sedimentary basin geometry and geology after the database retrieval of boreholes with lithological logs from the RockWorks 17 geo-model code.

Sedimentary infill depth ranges between 10 m on boundaries and more than 1,000 m in grabens, and layers show continuity in most of the area with frequent changes in facies. Maximum thickness is found in the central basin part and all the stratigraphical units pinch out on the basin boundaries, although scarce quantitative data exist for defining vertical and lateral boundaries. Gernerally, lithological logs records are located in the central basin part and, consequently, in areas with a high density of points, where the sedimentary thickness estimated for the stratigraphical model is believed to better represent more accurate geometry (less uncertainty).

Most lithological logs records do not show total *CT* thickness; scarce information has been obtained on the subsurface depth to the bedrock (Cretaceous, crystalline rocks) as deep boreholes only exist in a few spots. Given the uncertainty in the position of the bedrock surface level, this deep boundary was not considered. For further hydrologic modeling purposes and working scale constraints (it is very difficult to represent *LPli* aquifer thickness due to data availability), a decision was made to group the *LPli* and *CT* hydrostratigraphic units into a single aquifer layer, which is also the model's deeper layer.

Two multilayer aquifers are defined from the hydraulic point of view: the upper unconfined aquifer (Quaternary) and the deeper aquifer confined-unconfined composed of the Lower Pliocene and the Continental Terminal. The connection between the upper and lower aquifers is restricted by the clay layers of the Upper Pliocene, which are mainly in contact with the basin's southern area where it outcrops and is hydraulically connected to the Quaternary.

In the unconfined aquifer, the general groundwater flow s from S to N, and perpendicularly to the groundwater contour lines. In depressed (e.g. Kazdell, Chari Baguirmi) or recharge (e.g. Kanem) areas, it takes a different direction.The highest measured groundwater level was 370 m above sea level (m.a.s.l.) and is observed in the basin's southern part, where the main natural recharge takes place. The groundwater level generally lowers toward Lake Chad and to the upper northern part of the basin (the Lowlands). However, very little information exists for this last area. The lowest values are always observed in depressed zones with a minimum value of 240 m.a.s.l. (Chari Baguirmi).

As previously mentioned in previous paragraph, in order to explain the existence of these anomalies, different hypotheses of hydrologic processes have been proposed, and this conceptual model considers lack of a natural recharge and deep flow to the basin's upper north (Lowland).

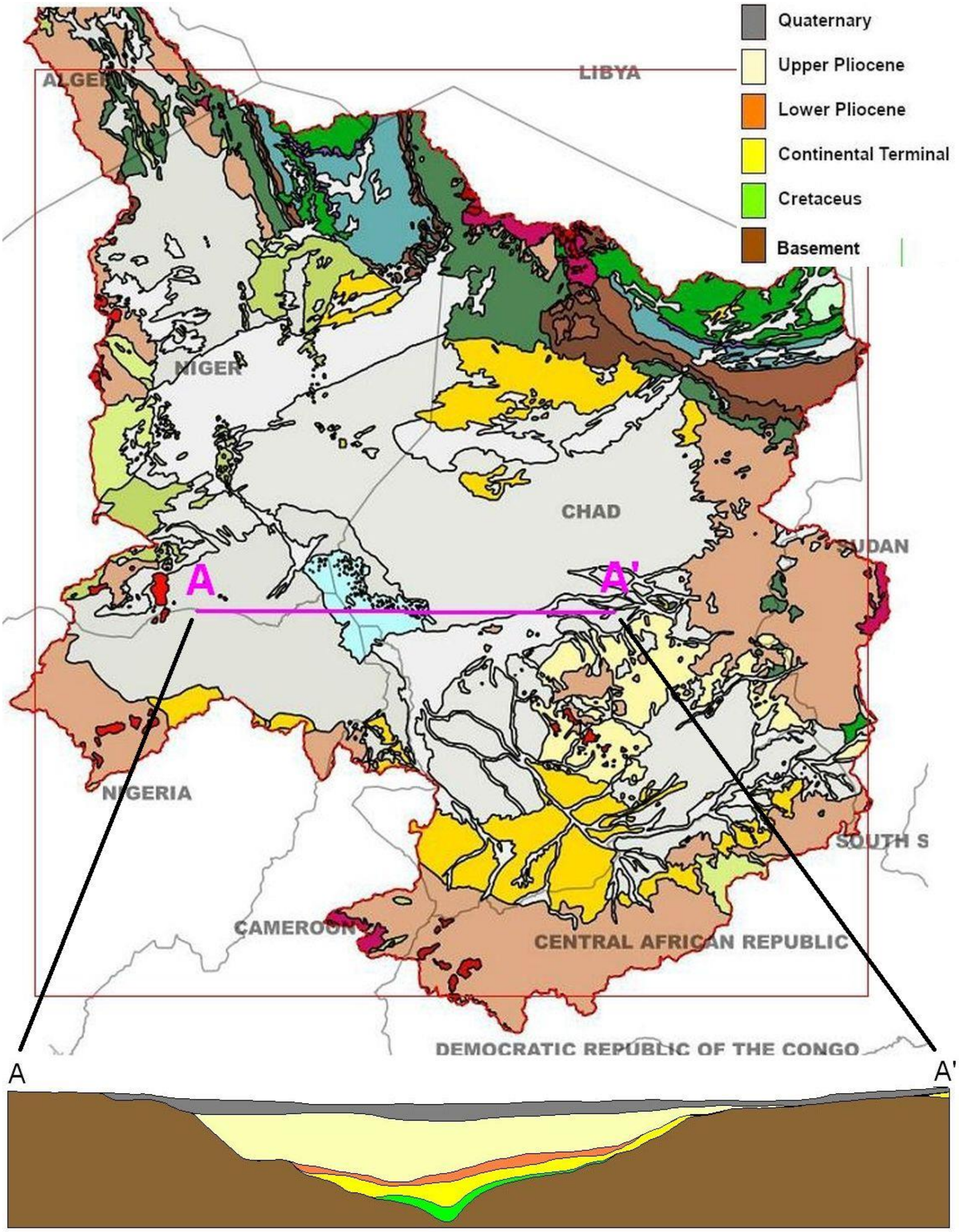


Figure 22. Subsurface geology (cross-section) obtained after retrieving the lithological logs from the Rockware geo-model code. For illustrative purposes, the vertical scale is enhanced (x 50) as regards the horizontal scale.

The main mechanisms of groundwater inflow for the upper aquifer are rainfall infiltration (direct recharge) followed by river infiltration, return irrigation flow (mechanisms also for the lower aquifer), and by lateral inflow from other aquifers (Ounissoui, Koutos) and contributions via weathered bedrock on the eastern and southern boundaries. Recharge form rainfall takes place where aquifers outcrop, mainly from 15ª N of latitude to the south. The local recharge from the Chari-Logone and Komadougou Rivers takes place by floods during extreme events. Important irrigation return flows take place in the land surrounding Lake Chad (Nigeria), irrigation areas of Niger (Komadougou-Yobé) and Cameroon, and most irrigation water comes from existing dams. In addition, the vertical flow to the Quaternary aquifer occurs mainly south of Manga, where the Upper Pliocene is confined.

Discharge is produced mainly through pumping for domestic water supply, husbandry and agricultural irrigation purposes, and through riverbeds (Komadougou-Yobé and Chari-Logone) during the dry season. A limited connection exists with Lake Chad. High evaporation and evapotranspiration (ET) losses are expected mainly in wetlands and surface waters. However for saturated porous media, when the groundwater level exceeds 10 m deep the water table is generally not subject to direct evapotranspiration, except for the areas covered by acacias trees, where the net recharge may be less than the total ET. It is also assumed that substantial groundwater loss may take place to the upper northern area in the lowest discharge point (Lowlands, Bodelé), but mechanisms remain uncertain.

2.8. A review on modeling

This section summarizes different Lake Chad Basin numerical models built mainly on a regional scale, as well as previous modeling works performed locally in the basin. They have been developed for groundwater and surface water based on different tools, numerical methods and areal extension coverage (Fig. 23). The scope covered by these models described below focuses mainly on the central basin (Lake Chad and its surroundings), and more specifically on the Chari Baguirmi area. Generally, the detailed numerical documentation of previous models has not been obtained and this paragraph is based mainly on the literature review of published papers.

In the early 1990's, Eberschweiler (1993a) developed a numerical model for the Quaternary aquifer and the *L Pli* and *CT*. Data include existing lithological logs, pumping tests and piezometric data and rainfall from early reports of the 1960s. The modeled, based on the GARDENIA code, includes an area coverage of some 500,000 km^2 in a model grid sized 12.5 x 25 km in the modeled central part of the domain. Existing piezometric depressions (e.g. Chari Baguirmi and Kazdell) were simulated by considering lack of recharge infiltration and major evapotranspiration, besides the existing groundwater exfiltration from deeper zones.

i) Leblanc (2002) and Leblanc et al. (2007) built a transient model by combining satellite imagery data (Remote Sensing-RS) and GIS methods to better define groundwater recharge and discharge areas, the groundwater/surface water interaction and paleohydrological settings; and to also simulate all the major changes that have affected the Lake Chad Basin from 1960 to 2000, including hydroclimatic changes. Their work focused on the Quaternary aquifer and central Lake Chad Basin part that covered more than 500,000 km^2 (Fig. 24).

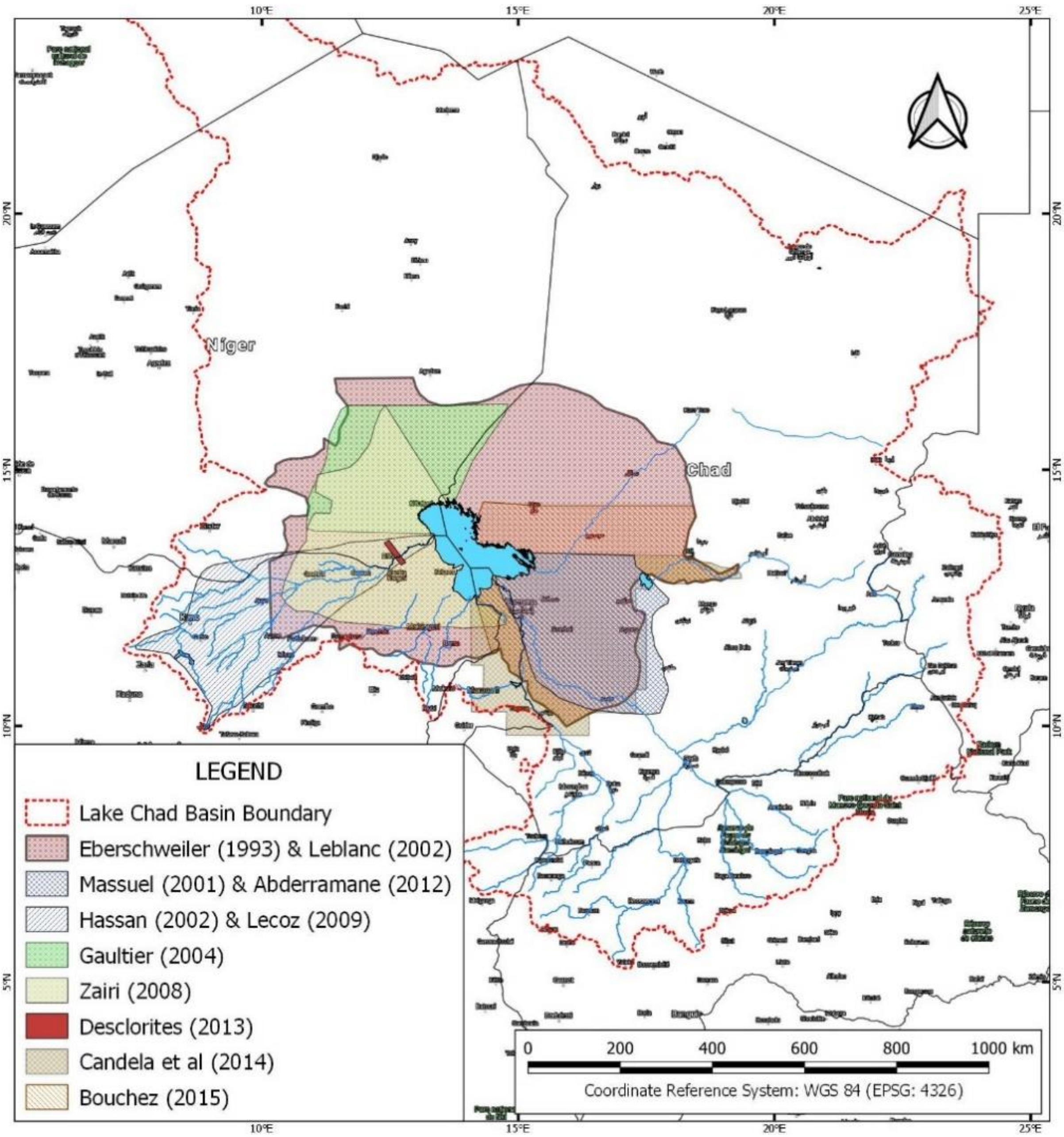


Figure 23. Developed models and area coverage.

To build his modeling work (steady state and transient simulation from 1960 to 2000), he used the MODFLOW 96 modeling platform and a single layer; each cell size ranged from 100 to 400 km^2. The input data were:

- aquifer geometry; lateral flow with bordering aquifers; pumping rates; time series of the river and lake levels; time series of the lake area; recharge and discharge zones; the initial piezometric level.

The calibrated parameters were:

- Transmissivity, lake/river conductance, and recharge and discharge rates.

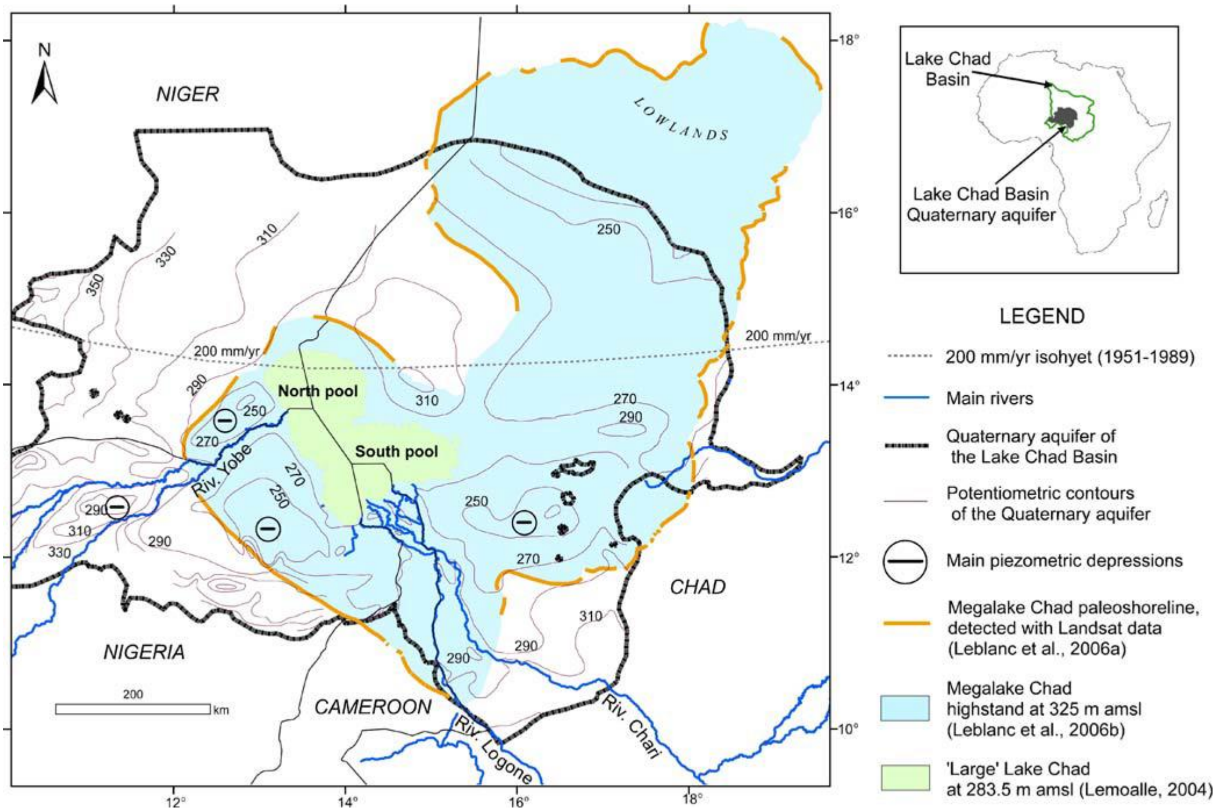


Figure 24. Model developed by Leblanc et al. (2007). Study zone coverage.

Concerning groundwater modeling, remote-sensing products were used to improve the model's calibration with a finer definition of the recharge and discharge areas, and for mapping major recharge and discharge areas. Satellite-based relevant applications for the delineation of recharge and discharge zones included: identifying and mapping ponding areas; soil moisture distribution; vegetation activity and surface water bodies. Different parameters, based on satellite-sensors measurements, were used for this work, e.g.: thermal (Meteosat, Advanced Very High Resolution Radiometer (AVHRR)), elevation (Shuttle Radar Topography Mission (SRTM)), optical (Moderate Resolution Imaging Spectroradiometer (MODIS), Landsat TM, AVHRR) and vegetation index (MODIS). The employed RS data improved the quality of the recharge results.

The most important result was the delineation of the recharge and discharge areas, together with their calculation, which included some key parameters, such as: infiltration, evapotranspiration and also exfiltration, which control the occurrence of large piezometric depressions (Chari-Baguirmi, Bornu, and Kazdell). Lack of long-term piezometric mesurements impaired good transient calibration and modeling results have to be qualitatively taken.

ii) Boronina and Ramillien (2008) did an analysis based on the NOAA-AVHRR and GRACE data to study the regional hydrogeology of the Quaternary aquifer in the Lake Chad Basin. Previously in Boronina et al. (2005), the steady-state and transient modeling of the Quaternary aquifer (based on the water table averaged for the years 1960-2004) was done with the FEEFLOW code based on finite elements. A single unconfined layer of the Quaternary aquifer extension, discretized into 11,427 triangular prismatic elements, was used. Recharge and discharge zones were previously specified by geomorphological, hydrochemical and isotopic information. Calibration was based on varying of transmissivity, recharge and evaporation values per zone.

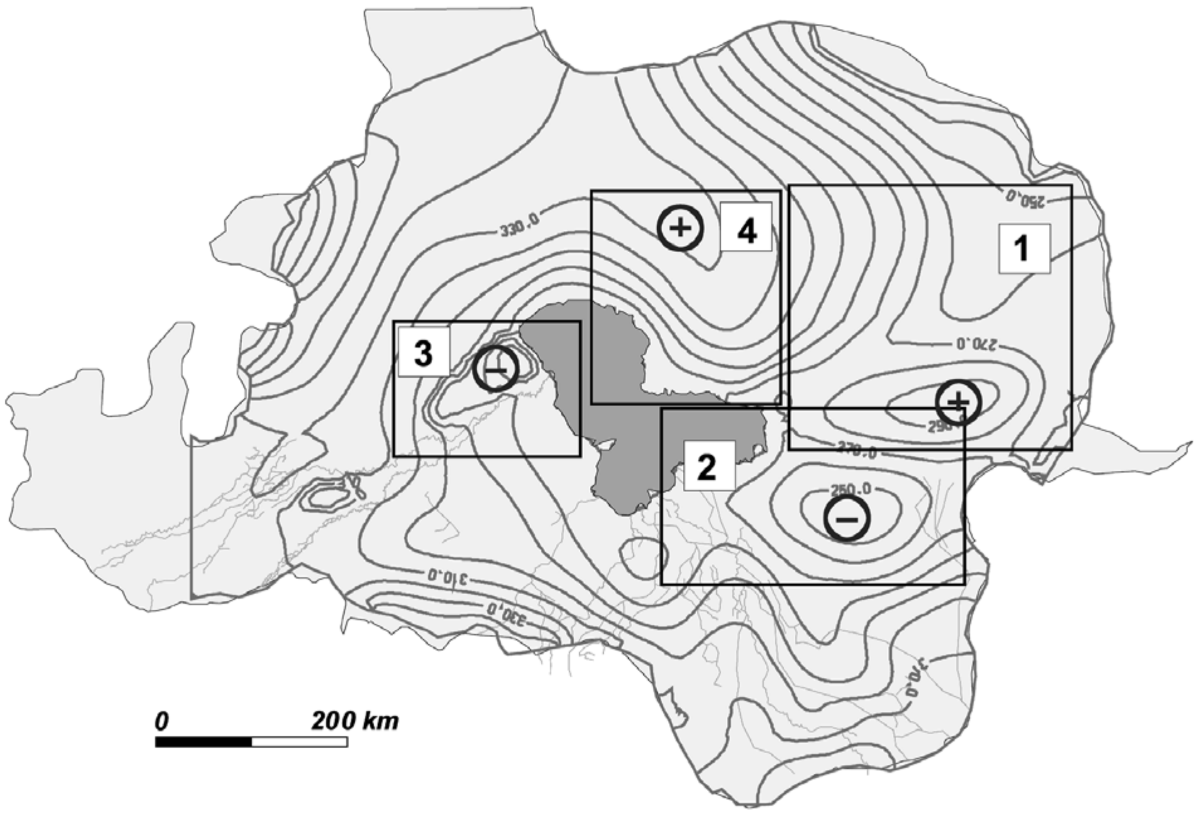


Figure 25. The model domain and simulated piezometric map of the Quaternary aquifer with screen windows location for AVHRR images. Screen windows show piezometric anomalies ((+) domes and (-) depressions): 1 –Harr piezometric dome and Bahr-el-Gahzal; 2 – Chari-Baguirmi piezometric depression; 3 – Kadzell piezometric depression; 4 –Kanem piezometric dome (Boronina & Ramillien, 2008).

iii) For surface waters, the publication by Delclaux et al. (2008) presents two models to model the surface hydrology of the Lake Chad Basin: the THBM model (Fig. 26a), named HYDRA, and the GR+THBM model (Fig. 26b), applied and confronted. Simulations cover the Chari-Logone river area.

In the first case, the study included flooded entities ("lakes") where water accumulates, and the "catchment" entities, where runoff is defined. The input data were: surface and subsurface runoffs using the IBIS Land Surface Model on the "catchment" grid cells; rainfall and evaporation to calculate water flow to "lake" grid cells; top soil surface description: elevation, potential depressions and outlets and drainage network. Depending on the water volume and geomorphology on the grid cell, a "catchment" or "lake" was defined by stating a coefficient between 0 and 1.

The THBM+GR model integrated a module to directly calculate runoff (discharges of the Logone/Chari system) based on precipitation and the reference evapotranspiration. The production functions (GR) developed by Makhlouf and Michel (1994) were also included.

To complement the work, the data from STRM30 Digital Elevation Model and the GRASS GIS software were used.

A sensitivity analysis of the Lake Chad water level modeling, simulated with the GR+THMB model, that considered irrigation scenarios, elevation (DEM) and lake infiltration, was performed. The model's sensitivity to abstraction for irrigation, and the relations among the lake, rivers and groundwater, indicated the need for accurate conceptualization and data acquisition.

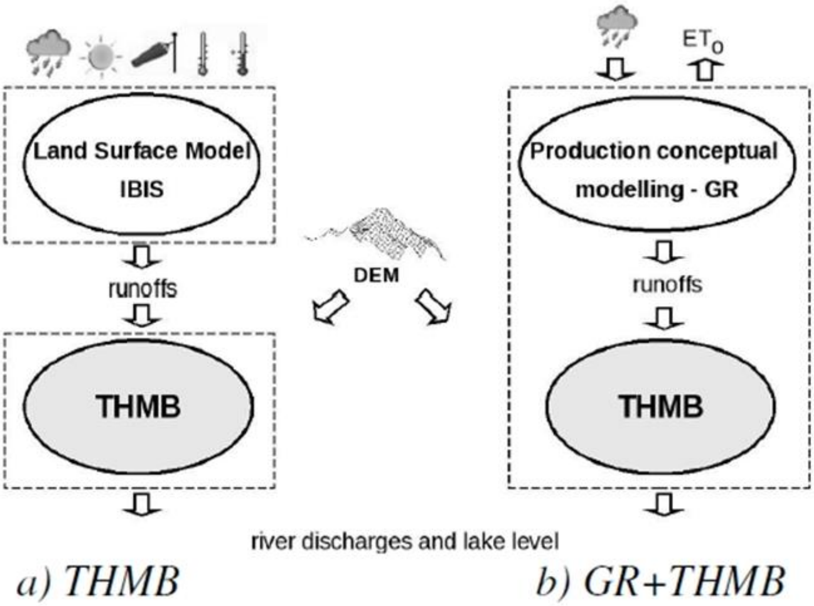


Figure 26. The two versions of applied models a) THMB and b) GR+ (Delclaux et al. 2008).

At the local geographical level, different surface water and groundwater modeling efforts have been made by a number of authors:

1) Massuel (2001) developed a groundwater flow model for the Chari Baguirmi area (190,000 km^2), which aimed to explain the presence of piezometric depressions based on hydrodynamic and isotopic data. The model main obtained results that indicated the minor contribution of Lake Chad to the Quaternary aquifer, the seasonal inputs from the Chari river and the long residence time of deep groundwater in some areas, probably recharged during the last pluvial period. Recharge predominates in the areas of Bahr Erguig and Batha de Laï ri and in the sandunes of Harr. In this model, exfiltration was the key parameter applied to explain piezometric depressions.

2) Hassan (2002) carried out a modeling analysis of the Yobé River Basin for 1998 (shallow Fadama aquifer, Nigeria) using MODFLOW with graphical interface groundwater VISTAS and a simple basic layer. The objective was to investigate the role of the different hydrologic parameters in the overall balance of the hydrogeological system to specifically assess river-aquifer interactions and to explore the effects of pumping in the aquifer. The simulated area (confined-unconfined) is a strip of floodplain aquifer measuring 1,500 m long, 4,900 m wide and 16 m deep, which was discretized three-dimensionally (blocks of 500 m in the x-direction; between 35 and 150 m in the y-direction, and 16 m in the vertical direction). Simulation consisted of 86 groundwater heads (corresponding to 86 stress periods, 2.4 yr) to calculate the river's recharge N and S of the studied area.

A simplified model was used (it did not include other parts of the river, including meanders) due to the adopted cross-sectional model; no accurate measurements of the river channel flow and depth exist, necessary to estimate flow through and from the aquifer. The water balance showed that the river to aquifer flow dominated the recharge with regard to rainfall and overland flooding.

3) In the work by Gaultier (2004), the Quaternary aquifer of the Kazdell plain (Niger) was modeled with MODFLOW (under transient conditions) by considering changes in precipitation in the last 30 yr. Geochemical and isotopic data were also considered in the study to assess groundwater salinity and water origin. The modeled period was 1994-1998, aquifer extension was 7,500 km^2 and the overimposed net size was 5 x 5 km. Only one layer was defined and an exfiltration of 1 mm/yr to reproduce piezometric depression was imposed for modeling. Calibration was based on the piezometric level measurements for the 1960-1970 period, which proved a task difficult for the western part of the depression because data were lacking. Transient state modeling was based on the groundwater level data taken from 1970.

According to the results, the effect of a drying lake on the aquifer was limited to the closest area of the lake shore with up to 10 m of groundwater drawdown. This effect was not observed at a few km from the lake. The Komadougou River was the most important input to the aquifer.

4) Zaïri (2008) developed a transient hydrodynamic model through MODFLOW of the Quaternary aquifer in Kazdell (Niger) and Bornu (Nigeria) to evaluate past and present hydrogeochemical processes. The modeled area covered 200,000 km^2, with a 25 x 100 km^2 net for the monolayer definition. Objectives included coupling Cl transport (based on the MT3D code) and simulating the groundwater level in equilibrium during Mega Lake Chad 6,300 B.C.) and after 6,300 A.C., when Mega Lake reduction started. To simulate piezometric depressions, a 1mm/yr exfiltration flow from deeper aquifer parts was applied for the modeling.

According to the modeling results, evapotranspiration was the key parameter in both depressions. The non-point recharge from Manga and from the Komadugou-Yobé River were most important inputs to the aquifer, while Lake Chad had barely any influence on balance.

Regarding the Cl simulations, the model was able to represent the observed chloride distribution in depressions and the importance of Komagougou-Yobé for the aquifer dilution process. The concentrations on the lake's shore were not well reproduced due to the values initially taken for simulations.

5) Le Coz et al. (2009) developed an appropriate method to aggregate SRTM DEM into the framework to model the water balance of the Lake Chad Basin (2.5 Mkm^2). The distributed hydrological models were based on the aggregation and assessment of the methods of six Digital Elevation Models (DEM). STRM30 was selected and integrated into the GIS software for data processing. For the hydrological model to simulate the water balance of the Lake Chad Basin (2.5 Mkm^2) (Fig. 27), the THBM code with biogeochemistry was used. A drainage network was obtained by using six aggregated algorithms (mean, median, mode, nearest neighbor, maximum and minimum) to the Shuttle Radar Topography Mission (STRM and DEM (from 3”: 90 m to 5’: 10 km).

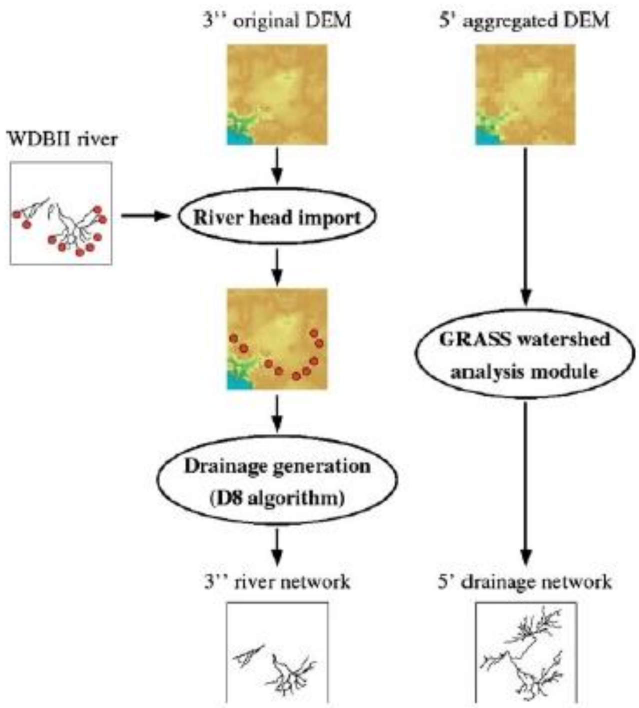


Figure 27. River network delineation at 3” and 5’ resolution (Le Coz et al. 2009).

Later in (Le Coz, 2010), a multiple-point statistics was used to model facies heterogeneities in the vadose zone of the Komadougou-Yobé River valley (SE Niger), which is presently undergoing intensive agricultural development.

The sand-clay heterogeneities were analyzed by a Landsat image, acquired during a high flow period over a 160-kilometer stretch in the downstream part of the valley, and by a set of 50 boreholes drilled near the town of Diffa (4 km x 4 km area). Heterogeneities were geostatistically characterized (variograms witha noticeably constant length scale of 380 m), and clayey objects were shown to be randomly distributed in space according to a Poisson process. A synthetic three-dimensional media was built which satisfactorily reproduced the second-order statistics of heterogeneities and the specific facies patterns.

HYDRUS results (2003-2009), based on a generated hydrogeologic model based, in turn, on hydrodynamic parameters obtained from the density of probability, was associated with the defined lithologic facies, and indicated wide variability for point recharge. However from the stochastic approach on the domain scale, uncertainty was less.

6) Bader et al. (2011) developed a water balance model by combining satellite data (Landsat MSS, Meteosat, AVHRR/LAC data) to simulate fluctuations of the surface area of Lake Chad. The water balance model simulated water level and flooded areas according to the lake's inflow (river discharge, precipitation) and outflow (evaporation, infiltration). It provided information on the lake system's processes and key hydrologic parameters for system functioning.

Whitin this model, which provided information on the lake's hydrological performance, Lake Chad was represented by three reservoirs (the southern basin connected to the northern basin and the archipelago). Water levels may differ during periods of low inputs (current situation) or can be similar during periods with surpluses (a pre-1973 situation). According to the field observations, the northern basin was represented by a geologic reservoir that had to be filled before water outflowed to the surface.

The model used seven optimized parameters: infiltration rate; soil reservoir depth; four exchange parameters between reservoirs, and the bottom surface level of the archipelago.

Calibration was performed using 1970-1996 period data, and validations for 1956–2008, with *in situ* or satellite data (river discharge, precipitation, evaporation, water levels and flooded areas) (Fig. 28).

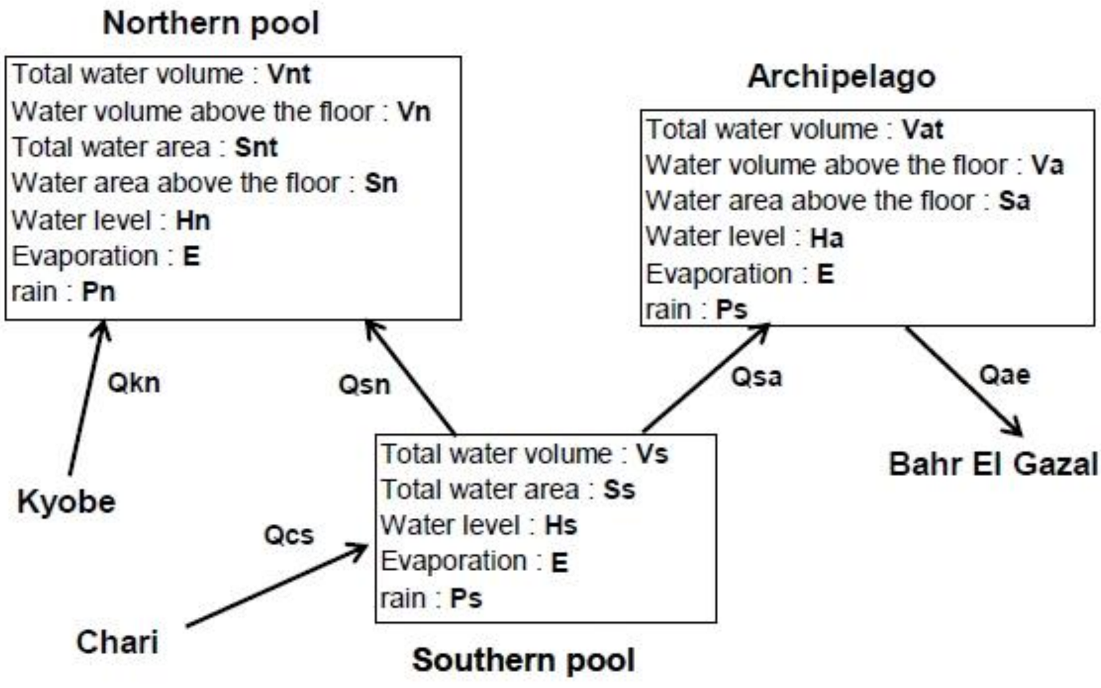


Figure 28. The Lake Chad hydrological conceptual model (Bader et al., 2011).

7) Abderamane (2012) presented a steady-state Quaternary aquifer numerical flow modeling of the Chari Baguirmi depression (around 70,000 km^2, Chad) through MODFLOW and for the 2008 period. A one-layer regular grid with 30,272 square elements (2,000 x 2,000 m) over-imposed the modeled domain. Calibration was based on the piezometric values obtained in December 2008. Sedimentological, chemical and isotopic data were also studied to assess groundwater salinity and aquifer hydrological behavior.

One of the main limitations of modeling the results was related to insufficient hydrodynamic data to cover the model domain area for simulation and further calibration purpose. The results indicated the presence of a clay layer on top of the sedimentary infill, which could impair groundwater level evapotranspiration and lead to a piezometric depression in the Quaternary aquifer and a deep groundwater flow drainage is suggested. Nevertheless, prevalence of the evaporation phenomenon was found in the western part of the depression and low evaporation in the rest of the area.

8) Descloitres et al. (2013) conducted geophysical research in the Komadougou-Yobé area (12-km geophysical profile to the SE Niger, near the town of Diffa) by applying two different geophysical methods to assess the geometry of the Quaternary aquifer and to support the hydrogeological properties for a numerical groundwater model data. The techniques followed were Time Domain Electro-Magnetic (TDEM) and Magnetic Resonance Sounding (MRS).

TDEM allowed the main geological units within the first 100 m of soil depth to be delineated (Fig. 29). Several parameters were estimated with MRS: water content (Fig. 30); hydraulic conductivity; transmissivity.

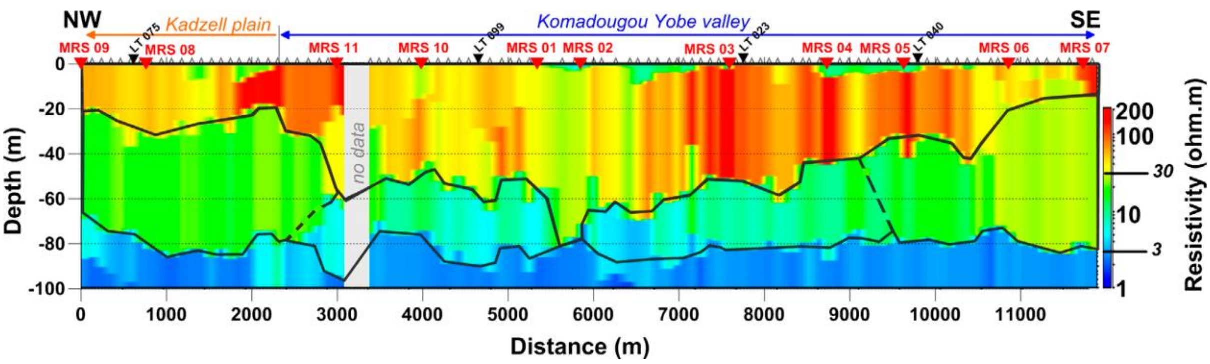


Figure 29. Results of the north-west to south-east TDEM profile across the Komadougou-Yobé valley (Descloitres et al., 2013).

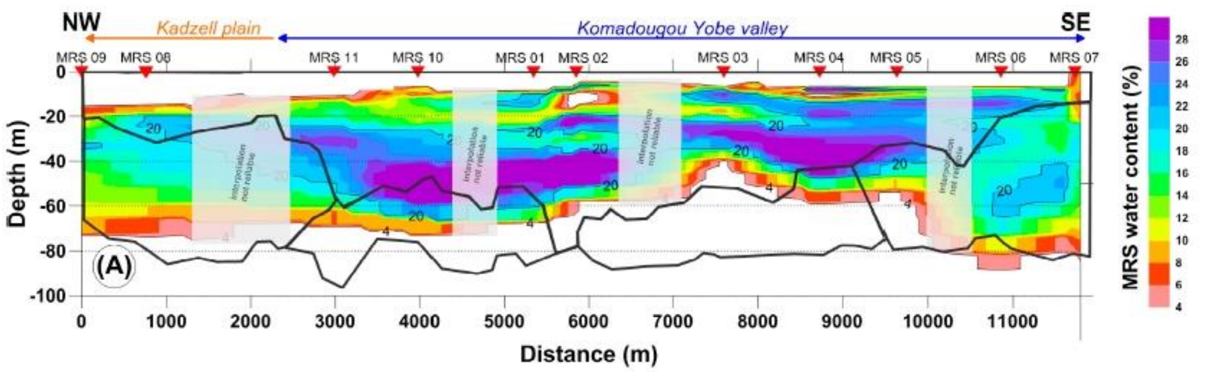


Figure 30. MRS profile across the Komadougou-Yobé valley. Water content (Descloitres et al., 2013).

9) A groundwater model to simulate hydrodynamic performance of the Quaternary aquifer in the Chari-Logone area was developed by Candela et al. (2014). Located in the Lake Chad Basin, the study covered an area of almost 96,000 km^2 between coordinates 8º 12' and 12º 02' N and 14º 06' and 18º 45' E. To overcome lack of data, dynamical downscaling approach modeling was applied.

A pre-existing regional-scale (Fig. 31a) model based on the GARDENIA code was updated with the VISUAL MODFLOW 2009.1 code. The objective of this model was to obtain the boundary conditions of the local-scale model (Fig. 31b), and to assess flow direction, discharge and recharge areas, as well as the definition of exfiltration/infiltration areas.

The second modeling step focused on the Chari-Logone area. Specifically, modeling covered three possible scenarios of natural recharge and groundwater water extraction with medium, humid and dry climates. The scenario simulation foresaw aquifer responses during medium, dry and humid climate periods.

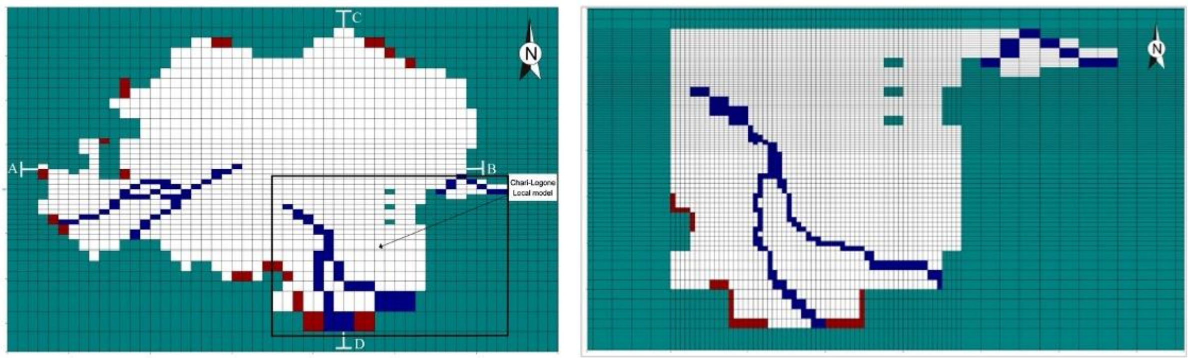


Figure 31. The Chari-Logone numerical model: a) Regional model. b) Local model (Candela et al., 2014).

10) Bouchez (2015) developed Lake Chad water level modeling and Chari-Logone floodplain between 1955 and 2011, based on hydrological, chemical and isotopic data. A rainfall-runoff model (GR2M), coupled with a Lake water balance model (based in Bader et al., 2011), including geochemical and isotopic data (major ions and ^{36}Cl, ^{18}O as tracers) since the 1950s, simulated the Lake Chad level by the HYDRA code.

The model simulations agreed with the lake levels and flow at N'Djamena for the complete considered period. Evaporation between 85% and 98% of lake waters in the surroundings of Lake Chad was estimated by comparing the model-calibrated infiltration rates with groundwater geochemical data. Isotopic data indicated that the Bahr El Ghazal was the natural overflow channel of Lake Chad when it exceeded 283 m, while the geochemical patterns of deep piezometric depressions indicated that recharge was produced during the last old humid recharge period. The modern recharge of the Quaternary aquifer was essentially related to the Chari-Logone system, while the contribution of Lake Chad was weak.

11) In the last work, Buma et al. (2016) analyzed changes in the Lake Chad Basin's hydrological behavior under extreme climatic and environmental conditions. The objective was to also infer the effect of rainfall on water storage, to investigate subsurface water changes, and to make comparisons with the groundwater outputs from the Water Gap Hydrological Model (WGHM). The WGHM computes groundwater recharge, surface runoff, river discharge and storage changes in: canopy, rivers, soil, lakes, wetlands, groundwater and snow at a spatial resolution of 0.5º. The total water storage (TWS) from GRACE, the lake level variations from satellite altimetry, and the water fluxes and soil moisture from the Global Land Data Assimilation System (GLDAS) were used to assess the space-temporal variability of the Lake Chad Basin's hydrological parameters.

For this study, the monthly land mass grid observations were used (Level 3), provided by the Center of Space Research (CSR), University of Texas, Austin, from January 2003 to December 2013. The results indicated changes in groundwater content in depth for the Komadougu-Yobé, Kazdell and Bornou, and a lower water content was clearly seen in both depressions.

3. GROUNDWATER MODELING

3.1. Introduction

To date in the Lake Chad Basin, a number of groundwater simulation models have been, or are being, developed as previously presented. The aim of the steady-state present model is to quantify and analyze the spatial effects of surface-water and groundwater fluxes on water balance dynamics.

The new model approach will: *i*) assess surface-groundwater interactions; *ii*) stablish a quantitative framework to develop abstraction scenarios and analyze its further impacts on groundwater, lake and connected rivers; *iii*) provide guidance and recommendations for sustainable abstraction scenarios.

Steady-state models are used to model equilibrium hydrologic conditions and/or conditions when changes in storage are insignificant. Transient models are used to model time-dependent stresses and/or conditions when water is released from or taken to storage. In this study, establishing a steady-state groundwater model will provide insight into the system's behavior, which will be useful for implementing a more complex transient solution in the future. The time period set for steady-state modeling went from 2008 to 2011 (baseline).

This chapter delivers the technical information about the new developed numerical groundwater flow model. It includes the following changes:

- Updated model layers and boundaries for the Chad Formation aquifer system with a detailed review of hydrostratigraphical information
- Revised recharge zones and rates from a soil-water distributed model
- Updated groundwater heads and surface water data

The process includes different interdependent steps, summarized as follows:

- Numerical code selection, adaptation and input of hydrogeological data
- Compatibility assessment of the numerical code as regards other necessary information and hardware support (model size)
- Groundwater flow model design and construction: model structure, domain, grid, initial and boundary conditions
- Groundwater model calibration
- Model assessment

Concerning the groundwater flow description and its mathematical description in a numerical model, three key points are needed:

- The model domain geometry and structure (i.e. extension)
- Identification of hydrological processes (i.e. recharge, discharge)
- Parametrization of hydrodynamical properties (i.e. considered hydraulic parameters)

For this aim, the required quantitative data are: geographical, geological, aquifer hydraulic parameters (transmissivity, hydraulic conductivity, storage coefficient, etc.), stress (pumping rates, recharge), boundary conditions (rivers, lakes, dams) and initial conditions of the hydrological system (baseline conditions). Key aspects of hydrogeological information and the conceptual model have been detailed in a previous section.

Outputs include simulating the groundwater level at the basin level and in the focus areas of the Chari-Logone and Komadougou-Yobé River Basins.

3.1.1. Model Construction

The model herein presented is a revised, updated and enlarged hydrogeological flow model, based mainly on the Lake Chad Basin Quaternary model, as previously established by Eberschweiler (1993a). Unlike previous models, this model domain is defined to comprise the entire hydrogeological Lake Chad Basin in order to cover the whole basin and in an attempt to integrate hydrological processes for most of the Lake Chad Basin.

For some basin areas, it is a complex task due to data scarcity. However, hydrogeological work carried out as part of this project provides a better understanding of the system's regional functioning, which allowed the model to be developed.

3.1.2 Software. Numerical CODE

The code selected for modeling is MODFLOW 2005 (Harbaugh et al. 2000) with the ModelMuse interface (Winston 2009). It was selected for its wide application, portability and reliability, and it is well documented.

MODFLOW is a groundwater modeling software designed for Windows with a graphic interface developed by the USGS, to simulate constant and nonstationary flows in an irregular shaped flow system. This code is capable of representing conditions related to groundwater flow, such as evapotranspiration, recharge, drainage, river interaction, among others. The mathematical solutions for solving flow equations are based on the finite differences method, which provides the ability to calculate the flow regime by controlling discrepancies of water balance.

ModelMuse is a graphical user interface (GUI) for MODFLOW 2005. It allows spatial input-output definition by drawing points, lines or polygons in the upper views of the 3D model, and on the front and side of the model domain. Objects can have up to two formulas to define their extension perpendicular to the plane of view to allow objects to be three-dimensional. In ModelMuse, spatial model data are independent of the grid, and temporal data are independent of stress periods. Being able to input these data independently allows users to redefine spatio-temporal discretization at will. It also enables the seamless integration of data from other groundwater simulation platforms.

Model data can be exported from a variety of sources, such as QGIS, Excel files and many other software. In this project, for all geographical data, the applied coordinate system is UTM (WGS 84 zone 33N).

3.1.3 Working units

The MKS system, International Standard System of Units, was selected for the different data used in modeling. Table 7 presents the applied parameters and units. Temporal discretization is not needed for the steady-state model.

Table 7. The parameters and units used in modeling.

Precipitation	mm
Time	second (s)
Depth	meter (m)
Length	meter (m)
Elevation	meter (m)
Coordinates	UTM
Hydraulic conductivity (k)	meter/second (m/s)
Transmissivity (T)	meter^2/second(m^2/s)
Storage coefficient (S)	dimensionless
Porosity (m)	%
Recharge	meters/second (m/s)
Evapotranspiration	meters/second (m/s)
Groundwater allocation and use	million cubic meter/year (Mm^3/yr)
Pumping rate	cubic meter/second (m^3/s)
Head potential	meter (m.a.s.l)

3.1.4. Model domain and numerical mesh

3.1.4.1. Model domain

A three-dimensional (3D) model was defined based on the conceptual model described in Section 2.7. Horizontally, the model covers approximately 1,900,000 km^2, from 5ºN to 25ºN and from 5ºE to 25ºE. The model domain was defined by taking into account the hydrological basin extension, except in the northern part, which was based in the known geologic physical boundaries and climate data. Figure 32 right presents the adopted groundwater model domain extent. The different hydrogeological units are somehow hydraulically connected, and a major horizontal flow exists within individual hydrostratigraphical units.

The horizontal model boundaries are defined based on the outcropping geologic materials and the hydrogeological boundary (Quaternary, Pliocene, Continental Terminal, Basement). Following good modeling practices and in order to reduce spurious model results from the assumed boundary conditions, a spatial buffer is included in the model domain. In the northern boundary, buffer definition was based mainly on climate conditions after considering that Sahelian climate predominated and amount of rainfall was below 10 mm/year. Therefore, aquifer recharge is scanty. For this reason, the model domain in that area was established in zones with permeable materials (Quaternary and Continental Terminal). In addition, geohydrological data are almost inexistent because it is a desert area.

Vertically, the adopted model domain is at a depth of 530 m from the ground surface, based on the descriptions of the hydrostratigraphical units presented in Chapter 2.6.

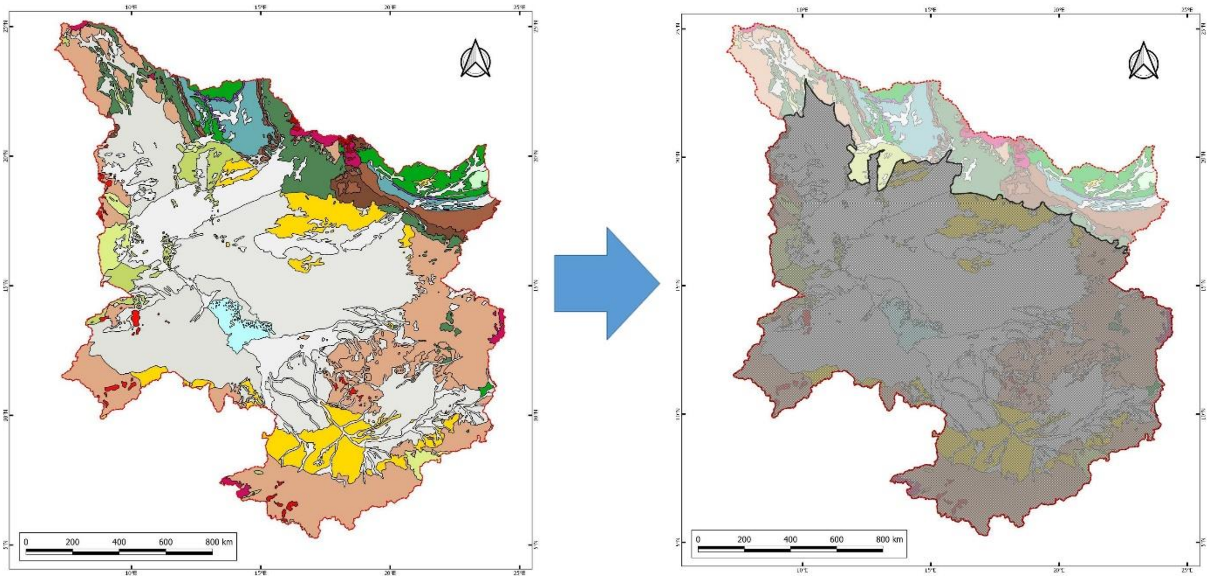


Figure 32. Hydrological Lake Chad Basin (left) and Groundwater Model Domain (right).

3.1.4.2. Numerical mesh

For model meshing (horizontal 2D grid), a grid sized 10x10 km over the whole model domain was superimposed on the top soil surface (upper view of the 3D model). MODFLOW allows further local grid refinement. The model's domain boundary was manually controlled to avoid computational errors and numerical problems that derive from the existence of isolated cells in the mesh. The mesh is presented in figure 33.

Consequently on the model domain's surface, the grid is defined by 198 rows and 187 columns, which accounts for 37,026 cells. The modeled area (18,967 active cells, blue) is the defined model domain's inner zone.

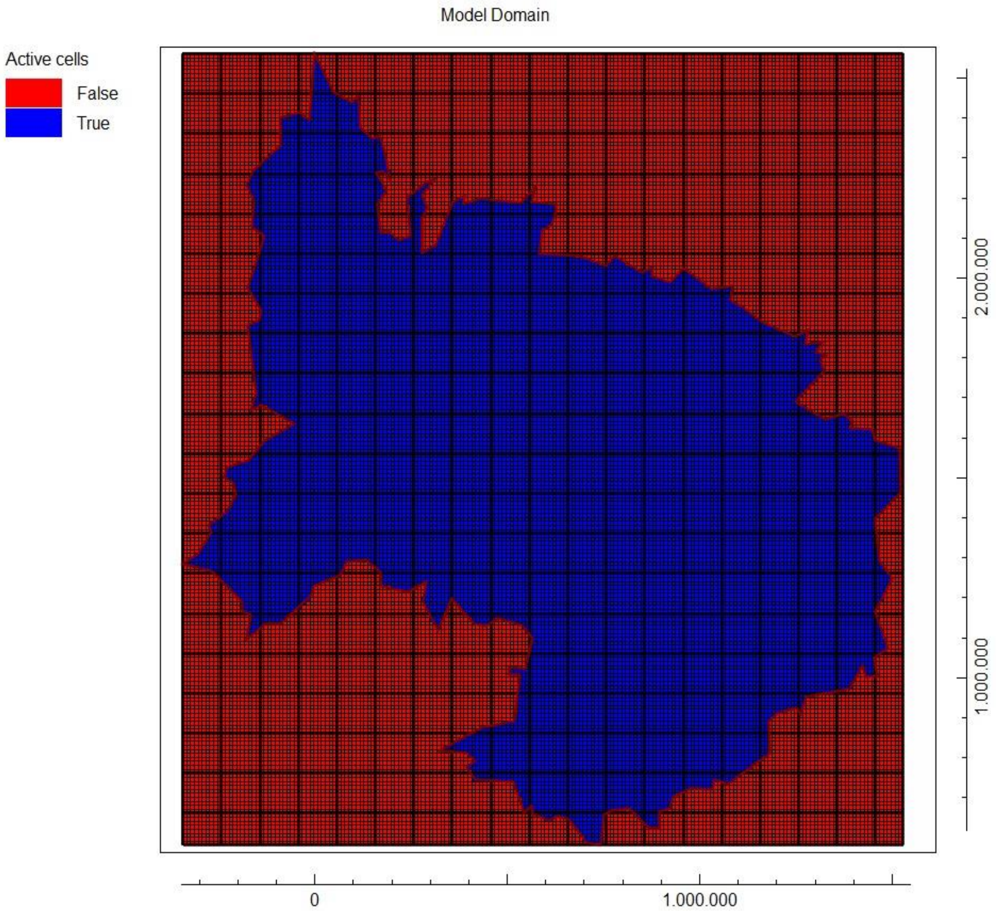


Figure 33. The 10x10 km regional model grid (2D view upper layer) and active cells (blue).

The model domain is vertically discretized in 20 numerical layers (530 m thick), based on the hydrostratigraphical information described in the previous section. As a result, the vertical distribution is (Fig. 34):

- 5 defined layers, each 8 m thick (40 m in total). Unconfined.
- 5 layers, 30 m each (150 m total). Confined/Unconfined
- 5 layers, 28 m each (140 m in total). Confined
- 5 layers, 40 m each (200 m in total). Confined

Finally, the total number of active cells account for 379,340.

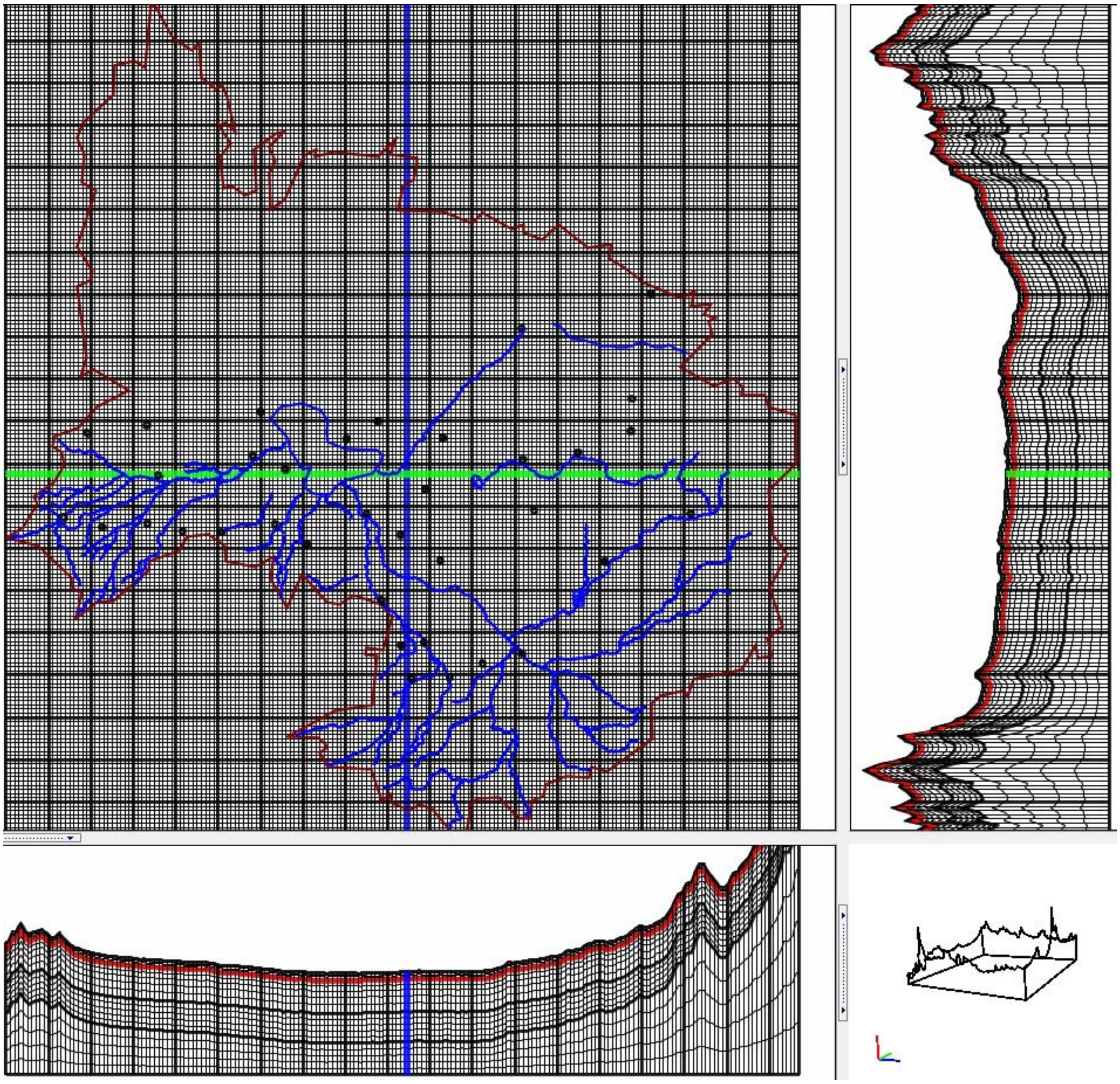


Figure 34. Representation of the vertical discretization: 20 numerical layers

Each cell of the numerical mesh is characterized following the hydrostratigraphical units of the Chad formation, which include three aquifer layers (Q, LPli, CT), one aquitard (Upper Pliocene), and the basement (Cretaceous and weathered granitic rocks), acting as a model buffer. The perched aquifers and the unsaturated zone are not directly simulated as MODFLOW is designed for saturated media. In this numerical code, model layers are defined as confined, unconfined, or capable of being either confined or unconfined, when hydraulic heads alternate between confined and unconfined conditions.

A Multi-resolution Terrain Elevation Data 2010 (GMTED2010; USGS) of 30 arc-seconds (resolution of about 1 km) (Fig. 35) was used to simulate the elevation of the model surface. The selected resolution was a compromise between the accuracy of the numerical code and computational limitations. In order to export to ModelMuse the source file format ".tiff", it is converted into ".dem" format (USGS) by QGIS.

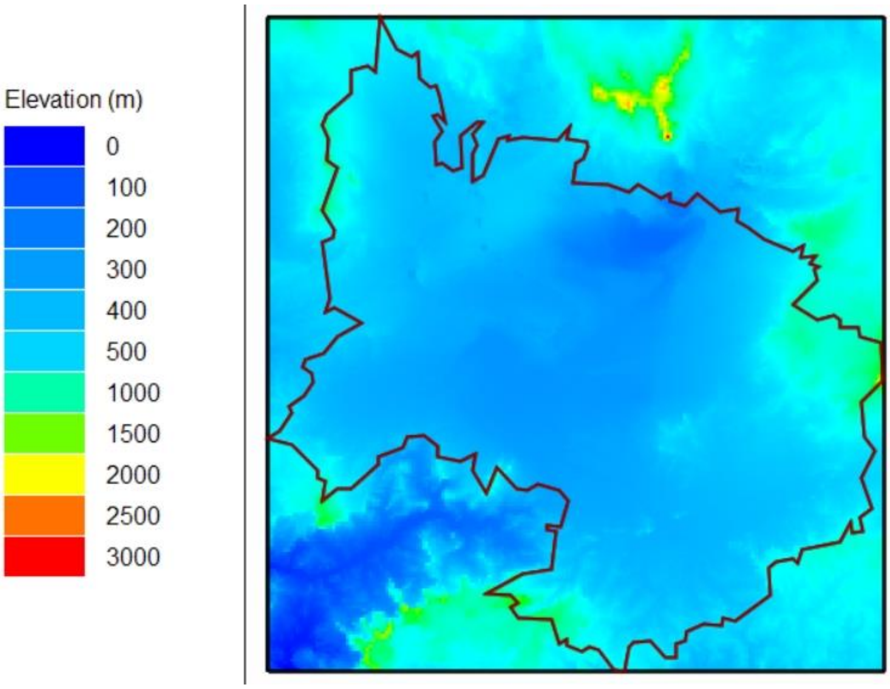


Figure 35. Topographic map (m) of the modeled area (from DEM and ModelMuse).

3.2. Hydraulic parameters

The quantitative values of the hydraulic parameters for aquifer formations (k_h, T, S,), which derived from the collected pumping tests and described in the conceptual model section (Table C1 of Appendix C), were assigned to the active cells of each layer of the numerical mesh. In those areas where data were scarce, a spatial constant parameters zonation of layers and hydrostratigraphical units was defined to cover the model domain for hydraulic conductivity (k), transmissivity (T) and the storage coefficient (S).

The initial parameter values for the different hydrostratigraphic units adopted for the first model runs are shown in Table 8. Due to the model's large scope, hydraulic conductivity was assigned to each geological material, based on the data mentioned in the paragraph above. Then, hydraulic conductivity values of the hydrostratigraphic units were assigned to numerical layers to make the model work properly.

Table 8. Initially adopted hydraulic conductivity values (m/s)

	Hydraulic conductivity k_x (m/s)
Quaternary	0.008
Upper Pliocene	$1E10^{-7}$
Lower Pliocene/CT	0.002
Basement	1 E-4

In the enclosed figure 36), the initial hydraulic conductivity values are plotted for the upper layer (first numerical layer), the 5th numerical layer, the 7th numerical layer and the 11th numerical layer.

Figure 37 shows the model cross-sections, exported from RockWorks, and the hydraulic conductivity values for each geological layer (in ModelMuse as a .grd file). This is a widely used method in very large models due to complexity in the definitions of hydrogeological layers. The vertical scale was enlarged 500-fold to better show the thickness of the numerical layers.

The spatial distribution of the different hydraulic conductivity values for the 20 modeled layers are presented in Figure G1 (Appendix G).

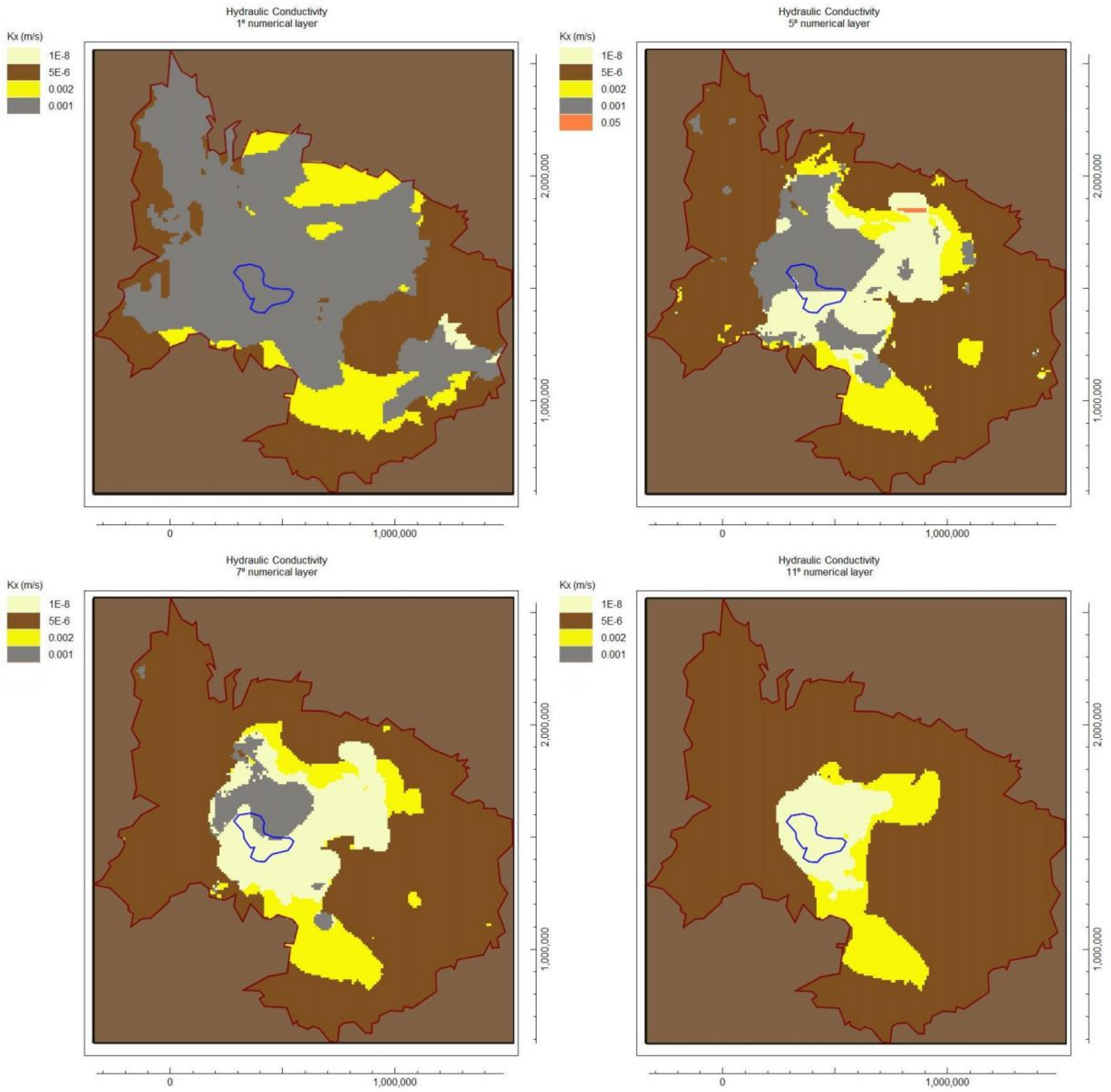


Figure 36. Initial hydraulic conductivity values (m/s). a) 1st numerical layer; b) 5th numerical layer; c) 7th numerical layer; d) 11th numerical layer.

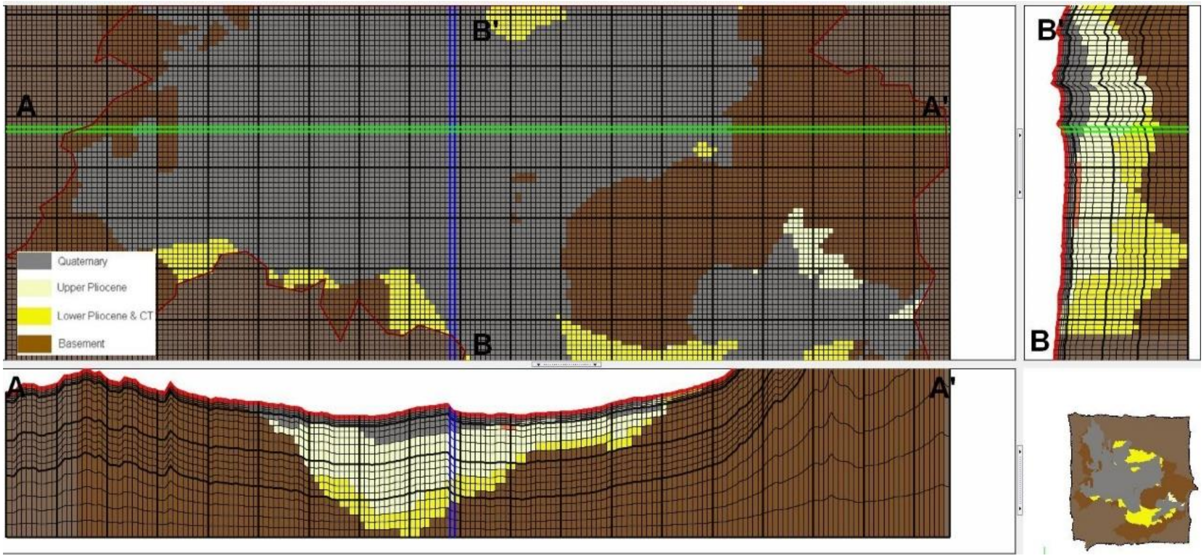


Figure 37. Cross-section example showing the distribution of the hydraulic conductivity values along the 20 numerical layers for the middle area of the Lake Chad Basin.

3.3. Initial and boundary conditions

3.3.1 Initial conditions

The initial conditions define the groundwater hydraulic conditions at the beginning of the model run. In MODFLOW, the adopted initial condition is "model_top", defined by the previous DEM data, which means that the head levels correspond to the values based on these elevations.

The observed piezometric levels obtained from ground data (Fig. 19) show the existence of several piezometric depressions (Chari-Baguirmi-Chad and Bornou-Nigeria areas). Despite the difficulties found for representing these specific conditions in a steady-state model, two different initial low piezometric conditions were established in the areas to more realistically represent the observed measures. The set conditions are 240 m.a.s.l. in Chari-Baguirmi, and 270 m.a.s.l. in Bornou of groundwater, according to the lowest measured values.

Theoretically, the selection of initial conditions for a steady-state model did not influence the model's outcome, but the steady-state solution is more rapidly obtained when initial conditions are defined reasonably close to the steady-state solution.

3.3.2. Boundary conditions

A model boundary is the interface between the model domain and the surrounding environment. Boundaries occur on the model domain's edges and at other points where external influences exist, such as rivers or wells, among others (Spitz and Moreno, 1996).

Hydrogeological boundaries are represented by the following three types of mathematical conditions (online guide to Modflow 2005):

i) Specified head boundaries for which the head is given and maintained steady
ii) Specified flow boundaries for which the derivative of the head (flux) across the boundary is given. A no-flow boundary condition is set by specifying flux to be zero
iii) Head-dependent flow boundaries for which the flux across the boundary is calculated given a boundary head value. This type of boundary condition is sometimes called a mixed boundary condition because it relates boundary heads to boundary flows; several types of head-dependent flow boundaries exist

The defined boundary conditions are groundwater stresses, input or output of the water in the groundwater domain associated with climate (natural recharge and evapotranspiration) and groundwater abstraction, jointly with river-lake interactions. In the first steady-state model runs, the recharge (RCH), constant head (CHD), abstraction (WELL) and rivers (RIV) were the boundary conditions.

The boundary conditions considered in this model are (Fig. 38):

- No flow boundary condition: the outer boundary of the model domain in the lateral part and at the bottom
- Head-dependent flux conditions: Lake Chad, Lake Fitri and Rivers
- Constant head boundary condition: for some areas where water evaporates at the ground level
- Water abstraction (wells)

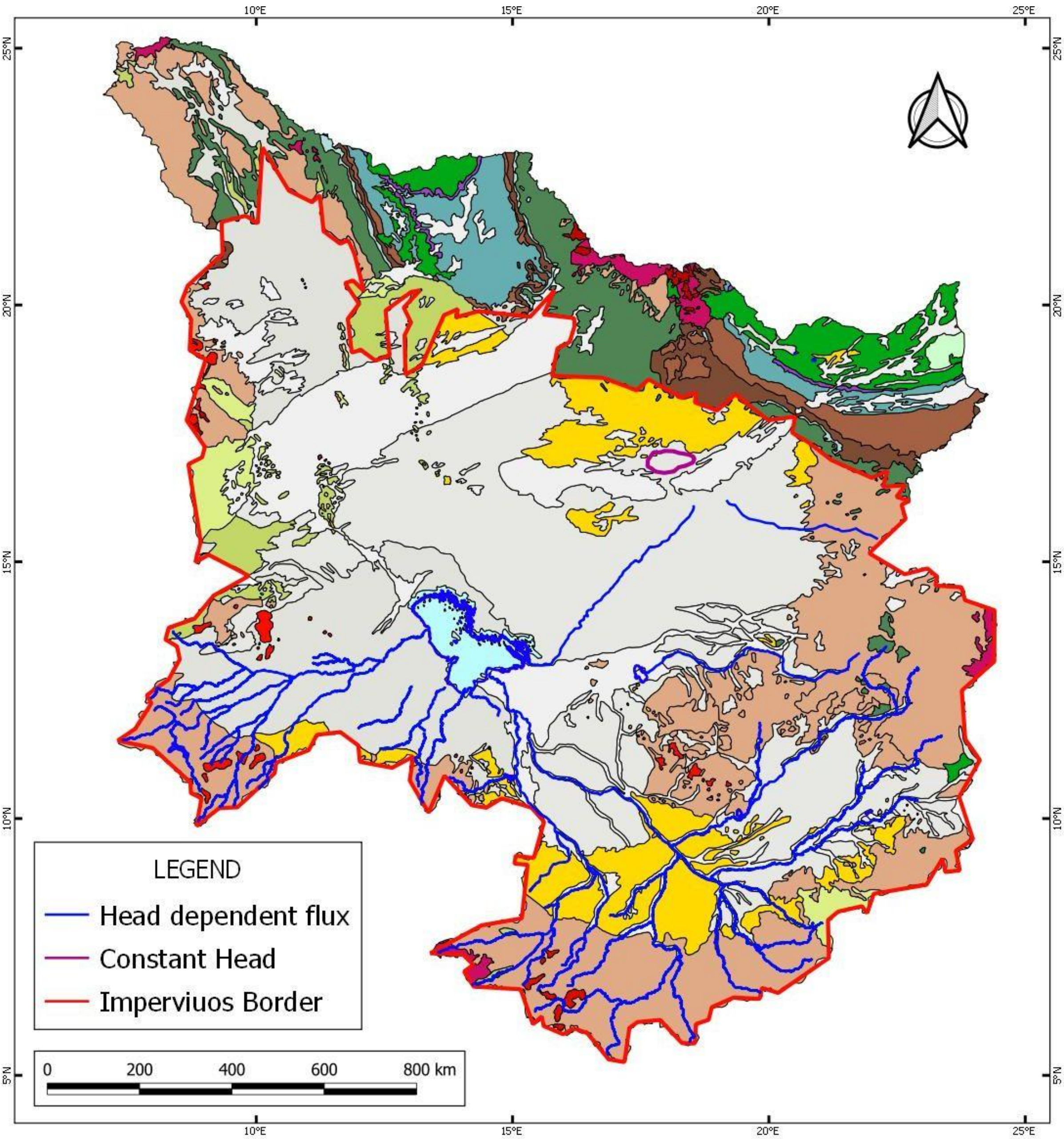


Figure 38. Model boundary conditions.

3.3.3. Recharge distribution

Recharge includes only the portion of water from precipitation and irrigation that actually reaches the water table. The recharge values spatially distributed in the active cells of the domain were independently estimated with a water-soil-plant distributed model for 2008-2011(Appendix E). Recharge was applied to the upper active cells, the top level of the modeled area. It takes place mainly in the SE of the domain, the Kanem and Harr areas.

Recharge values (mm/s) were exported directly to ModelMuse and the result is shown in Figure 39. The range of these values goes from 8E-10 m/s in the high recharge areas, to 8E-11 m/s (and zero for the non-recharge areas). The recharge package (RCH) simulates the specified flux distributed over the top of the model (LT^{-1}). The RCH input provides recharge rate values in layers (aquifer surface), where recharge takes place for each time step.

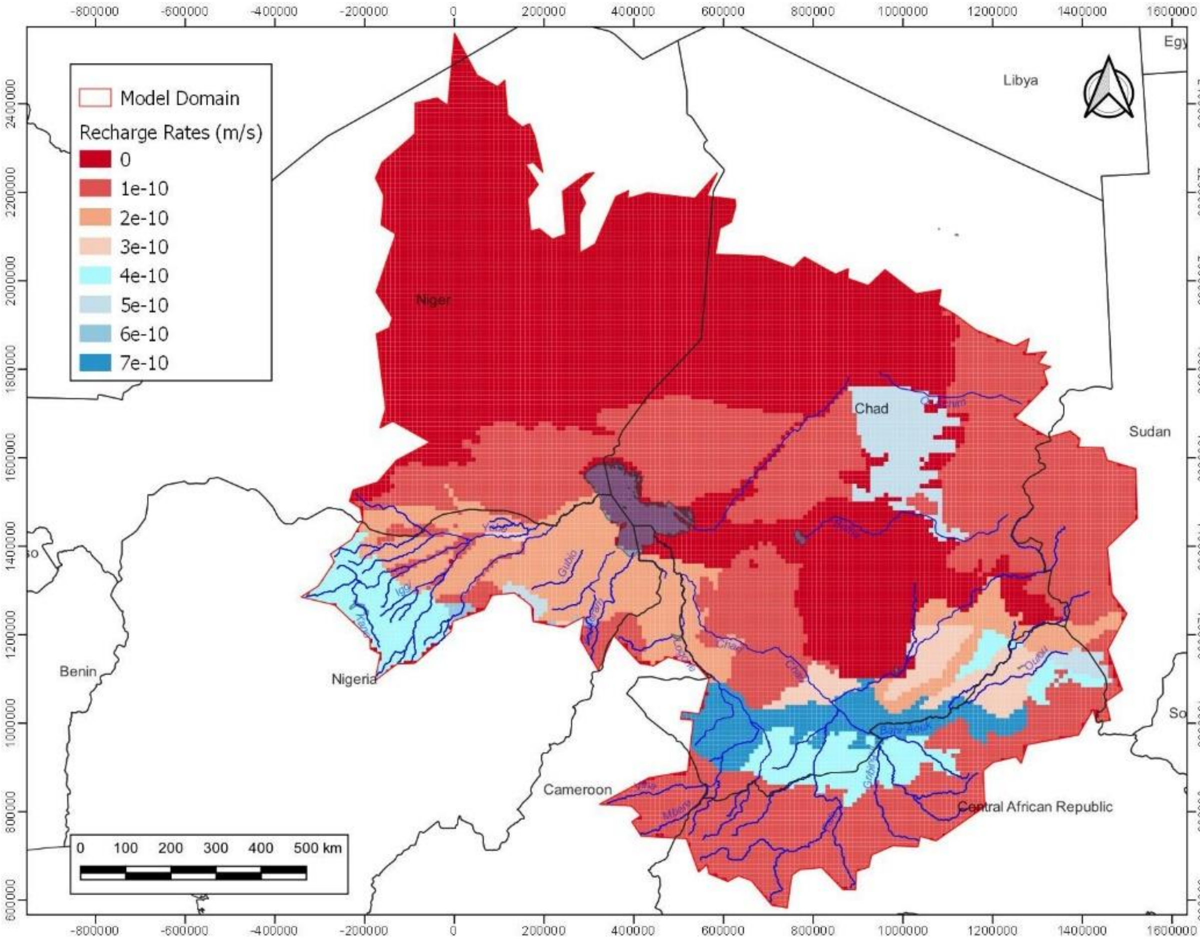


Figure 39. Spatial distribution of the recharge rate (m/s) in ModelMuse.

3.3.4. Groundwater abstraction distribution

This boundary condition corresponds to the water abstracted from exploited wells (L^3T^{-1}). Groundwater abstraction from wells was estimated according to agricultural and water supply demands, as indicated in the hydrogeological section. Abstraction takes place mainly in shallow wells from the Quaternary aquifer, so they were modeled at an average depth of 40 m.

The WELL package allows the simulation of pumping wells (steady-state flow) for a defined time period for flow independently of the head potential in cells and the area of cells. When water abstraction takes place in two layers or more, the corresponding fraction amount of each layer is allocated in the model. In the developed model, abstraction data are spatially distributed.

As there are no data available of the exact location and the spatial distribution of groundwater abstraction in populated areas for water supply, where abstraction is assumed to be greater, location was obtained from satellite images of the largest settlements (Fig. 40) and well fields were defined. The water abstraction rates for domestic and agricultural uses, which were applied to the model, are shown in Table 9.

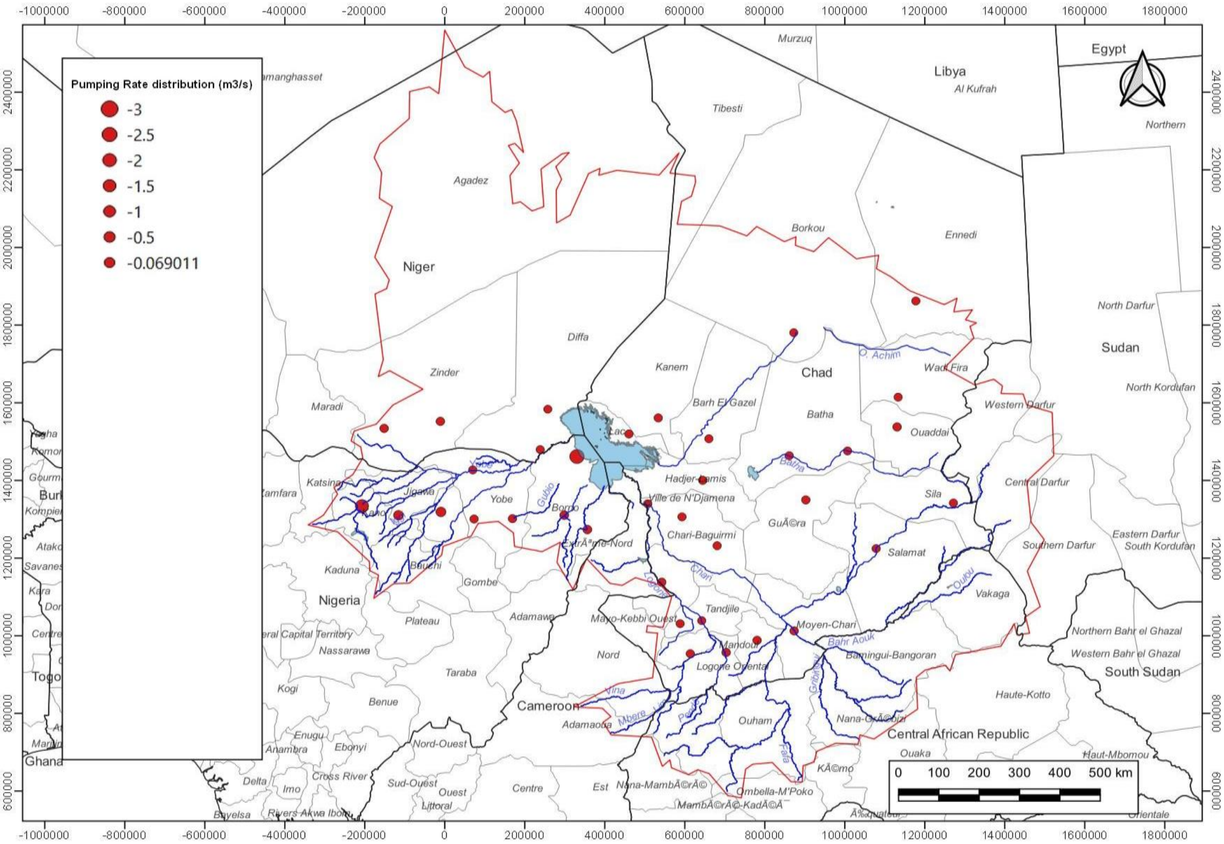


Figure 40. Water abstraction locations and pumping rate (m^3/s).

3.3.5. Surface Water

The main rivers in the basin, namely Chari, Logone, Komadougou Yobé and tributaries, Lake Chad and Lake Fitri, as well as other surface waters interacting in the model domain, such as the Maga Dam, were also included in the modeling.

Due to the model domain's large scope, other surface water bodies (of a limited size or ephemeral in nature) did not significantly influence simulations. The considered elements are found in figure 41.

The riverbed elevation along its longitudinal profile was obtained from SRTM30 DEM. Although this approach is a simplification of the real system's complexity, it provides an initial estimation for river-groundwater interactions assessment. A constant water level was defined for lakes and dams. According to the average Lake water level for the selected time period (2008-2011), a constant head of 280 m was applied in the simulations.

For modelling rivers and lakes, the River (RIV) Package (Head-dependent flux Package) was applied and the flow-dependent conditions were employed.

Table 9. Pumping rates and areas (well-fields) as adopted in the model.

Location	Pumping rate (m^3/s)	Location	Pumping rate (m^3/s)
Borkou	-0.069	**Yob.e (3)**	-0.255
Diffa	-0.077	**N'Djamena**	-0.267
Diffa (2)	-0.077	**Lac**	-0.288
Wadi Fira (2)	-0.165	**Guera**	-0.335
Ennedi	-0.165	**Hadjer_Lamis**	-0.348
Tandjile	-0.100	**Moyen Chari**	-0.357
Tandjile (2)	-0.100	**Mandoul**	-0.375
Bahr El Gazal	-0.107	**Ouaddai**	-0.417
Salamat	-0.117	**Mayo Kebbi est**	-0.442
Sila	-0.137	**Logone Oriental**	-0.444
Batha	-0.156	**Zinder**	-0.451
Batha (2)	-0.156	**Zinder (2)**	-0.451
Chari Baguirmi (2)	-0.176	**Borno**	-0.680
Chari_Baguirmi	-0.176	**Borno (2)**	-0.680
Logone Occidental	-0.206	**Jigawa**	-1.353
Kanem	-0.242	**Bauchi**	-1.518
Yobé	-0.255	**Kano**	-3.031
Yobé (2)	-0.255	**Around Lake (SW)**	-3.168

The RIV package was used for the boundaries, in which the flow into or out of the groundwater system is a function of the head. Establishing a proper value for Conductance depends on riverbed materials; however, no detailed data from the riverbed are available. More hydrologic data on the Chad river system are needed, such as the thickness of riverbed materials, its conductance and river water sheet thickness. Nevertheless, the conditions that correctly satisfy the system were established by assigning conductance values depending on the geological materials of the river, and by estimating an average river depth.

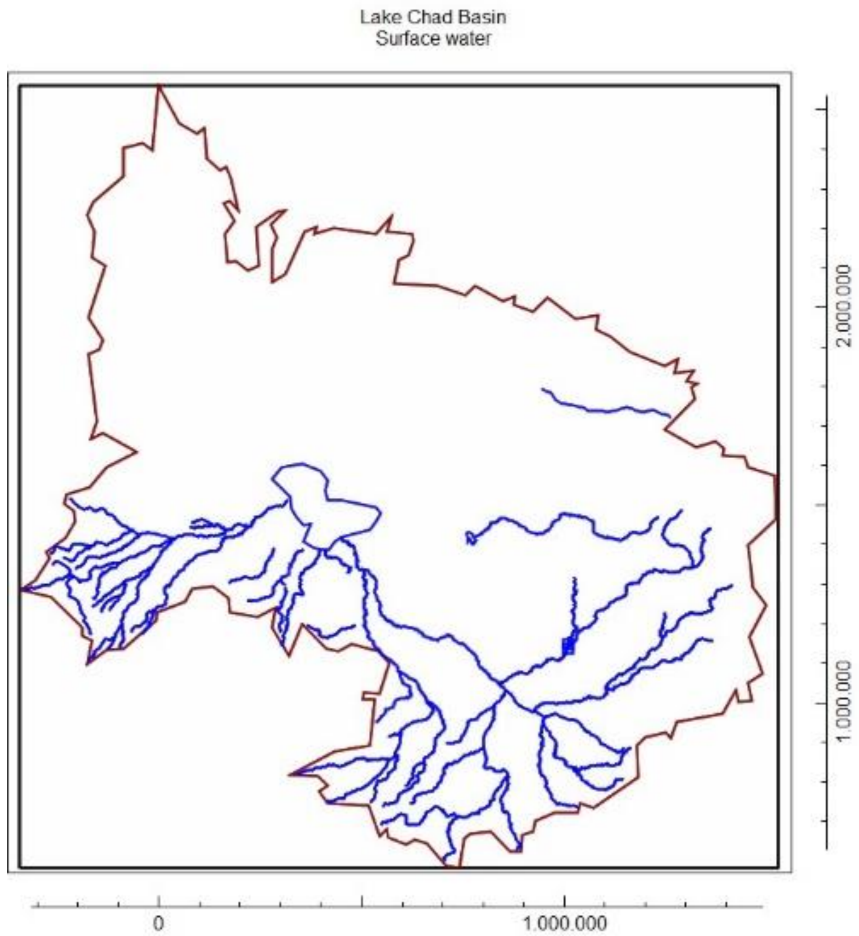


Figure 41. Rivers, lakes and dams taken into account in the model.

3. 4. Model Calibration

For a groundwater model to be used in any type of predictive role, it must be demonstrated that the model can successfully simulate the observed aquifer behavior. Calibration is a process wherein certain model parameters, such as recharge and hydraulic conductivity, are altered systematically and the model is repeatedly run until the computed solution matches the field-observed values at an acceptable level of accuracy (www.aquaveo.com).

The final estimates of the hydraulic parameter values were obtained through model calibration based on the observed values of the piezometric heads (Fig. 19, 42).

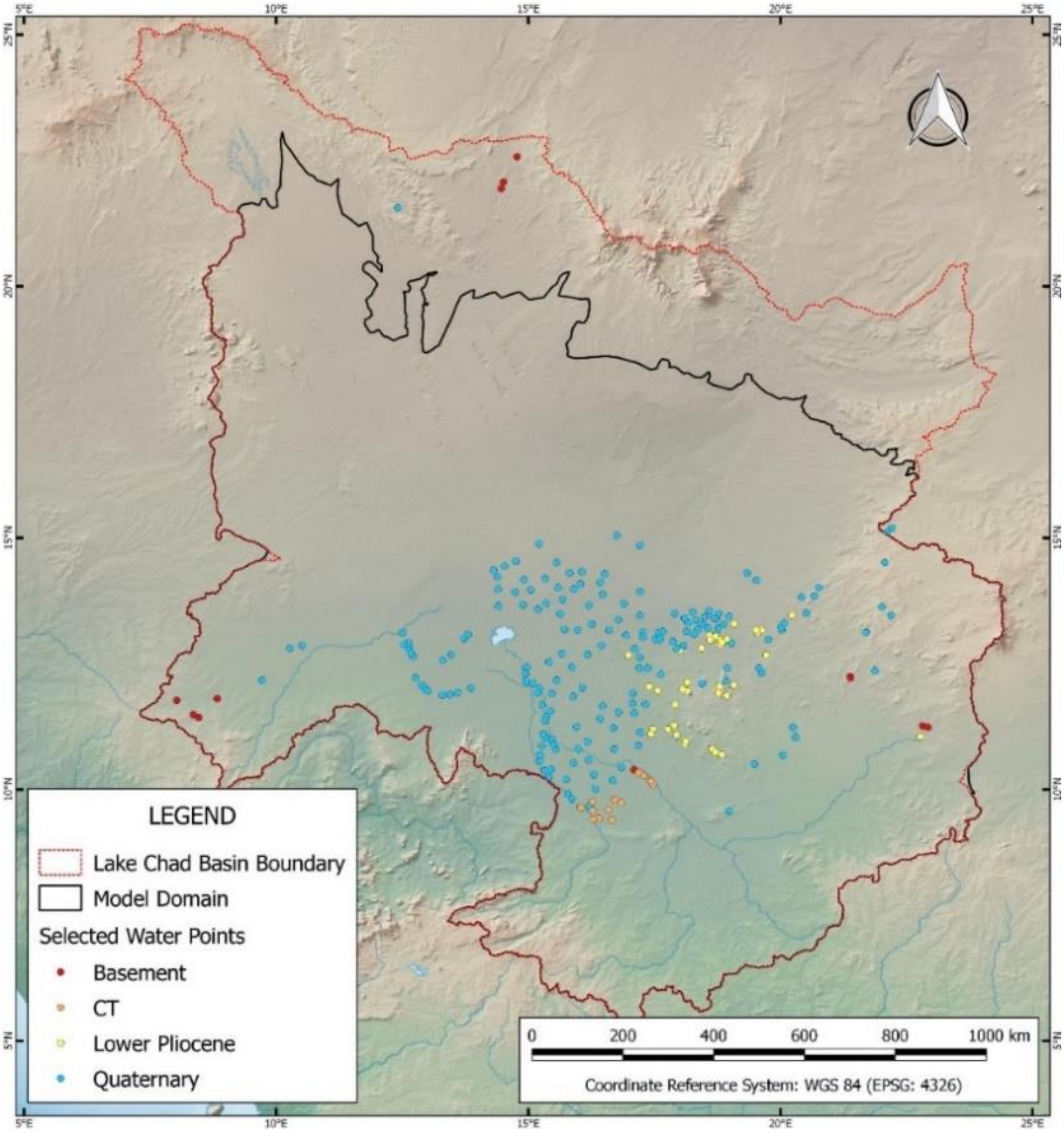


Figure 42. Wells with groundwater level observations for the 2008-2011 period. Aquifers and wells with existing piezometric data used in modeling.

Calibration was carried out by modifying the hydraulic conductivity values of each hydrostratigraphical unit, and then locally modifying the hydraulic conductivity of some specific areas to minimize the differences between the observed and simulated piezometric heads. The results are shown in Table 10. For the vertical hydraulic conductivity values (k_z), the k_x/10 ratio applies.

Table 10. Initial hydraulic conductivity values (m/s) and values adopted after calibration.

	Initial kx (m/s)	Calibrated kx (m/s)
Quaternary	0.008	0.001

Upper Pliocene	1 E-7	1 E-8
Lower Pliocene/CT	0.002	0.002
Basement	1 E-4	5 E-6

In order to take into account the existing flow conditions in Chari-Baguirmi and the Bornou depression, and by also assuming that groundwater flows toward the northern basin zone (north of Kanem), the model included a layer with higher hydraulic conductivity values to act as a draining layer from those singular areas.

To simulate the existing flow conditions in the Chari-Baguirmi depression (Fig. 19), the assumption was that the groundwater flow moved toward the northern basin zone (Bodelé, north of Kanem), where a minimum topographic elevation in the basin of 165 m (Fig. 43) exists. To this end, the model definition included a layer of high hydraulic conductivity (an adopted hydraulic conductivity value of 0.05 m/s) at a depth of 40 m to act as a draining layer from the old MegaTchad extension in the Chari-Baguirmi and Bornou areas which, according to paleostratigraphical data, could result from sediments deposition during the ancient Mega Chad Lake. High evapotranspiration levels appears in the northern basin part. In the model, a CHD boundary condition was imposed in this depressed area for simulations.

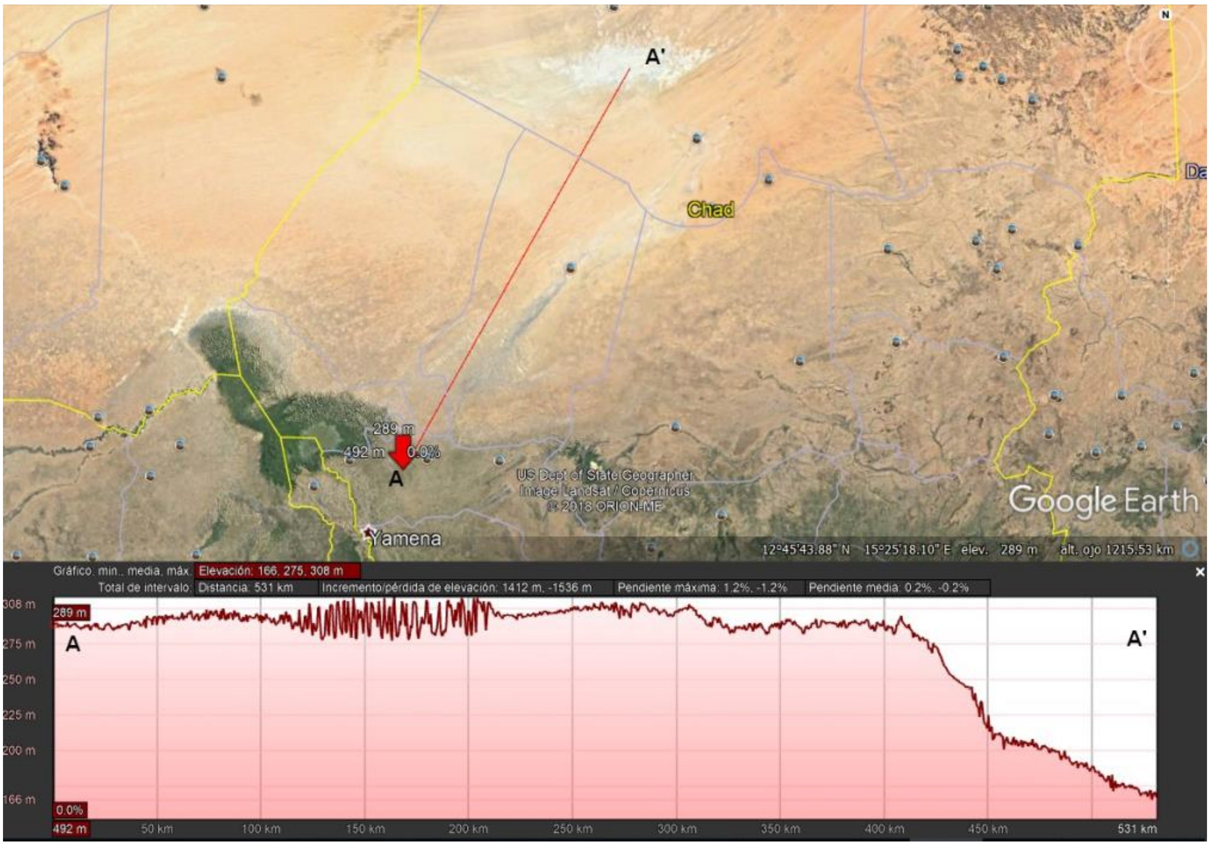


Figure 43. Topographic profile from the Chari-Baguirmi area to the North topographic depression (A-A').

Finally, the hydraulic conductivity values are those presented in figure 44.

The simulated *vs* observed groundwater heads in piezometers are illustrated in Fig. 45. The model's initial conditions in the simulations was the observed piezometric level for the 2008-2011 period (Figs. 19).

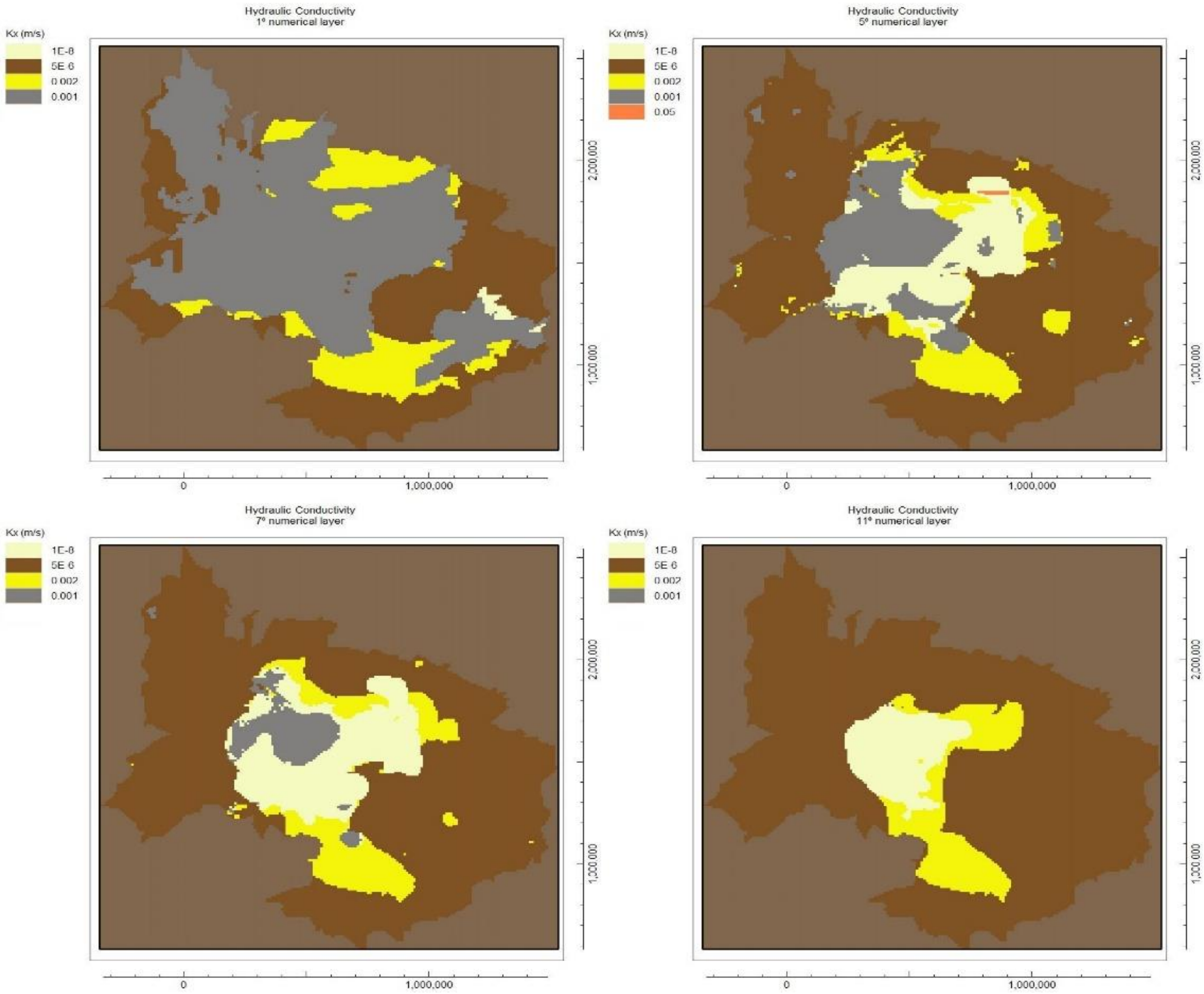


Figure 44. Adopted hydraulic conductivity values (m/s) after calibration. a) 1st numerical layer; b) 5th numerical layer; c) 7th numerical layer; d) 11th numerical layer.

To assess model calibration results the root mean square (RMS) statistics of residuals was applied. The RMS residuals, a good indicator to evaluate the performance of the of the simulation, indicates the standard deviation of the residuals or how far points are from the regression or modeled line.

In the initial runs, the root mean square residual value was about 32.41 m. After a first calibration, the residual RMS was 25.4 m. In the final simulations, the result was 18.38 m, while the dispersion of the positive and negative residuals was more uniformly distributed (Fig. 45). This last obtained value is acceptable when considering the model's dimension and the amount of available data.

Figure 46 presents the distribution of the residuals in different wells after model calibration. The “positive residuals” indicate the observed level higher than the simulated one; "negative residuals" are the opposite. As seen in the figure, more negative residuals concentrate mainly in the areas where a piezometric depression exists and heterogeneity is higher.

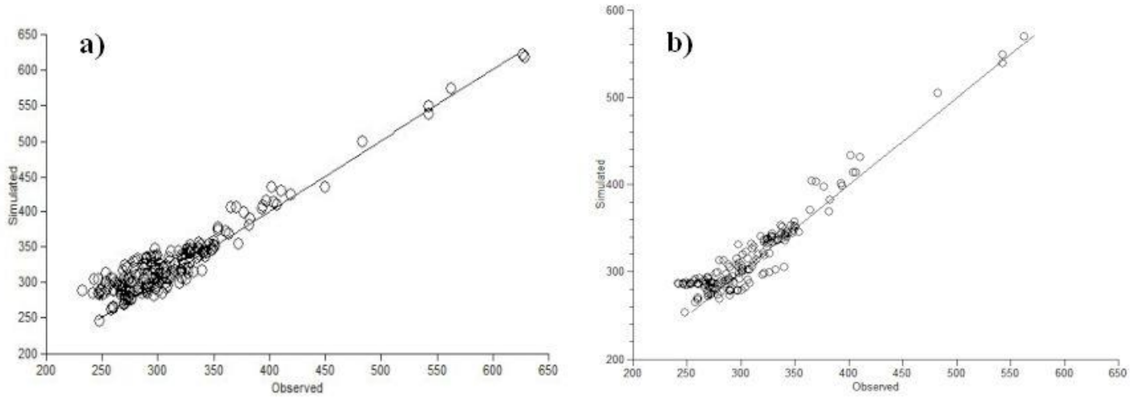


Figure 45. Residuals a) before and b) after calibration

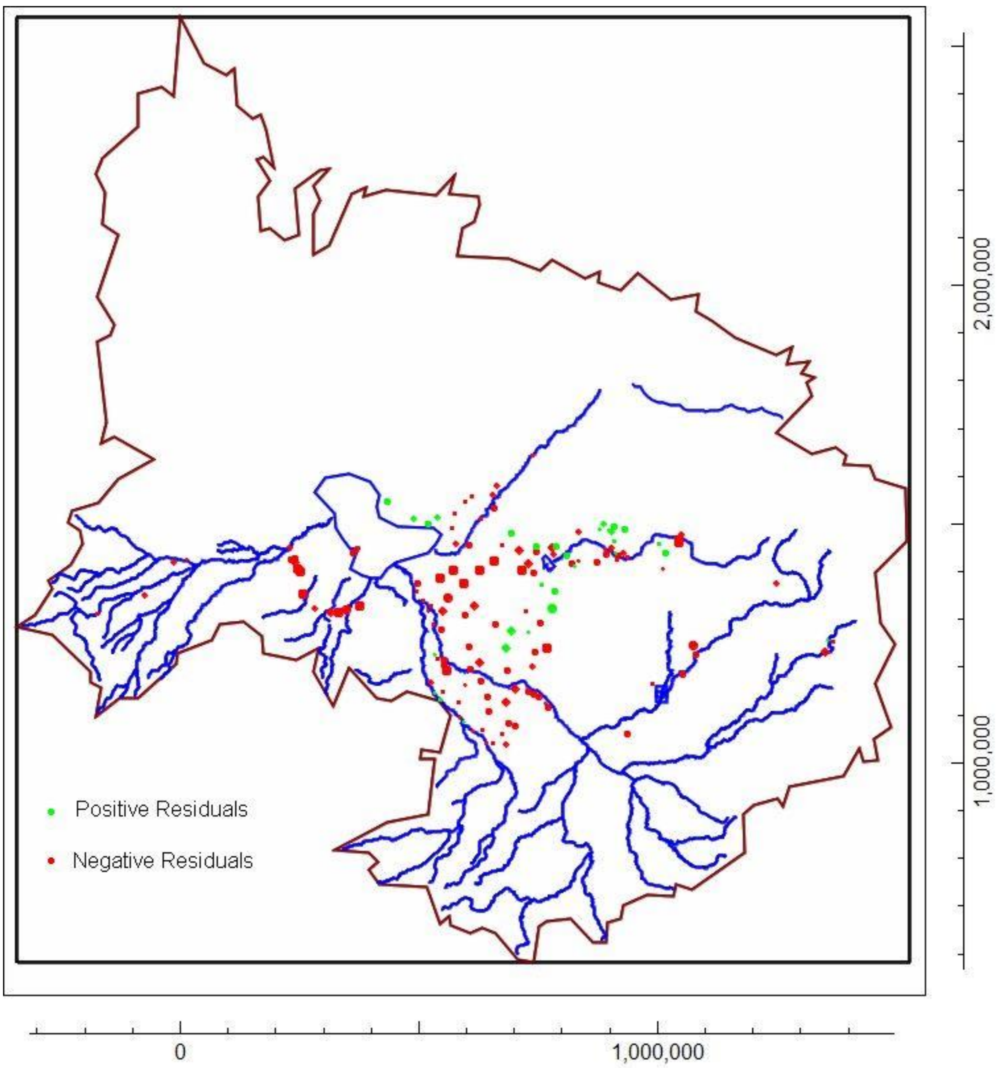


Figure 46. Final piezometric level residuals (positive and negative, see the text) of the observed *vs.* simulated values.

3. 5. Results

For the study period (2008-2011), the groundwater level and water balance for the surficial aquifer and *LPli-CT* were obtained from the model runs and are herein presented below and in Annex G.

The results are presented for the unconfined aquifer (at a 40 m depth layer) and for the semiconfined aquifer (at 250 m depth layer) in appendix G. They correspond to the more representative depth for the unconfined and the semi-confined aquifer, respectively.

The model groundwater balance outputs in figure 47 show that the difference between input and output is only 0.05 Mm^3/yr (accounting for 0.025%) of the budget difference.

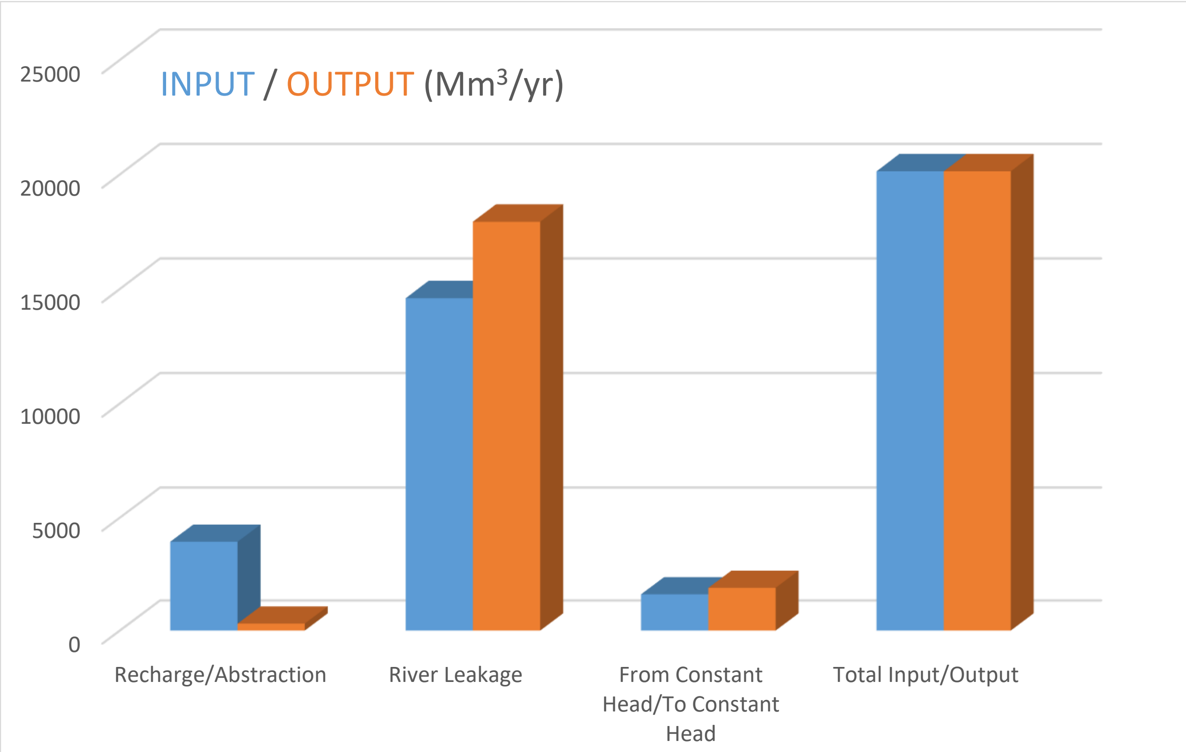
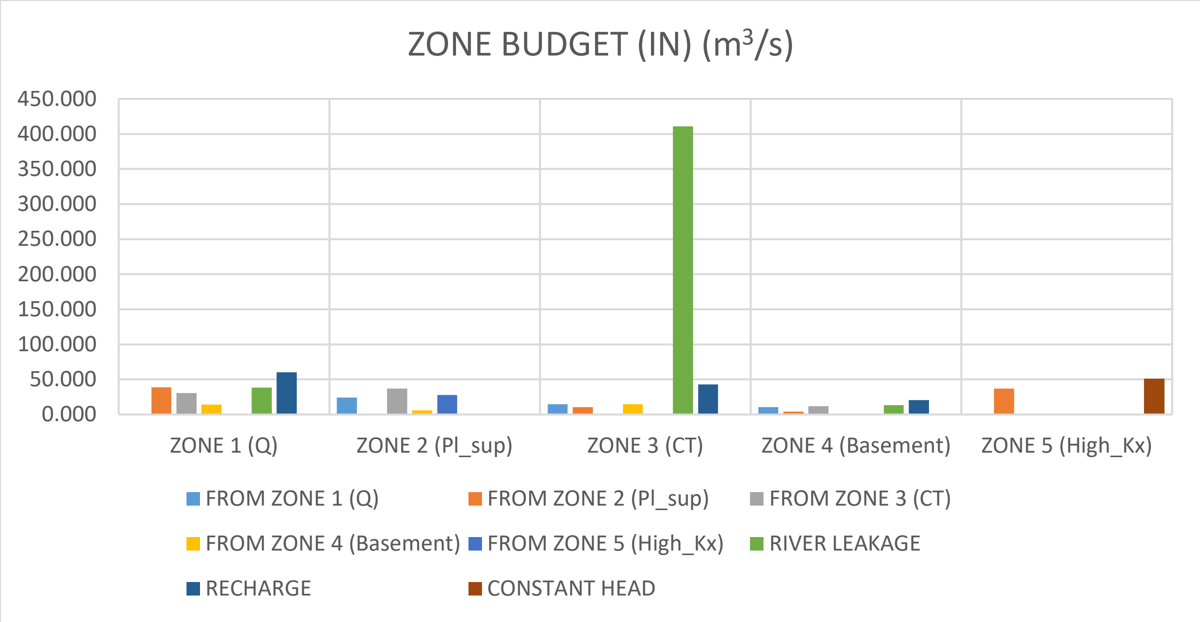


Figure 47. Model groundwater budget. Input and output

The water budget between the different hydrostratigraphical layers and the rivers-lakes interaction from calibrated model are represented in Figure 48 and Table 11. Obtained results are within the range of values of the tentative balances of Tables 5 and 6.



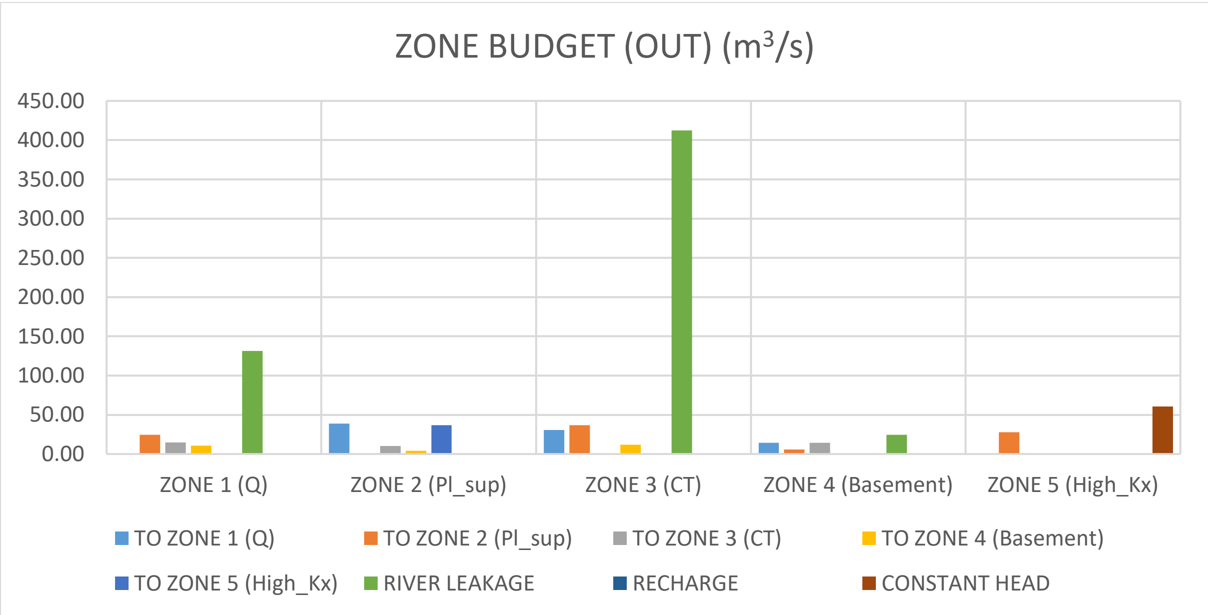


Figure 48. Balance calculation between the defined stratigraphical layers and rivers (inputs and outputs)

The simulated groundwater level for the surficial aquifer (unconfined) is in figure 49. As see in Fig. 49, regionally the unconfied aquifer groundwater level is reproduced; each image represents the first 4 model layers (real depth for each layer is 8 meters). The regional flow goes from SW to NE, aquifer discharge is to the basin’s central part and into rivers; domes and depressed areas are reproduced on the groundwater level map. Regionally, the simulated groundwater levels are reasonably accurate considering the scarce data availability for model construction and the working scale. It is important to consider the interpolation of the DEM elevation made by ModelMuse to adjust it to a 10x10 km cell.

Table 11. Model water balance for defined stratigraphic layers.

QUATERNARY

Input	Mm³/yr	Output	Mm³/yr
Recharge (precipitation and irrigation return)	1,891	**Pumping**	39
Upper Pliocene	1,229	**Upper Pliocene**	768
From LPli/CT**	960	**To** LPli **/CT****	459
Rivers and Lakes	1,214	**To rivers and lakes**	4,138
		To lowland	4
Bedrock and lateral input	449	**Bedrock lateral output**	335

LOWER AQUIFER (Lower Pliocene/continental Terminal)

Input	Mm³/yr	Output	Mm³/yr
Recharge (precipitation and irrigation return)	1,356	**Pumping**	65
Quaternary	459	**Quaternary**	960
Upper Pliocene	328	**Upper Pliocene**	1,161
Rivers and Lakes	12,958	**To rivers and lakes**	13,000
Bedrock and lateral input	457	**Bedrock lateral output**	371

A comparison between the simulated and observed values in Figure 19 (hydrogeological section) shows the agreement between them. However, the simulated values are higher in the depressed areas than those measured in Chari-Logone and Bornou. Nevertheless, due to the steady-state modelling conditions, the system indicates an end state with absence of piezometric depressions.

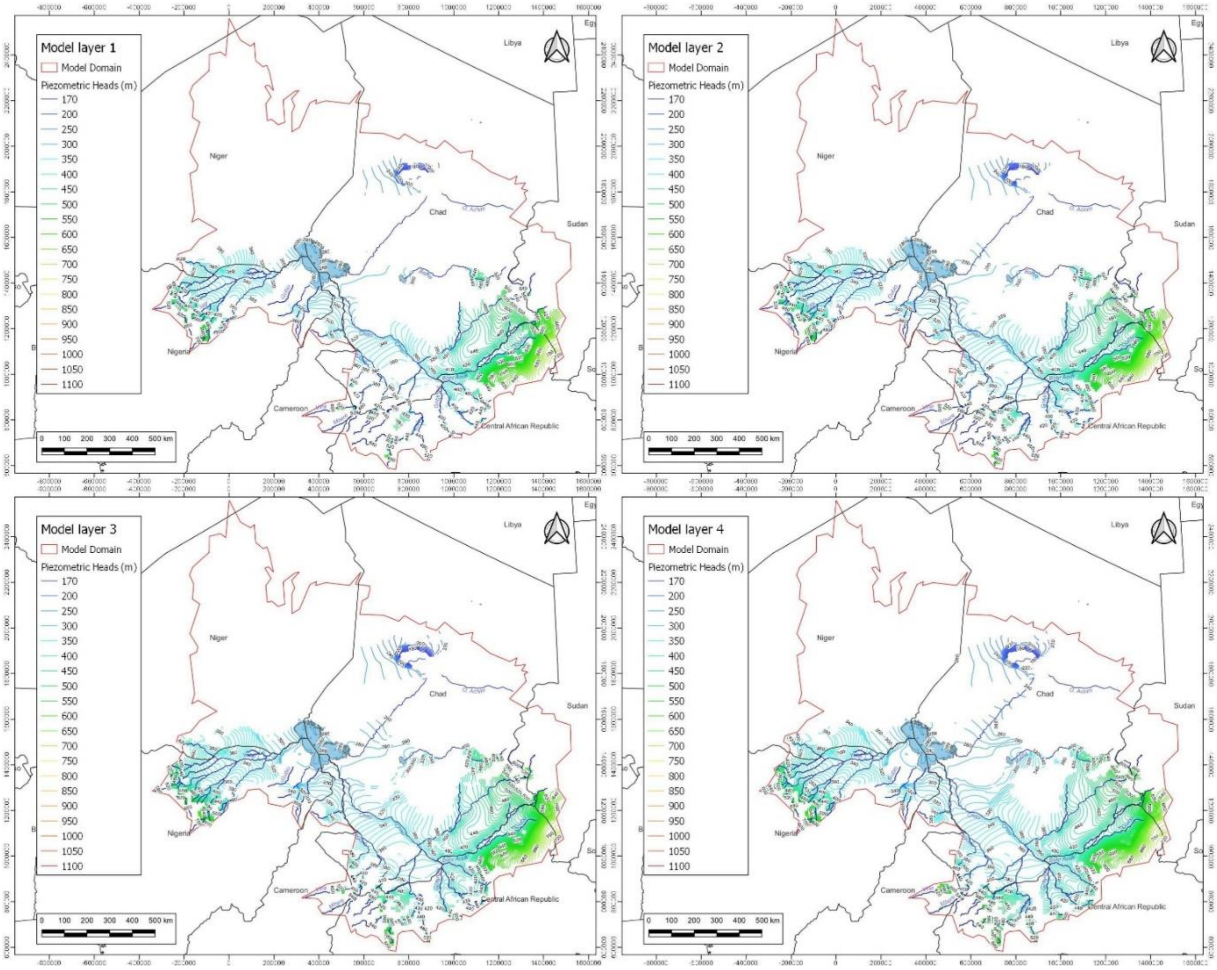


Figure 49. Unconfined aquifer: the simulated piezometric level.

The values in the Logone River seem correct and are slightly higher in the Chari River (Fig. 50). In the areas farthest from the lake in the Komadougou-Yobé river (only 4 data points), the results appear to be acceptable, with an error less than 10 m (data inexistence and grid size needs to be considered, Fig. 51).

As for the Lower Pliocene/Continental terminal aquifer simulations (Appendix G, Fig. G2 to G4), comparison between simulation and observations is not possible due to scanty observations except for areas where some observation points exist where the simulated results present an acceptable behavior. In the northern topographic depressed area of the domain, the model indicates that evaporation does not appear to substantially control the presence of groundwater.

By simulating rivers as a CHD boundary condition, the areas close to the river's upper course became flooded. The modification and adjustment of these conditions by changing the package to the more adequate River package presented a better interaction with the system, and a more accurate steady-state condition along the river course in the whole basin.

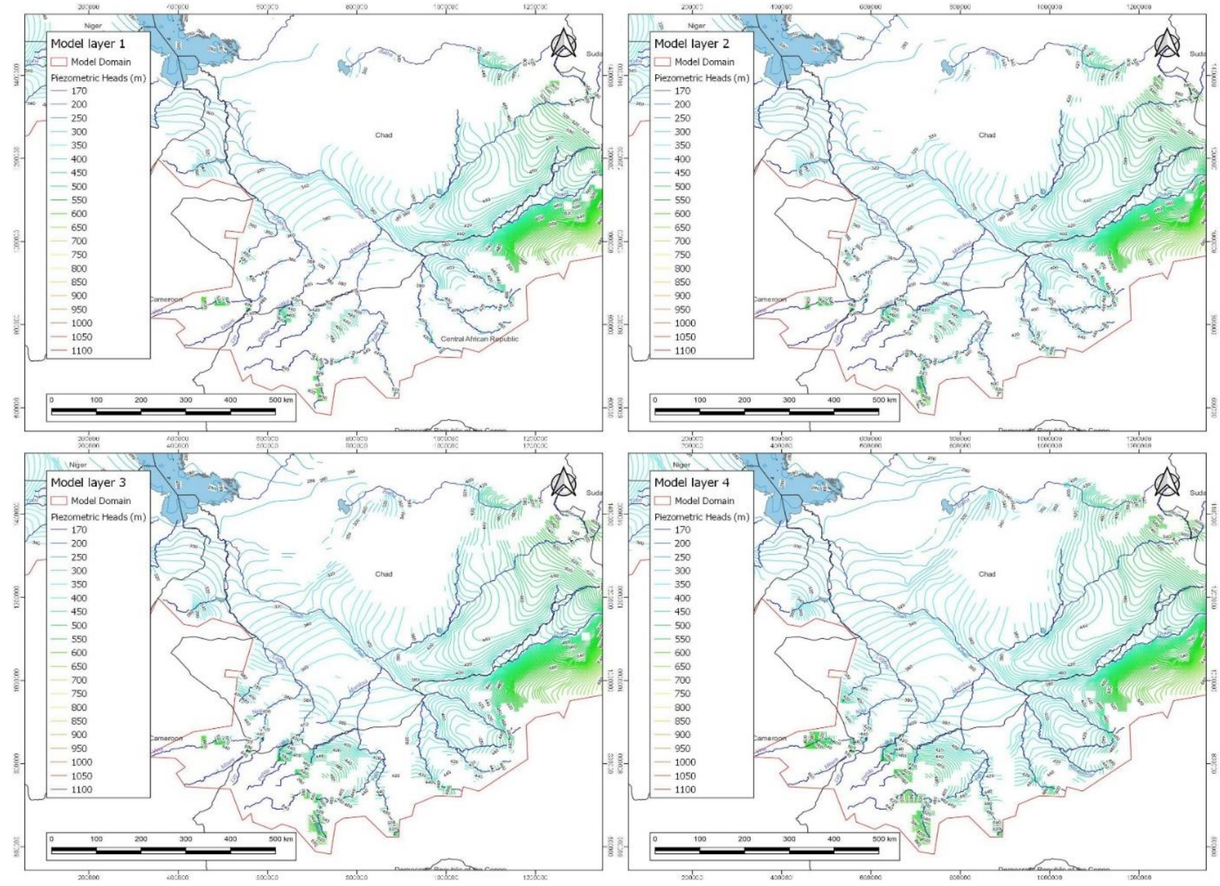


Figure 50. The Chari-Logone area unconfined aquifer. The simulated piezometric level.

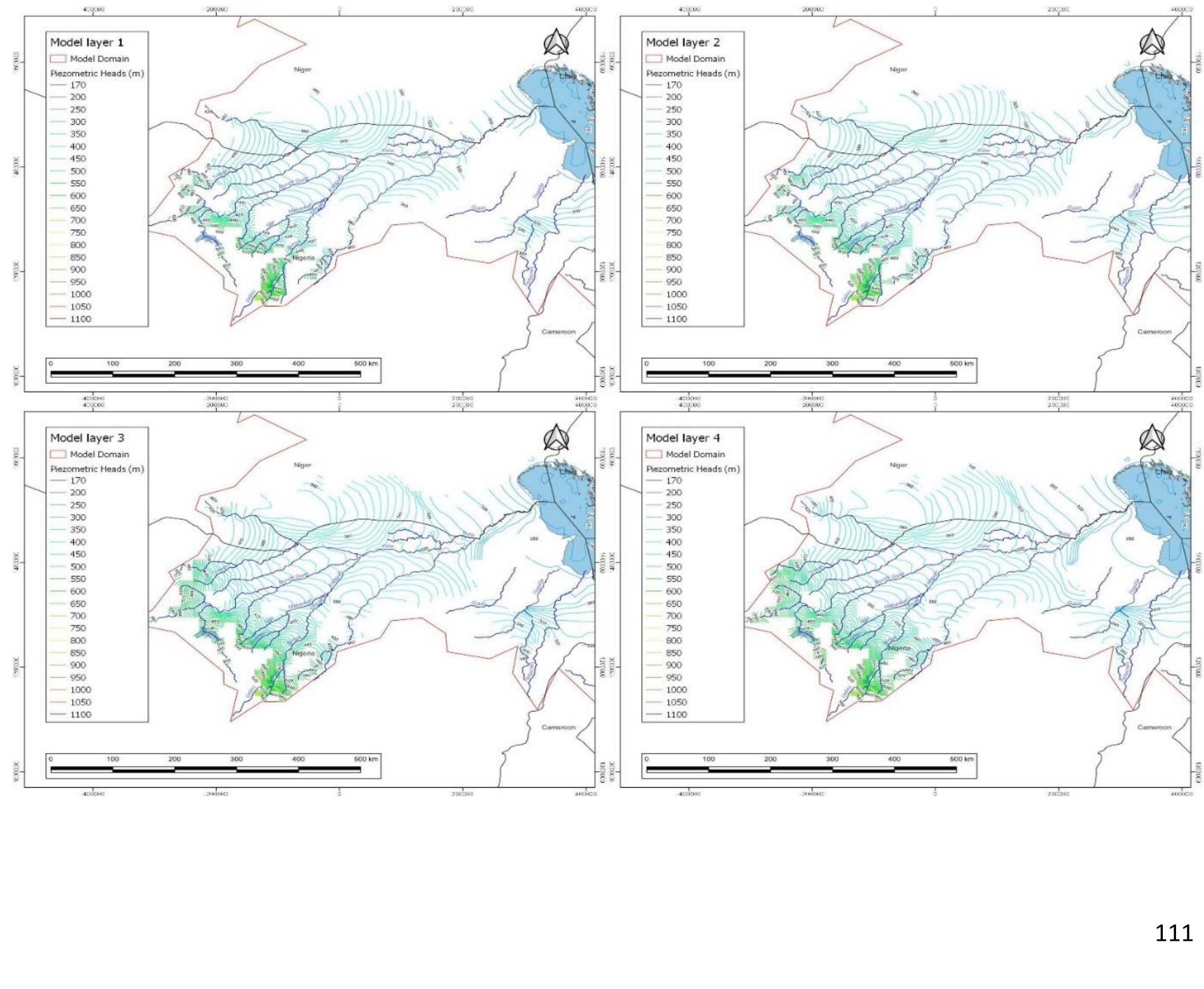


Figure 51. The Komadougou-Yobé area unconfined aquifer. The simulated piezometric level.

3.6. Sensitivity analysis

The objective of the sensitivity analysis was to identify the input data and model parameters that most significantly affect the model's results. The adopted approach will serve as a guide as to how the system changes when modifying inputs, and to identify the factors that mostly contribute to the model's output variability. However, further research is necessary to enhance model performance.

In this particular case, the sensitivity analysis was carried out by modifying the parameters 'recharge and water abstraction' in the calibrated model (baseline) by different amounts and making a comparison of the obtained results (groundwater level) to the baseline data. The model runs include: *a*) 10% of recharge reduction; *b*) 10% increase in water abstractions; *c*) 10% recharge decrease and 10% increase in water abstraction.

Regionally, the results indicate that the piezometric levels are not highly sensitive to a 10% reduction in the net recharge (a) or to a 10% increase in water abstraction, (b), as seen in Figure 55. Changes in recharge rates were much more sensitive compared to changes in water abstraction which represents a small part of the budget. Nevertheless, this change was not excessively marked.

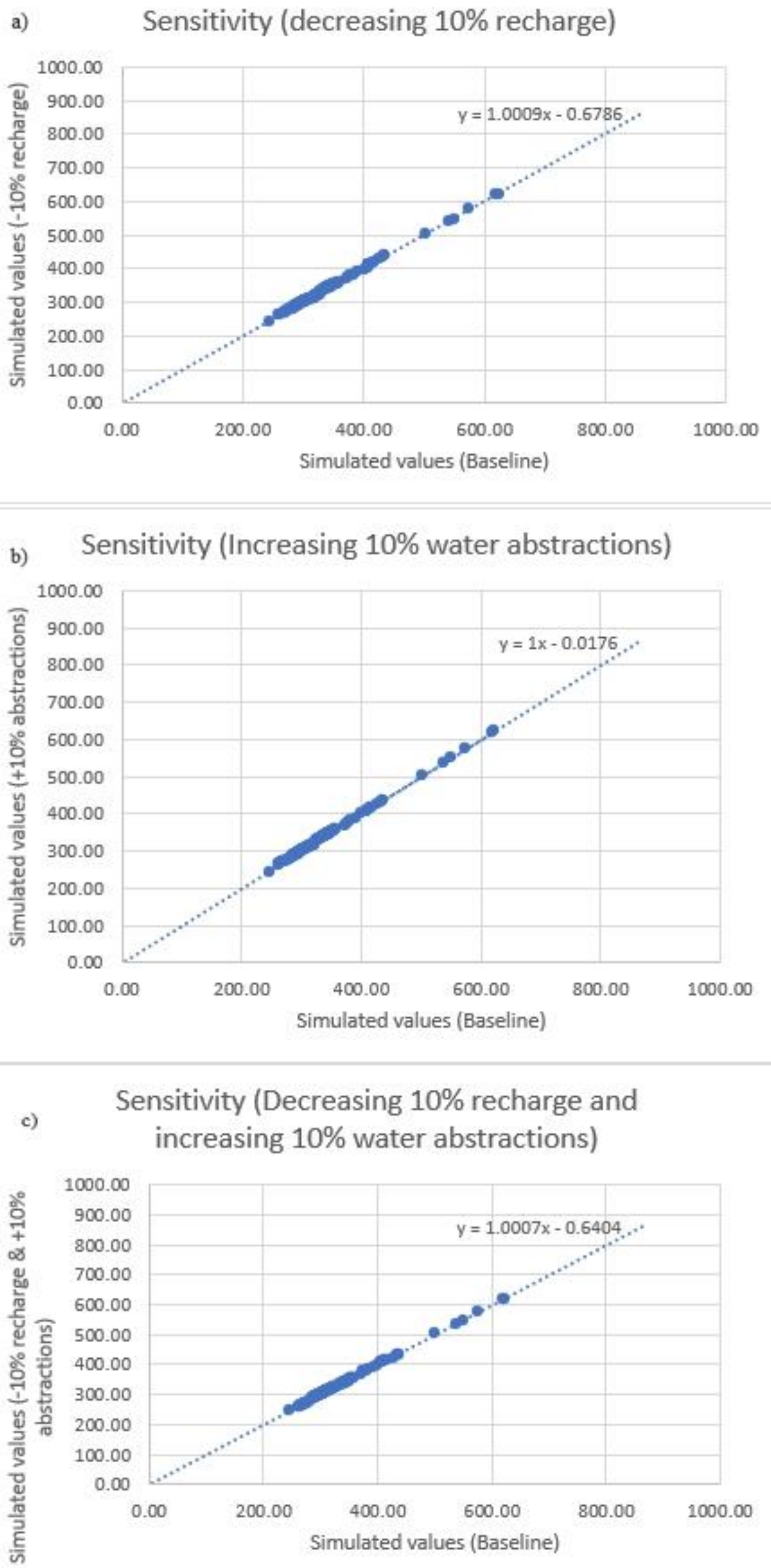


Figure 52. Unconfined aquifer. The baseline simulated groundwater levels *vs.*: a) levels for a 10% decrease in the recharge rate; b) levels for a 10% increase in the water abstraction rates; c) decrease in recharge and increasing water abstractions.

When recharge and abstraction (c) were simultaneously considered (10% decrease in recharge and 10% increase in abstraction) similar values were obtained as for (a) case (10% decrease in recharge), which indicate the importance of recharge in the modeled area which also supports the model's robustness.

In general terms for the defined model, output was not very sensitive to the proposed changes, but the biggest differences were found in the areas where no observation points were available. Nevertheless, it is worth mentioning that changes in the results were observed according to the perturbations applied to the aforementioned parameters.

3.7. Model limitations and recommendations

The steady-state model was developed based on new information from hydrogeological research works since 2005, and it is important to recognize limitations when using it. The model has its limitations due to current existing information on the working scale and hypothesis not fully validated in the conceptualization. Some hydrogeological and hydrological features were simplified to reflect the model's needs.

The working scale applied for the Chad Formation's regional modeling may limit its use as a predictive tool for groundwater local effects in, for example, the Borno area. The defined model grid is quite coarse and cannot be refined beyond 10x10 km per cell due to computational and data limitations. For specific groundwater issues, local numerical models, based on boundary conditions at the basin level, should be developed in areas of interest.

The upper aquifer (unconfined) and the Lower Pliocene/Continental Terminal (semi-confined) were modeled. As information is scarce for modeling the confined part of the aquifer, composed of the Lower Pliocene and the Continental Terminal, the model for these hydrostratigraphical layers is even more uncertain and the model's results are also much less reliable.

In this study, acceptable total groundwater abstraction estimates for the baseline simulation were obtained, but the groundwater abstracted at specific local point allocations would facilitate better calibration. The spatial point distribution of the groundwater abstraction wells would provide more accurate results.

Natural recharge zones and rates were previously defined using a distributed model, and are based on the best available information. The approach is based in a physically robust process for recharge estimation, but there is some associated uncertainty owing to the time series of groundwater levels not being available on the regional scale. The time series of the groundwater level (if provided) could be used to improve the hydrological parameters calibration in order to reduce this uncertainty.

In general, the model calibration is acceptable in the upper aquifer, this being the main modeling objective. However, the head calibration was not ideal in the depressed areas (Chari-Baguirmi; Komadougou-Yobé) with a poorer match between the simulated and observed heads.

Under a steady-state model condition on the basin scale, it was not possible to reproduce existing piezometric depressions without including exfiltration processes or other mechanisms capable of extracting groundwater from the system. This phenomenon is difficult to explain naturally as the groundwater depth is about 40 m. For the steady solution, the more accurate way to represent current conditions is by imposing a singularity to the model, based on the theoretical approach of the groundwater deep drainage to the basin's northern part (Fig. 43). However, such singularity is not yet fully validated conceptually or at the numerical level, as several conceptual explanations exist among professional partners and more research and data are needed to fully establish agreement in the interpretation of this phenomenon.

More information about the river network characteristic in the whole basin is necessary as it is particularly relevant in groundwater-river interactions. The input need is related to the watershed, riverbed geologic materials and seasonality. More accurately establishing how rivers are numerically defined will help to improve this large-scale model.

4. CONCLUSIONS and RECOMMENDATIONS

The efforts presented in this report attempt to integrate data and knowledge across the basin and from past hydrogeological work in different parts of the basin, creating an integrative and basin-wide understanding of groundwater resources and their dynamics. This integrative understanding, concretized with an updated conceptual model and the start of a basin-wide numerical model, is the foundation for the development of an integrative tool which can inform planning and management decisions under future development and climate conditions. This work also provides an understanding of the spatial uncertainties in both the model and the data.

Current modeling efforts included updating the groundwater dynamics conceptualization and model development of the Chad Basin Formation (conceptual model). The conceptual model proposed to support a numerical model was based on the best-available preexisting hydrogeological data for the Lake Chad Basin.

Carrying out calibration was complex because of data scarcity in certain areas and the model's large scale. In the domain areas where piezometric depressions were observed (SW of Lake Chad and the Chari-Baguirmi area), it was not possible to accurately reproduce the hydrogeogical conditions. A second model, based on the exfiltration concept for piezometric depressions simulation, is presently an ongoing work. The adjustment of the conceptual model (e.g. the paleo-channel draining the Chari-Baguirmi piezometric depression) or of the geometrical discretization of the lithological units (e.g. representation of the aquitard layers and number of model rows per lithological unit) are alternatives which can be tested in the next modelling stages.

The applied sensitivity analysis indicated that the obtained results were as expected for this large scale regional model. The model was not very sensitive to changes in water abstractions as they only took place locally. A more detailed network for water abstractions (with more accurate pumping rates) is needed that would, in turn, provide more accurate results on bigger scales.

By establishing a good 'baseline model', parameters can be modified in such a way that the calculations for different climate (i.e. precipitation, recharge) and development (i.e. irrigation, water use) scenarios would provide results that would come as close as possible to their future impacts.

A better assessment of natural recharge changes and impacts to the basin's water balance would require developing specific hydro-climatic change scenarios using information from General Circulation Models (GCM, IPCC).

As a result of the conducted work, the following outputs were developed:

- Updating the regional hydrostratigraphic framework boundaries of the Lake Chad Basin
- Developing a new hydrogeological map at the basin scale
- New hydrogeological cross-sections
- Updating the interpretation and understanding of the aquifer piezometric level data and a water table contour map for the basin for the 2008-2011 period
- Updating the basin's conceptual hydrogeological model
- Making a preliminary water balance assessment.

The conceptual model's updated geometry was obtained from boreholes with groundwater and stratigraphical information (including deep stratigraphical data) in the entire basin. Four hydrostatigraphic units, water-bearing formations with more or less hydraulic connections, were defined: Quaternary, Pliocene (clays, aquitard), Lower Pliocene, Continental Terminal. Significant data and knowledge gaps can influence uncertainty in the hydrogeological conceptualization. In particular, previous regional-scale hydrogeological assessments covering the whole basin area are lacking, and most previous works focus on the Quaternary aquifer.

The connectivity between the groundwater and surface water systems (exchanges among rivers, lake and aquifers) is likely to exist in some parts of the Chari-Logone and Komadougou-Yobé basins. The reduced streamflow (natural or manmade) of both river systems may further result in the groundwater level in basin areas to sharply drop. The main input to the groundwater system comes from natural recharge; some lateral recharge is also expected from the weathered granite (bedrock) that come into lateral contact with the upper aquifer in the southern part.

Abstractions by pumping are also a groundwater issue for the basin, and the region also has a high, and growing, population. A large amount of water is required to support irrigation requirements. This makes it particularly susceptible to impacts during low rainfall periods.

A summary of the data availability and accuracy obtained through data collection, analyses and the final selection includes the following features:

- Lack of applied irrigation dose and timing. Irrigation-application was estimated according to crop needs in agricultural areas
- Available rainfall and temperature field-based data on a daily scale
- Available reliable land-use and soil-mapping data
- Good quality adequate spatial coverage of the digital elevation model (DEM) to define ground surface elevation
- Metered or current groundwater extraction data are unavailable, based on the demand estimation according to literature

The most important identified gaps are:

- Limited stratigraphic and geophysical data available in the northern and western basin parts to improve the definition of key groundwater parameters and processes
- Widespread (spatial distribution) and detailed information on the thickness, continuity and hydraulic parameters of aquifers is necessary. Characteristics of and hydraulic information on the deep aquifer (LPli-CT) are poorly understood
- Updated and continuous stream gauging data to support base flow analyses and surface-groundwater interactions are necessary
- There are several local studies to help to understand the connectivity between surface water and groundwater with a wide range of variability of their results. Understanding how this interaction affects the hydrologic cycle is crucial
- Groundwater level measurements are not continuous and present important gaps. A monitoring program is lacking. Long-term systematic measurements provide essential data required to evaluate changes in the resource over time
- Observation wells at different depths (nested boreholes) to understand interaquifers connectivity, magnitude and groundwater flow in the hydrostratigraphic units do not exist
- Geophysical surveys and hydrogeological testing are required to determine estimates of vertical gradients
- The water volume estimates required for water balance assessments are poorly constrained, due mainly to the uncertainty of the surface-groundwater interaction

Future hydrogeological studies of the basin should be targeted to collect data to improve current interpretations with main emphasis in the Upper unconfined aquifer. Further work is required to elucidate the hydraulic properties of key aquifers and aquitards, particularly in the southern part of the basin for LPli-CT and to develop a better understanding of connectivity between different hydrostratigraphical units. Additional data are thus required. As new data may become available in the future, the conceptual model for the basin should be appropriately updated.

Recommendations for further actions to fill data gaps are as follows:

- New exploration wells drilling the Upper aquifer (around 150 m to bottom layer) for: extensive coring (lithological logs) to provide representative information on the subsurface aquifer thickness, extent and overlying hydroestratigraphic units; measuring water levels; conducting pumping tests and geophysical logging. It is hardly recommended that new programs for water supply provide in addition this aquifer information including observation wells installation.
- Areas of interest are mainly extending from 15ºN to the North (latitude) and from 13ºE to west, namely: Yobe and Jigawa (Nigeria); Zinder, Agadez, Diffa (Niger). In Southern Chad: Borku, Salamat and Moyen Chari; in central Chad: Kanem, Fitri area and Bodelé

area. Number of drilling test holes in the different areas (ranging from 5 to10 according to local conditions) need to be based in specific site investigations results.

- Subsurface investigation from detailed geologic logs of the encountered sedimentology and stratigraphic sequence (up to 100 m deep) in function of depth through test drilling in the Chari Baguirmi, Komadougou-Yobé and Bodelé areas for depressed areas to ascertain geologic and groundwater accurate conditions.
- Conduct new pumping tests of long duration (fully penetrating wells with simultaneous measurements in observation wells) to determine aquifer hydraulic parameters in the defined areas of interest and new drilled exploration wells.
- Carry out surface geophysical surveys (resistivity N-S transects at the Chari Logone basin) to delineate the contact in depth between the Quaternary and the Continental Terminal. For the proposed new drilled wells, borehole geophysical surveys are also recommended.
- Collect accurate quantitative information (at transects ranging from 50 to 100 km length) of river bed characteristics, river bed longitudinal profile and seasonal streamflow data of the Gubio, Ngadda, Yedseram, El Beid rivers. Data on Lake Chad and Fitri regarding: hydraulic conductivity lakebed, lakebed thickness, evaporation rates, runoff and withdrawals need also to be obtained for modelling purposes.
- Nested observation wells construction for water level monitoring should be placed in the southern part of the aquifer where the Quaternary and the Continental Terminal are under exploitation. Also along the river valley (three to four along river bed, distant maximum of 10-20 km of the river bed) of the Chari-Logone (Moyen Chari), Komadougou Yobé and southern boundary of Lake Chad, where surface water-aquifer exchanges occurs,
- Conduct water level measurements in observation wells for long term systematic measurements to evaluate changes over time, from 15ºN of latitude to south. Observation wells number, location and depth are critical to any water level program; they need to be selected based on field investigations and considering that measurements can be made for an indefinite time.
- The development of a basin-wide groundwater network (on-purpose built piezometers or network redefined), used to regularly monitor water levels and chemistry is suggested. In addition, regional geochemical research to determine groundwater age, residence times, flow paths (including recharge and discharge mechanisms) and connectivity between aquifers would further improve the understanding of the basin’s hydrogeology.

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APPENDIX

APPENDIX A. EXISTING RESERVOIRS AND GAUGE STATIONS
APPENDIX B. WELL LOGS AND GEOMETRY OF BASIN SEDIMENTARY FORMATIONS.
APPENDIX C. HYDRAULIC PARAMETERS.
APPENDIX D. THE GROUNDWATER MAPPING FOR THE 2008-2011 PERIOD.
APPENDIX E. NATURAL RECHARGE ESTIMATION.
APPENDIX F. MODEL PROJECT DATA BASE.
APPENDIX G. NUMERICAL MODEL. LAYERS AND SEMICONFINED AQUIFER SIMULATED GROUNDWATER LEVEL

APPENDIX A. EXISTING RESERVOIRS AND GAUGE STATIONS

Table A1. Reservoir area and storage capacity (LCBC-GIZ, 2016).

Dam	Country	Area (km^2)	Storage (Mm^3)
Alau	Nigeria	50	112.4
Bagadu	Nigeria	3.8	22.1
Birnim Kudu	Nigeria	6.5	1.2
Challawa	Nigeria	100	930
Galala	Nigeria	4.1	23
Gari	Nigeria	13.9	154
Gari	Nigeria	3.7	60
Guzugozu	Nigeria	6.4	24.6
Hadejia	Nigeria	20	14
Ibrahim Adamu	Nigeria	2.6	8
Jakara	Nigeria	16.6	65.2
Kafin Chiri	Nigeria	8.4	31.1
Karaye	Nigeria	2	17.2
Maga	Cameroon	400	625
Magaga	Nigeria	3.7	19.7
Maladumba	Nigeria	2	0
Marashi	Nigeria	2.2	6.8
Mokolo	Nigeria	1	5
Pada	Nigeria	4.1	12
Ruwan Kanya	Nigeria	7.5	0
Tiga	Nigeria	180	1,968
Tomas	Nigeria	15	60.3
Tudun Wada	Nigeria	3.5	20.8
Warwade	Nigeria	5.3	12.3
Watari	Nigeria	19.6	104.5

Table A2. Gauging stations and data span (Chari-Logone, data from LCBC, file provided by CDIG-ResEau).

Name	DB	Period	Data (m^3/s)	Data (cm)	Hydrologic basin (km^2)
N'Djamena	LCBC data	2000-2013	daily, complete		60,0000
	LCBC data	2015	daily, complete		
	LCBC data	1953-2003	monthly, a few gaps		
	LCBC data	2000-2015		daily, complete	
	UNESCO/CBLT	2000-2001	daily, complete		
	UNESCO/CBLT	2001-2002	daily, gaps		
Bongor	UNESCO/CBLT	1974-1975	daily, gaps		73,700
	UNESCO/CBLT	1991-2001	daily, gaps		
Bousso	LCBC data	1936	daily, complete		450,000
	LCBC data	1938-1940	daily, complete		
	LCBC data	1952-1979	daily, complete		
	LCBC data	1982-2003	daily, complete		
	LCBC data	2005	daily, complete		
	LCBC data	1952-2002	monthly, complete		
	LCBC data	1952-2003		daily, complete	
	LCBC data	2005		daily, complete	
	UNESCO/CBLT	1974-1975	daily, gaps		
	UNESCO/CBLT	1991-1997	daily, gaps		
	UNESCO/CBLT	1997-1999	daily, complete		
	UNESCO/CBLT	1999-2000	daily, gaps		
Lai	LCBC data	2000-2009	daily, a few gaps		60,320
	LCBC data	2011-2013	daily, a few gaps		
	LCBC data	1948-2002	monthly, a few gaps		
	LCBC data	2000-2016		daily, gaps	
	UNESCO/CBLT				
	UNESCO/CBLT				
	UNESCO/CBLT				
Moundou	LCBC data	1957-2002	monthly, complete		
	LCBC data	2015		daily, a few gaps	
	UNESCO/CBLT	2000-2001	daily, some gaps		
	UNESCO/CBLT	2001-2002	daily, gaps		
Sarh	LCBC data	2000-2008	daily, complete		193,000
	LCBC data	2013-2015	daily, complete		
	LCBC data	2000-2016		daily, complete	
	UNESCO/CBLT	1999-2000	Daily, some gaps		
	UNESCO/CBLT	2000-2001	daily, complete		
	UNESCO/CBLT	2001-2002	daily, gaps		

Table A3. Gauging stations and data span (Komadougou-Yobé, data from LCBC, file provided by CDIG-ReSeau).

Name	Data					Hydrologic basin (km^2)
	Country	Database	Period	Data (m^3/s)	Data (cm)	
Bagara-Diffa	Niger	LCBC data	1996-1998		daily, gaps	115,000
		LCBC data	2000-2005	daily, gaps	daily, gaps	
		LCBC data	2000-2018		daily, complete	
Bosso	Niger	LCBC data	2009	5	5	115,000
Geskerou	Niger	LCBC data	2009	5	5	
Chiromawa	Nigeria	IUCN	1964-1992	monthly, complete		
Challawa gorge	Nigeria	IUCN	1971-1991	monthly, a few gaps		
Bunga	Nigeria	IUCN	1964-1995	monthly, complete		

APPENDIX B. WELL LOGS AND THE GEOMETRY OF BASIN SEDIMENTARY FORMATIONS

To characterize the geometry of the basin and aquifer system delineation, datasets on water-well points (boreholes, wells, observation wells), obtained from projects since 1965, have been analyzed. Provided records and observations of groundwater interest are highly variable, and range from deep oil-exploration boreholes (more than 3000 m deep) to shallow excavated wells. Generally, borehole geo-localization refers to a village name and elevation is not reported. Further estimates of geographical coordinates (X, Y) were based on searching maps for the place or village name, and soil surface elevation (m.a.s.l.) was obtained through a SRTM30 DEM (https://earthexplorer.usgs.gov/). Doubtful data were discarded.

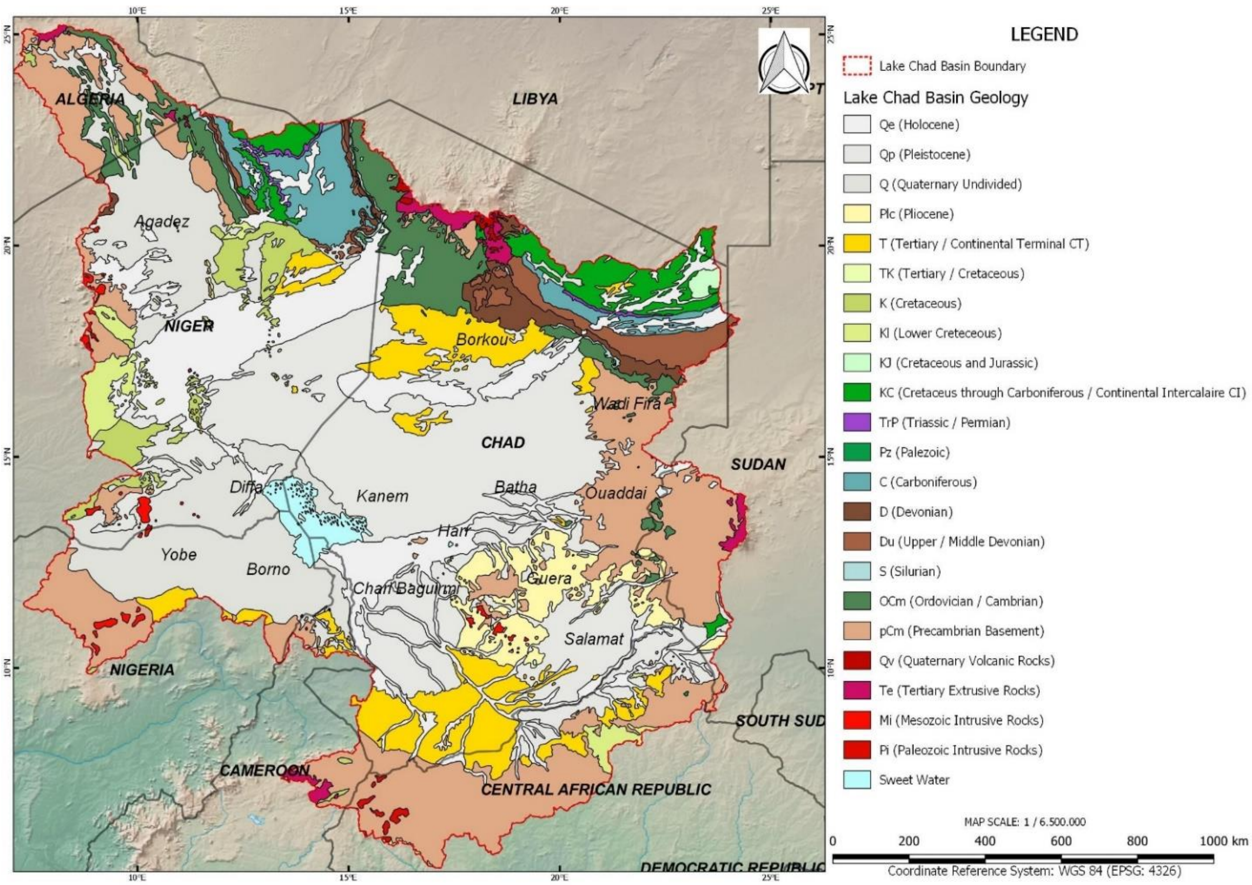

Figure B1. Geology of the basin area (compiled from various sources, USGS, BGS, BGR). The red line indicates the Lake Chad Hydrologic Basin.

The three-dimensional architecture of the basin was generated by the identification and definition of hydrostratigraphical units, and by the establishment of the geologic correlations between them.

In order to gain a better understanding of the subsurface hydrogeology, mapping was undertaken using lithological logs along with geophysical information and the RockWare geomodel (Rock Works 17). This software allows to further directly download stored information (layers definition and thickness) for aquifer modeling. Geologic digital mapping of the basin area was done while the project was underway (Fig B1) based on the GIS shapefiles collected from the BGS platform (http://earthwise.bgs.ac.uk) to further delimit the study area domain.

The basis for constructing a 3D conceptual geologic model was to analyze the geological/stratigraphical logs from the only representative boreholes after data base screening. The spatial distribution of the 430 selected boreholes with lithological logs (Table B1) in the study area is plotted in Fig. B2. Table B1 also indicates the maximum depth reached by drilling. The deepest depth corresponds to oil explorations. Regrettably, the geologic subsurface information coverage of the sedimentary package (lithological logs) for basin characterization purposes is almost nonexistent from the north of Lake Chad to the northern border of the hydrogeological system (Tibesti and Niger), which would considerably enhance geological knowledge.

A summary of the bore logs distribution shows that: 131 logs present only information on the Quaternary aquifer; 128 contain detailed geological and hydrostratigraphical descriptions for the Lower Pliocene (LPli) and CT aquifers; only 51 showed that wells were drilled during all the three water-bearing formations.

Table B1. Geological logs selected from existing subsurface geology campaigns.

Campaign	Number of boreholes	Average depth (m)	Maximum depth (m)
Schneider, 1989	50	305.5	673
BGRM	57	752.6	4261
10FED	48	67.5	107.9
9FED	35	71.8	96
Hydraulique Pastorale	13	95.5	156
Nigeria	70	249.2	1,044
Ouaddai	17	52.7	69
Sila	50	41.6	61
Wadi Fira	16	38.3	49
Moussoro	5	46.5	48
Bokoro	38	78.8	121
Koweit	3	135.8	149.5
Tibesti	5	14.5	20
Mayo Kebi	23	25	62
TOTAL	430		

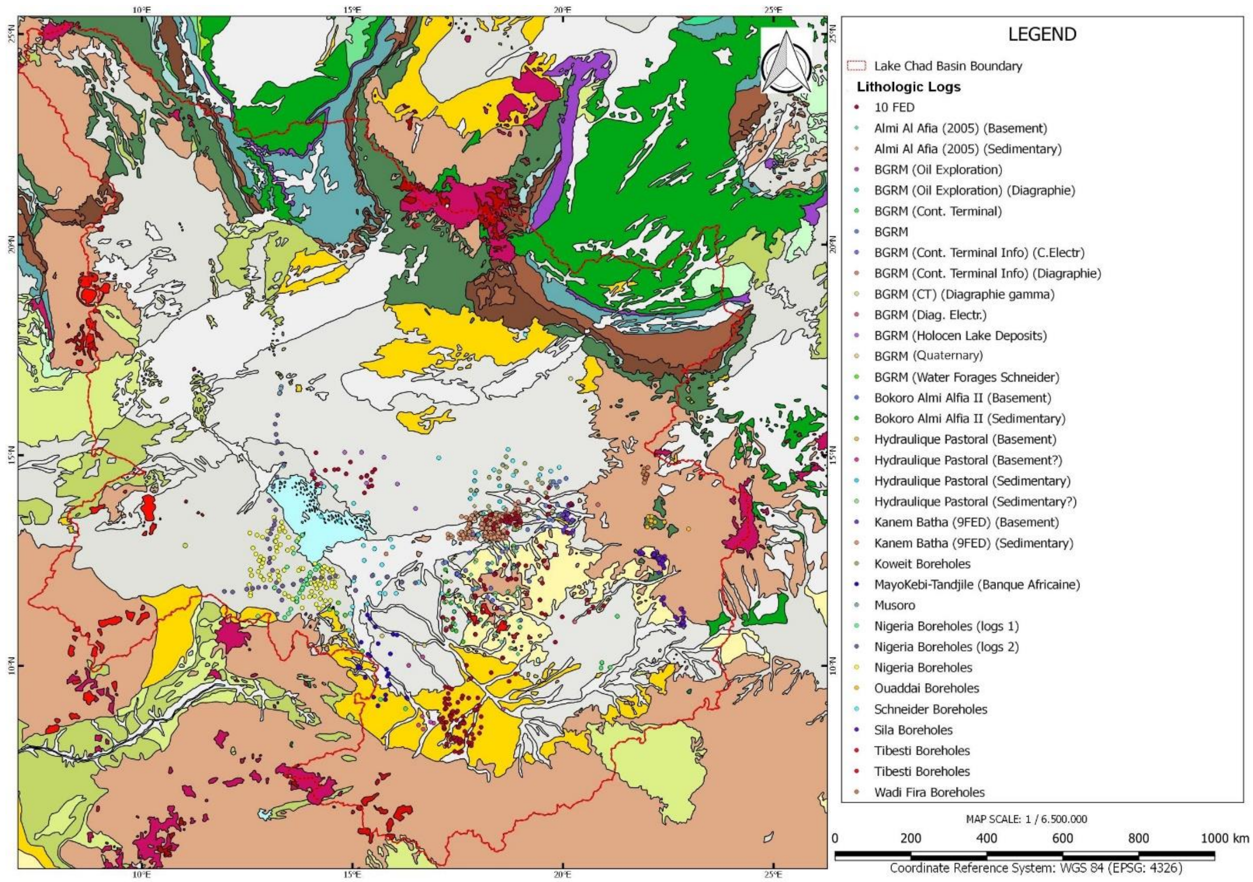

Figure B2. Spatial distribution of the lithological logs (430) in the study area. Colored dots indicate the different works with available information.

All the logs are stored in QGIS, a free open source database with graphic output for further data use. Geological logs were carefully analyzed from the stratigraphical point of view before DB storage. As an example of storage and output, borehole 13-SCH (Bol area) and its associated information are illustrated in Fig. B3. In this stage, all the stored information was ready for retrieval and visualization in 2D-3D (including cross-sections, borehole locations, etc.).

The depth of the top and bottom of hydrostratigraphical water-bearing units (aquifers) or nonwater-bearing units (aquicludes or aquitards) was calculated based on of the lithological log descriptions, subdivided into intervals corresponding to hydrostratigraphical units. The five defined hydrostratigraphical units are: Quaternary (*Q*); Upper/Middle Pliocene (*Pli*); Lower Pliocene (*LPli*); Continental Terminal (*CT*); basement (Cretaceous-*Cr*- and crystalline rocks).

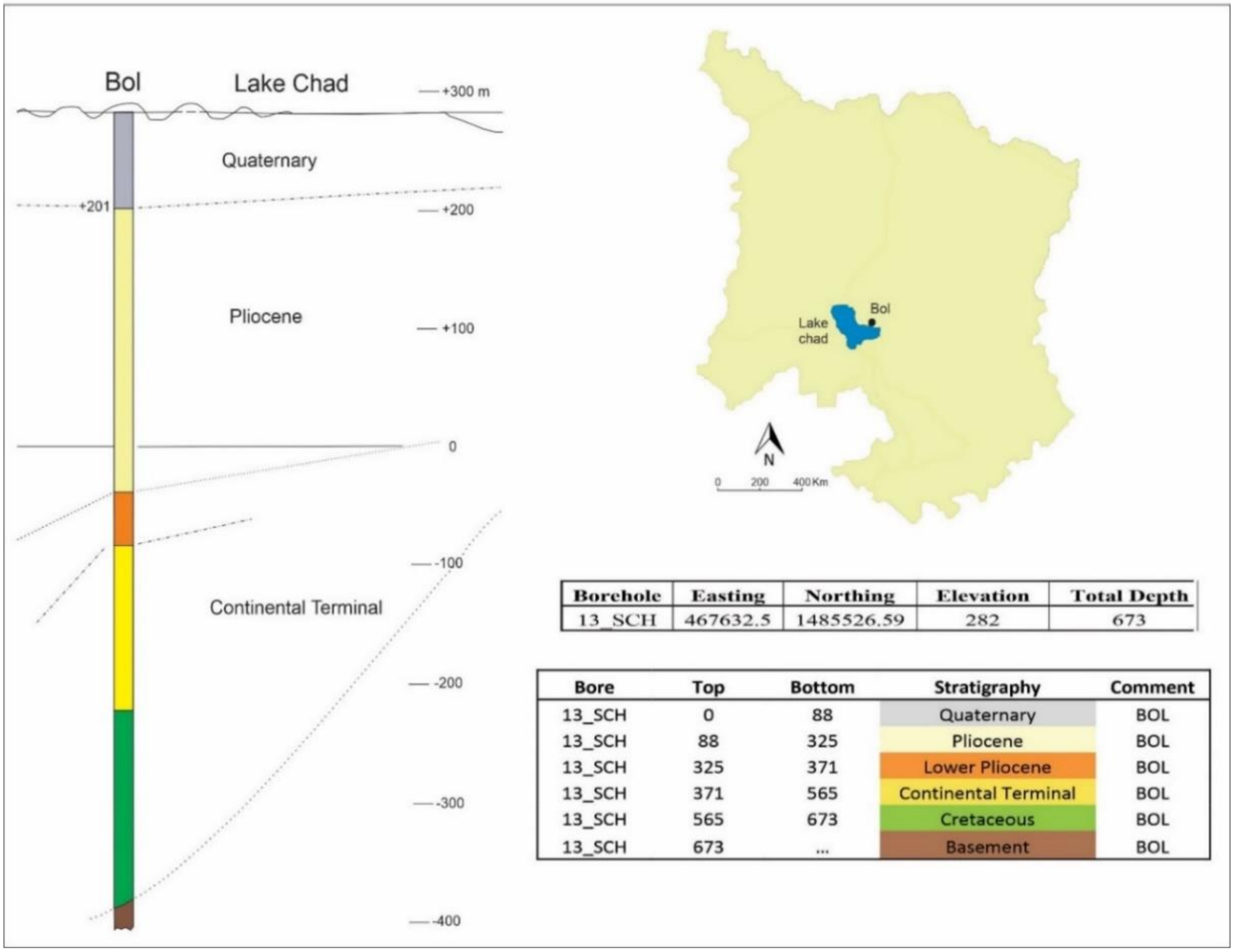

Figure B3. Record of successive stratigraphical layers, coordinates and depth for borehole 13_SCH after being coded for storage.

Hydrostratigraphical system boundaries

Over the areal extension and for Quaternary (*Q*), Lower Pliocene (*LPli*) and Continental Terminal (*CT*), the new contours of hydrostratigraphical units surface extension are plotted in Figs. 16 and 17 in Section 2.6 and Fig. B4 presents the surface extension for the Upper Pliocene. According to the geologic map (Fig. B1) Pliocene outcrops over the Guera area extension. However age and origin of geologic materials is controversial and as suggested by the LCBC they were not considered for modelling.

Selected boreholes with geological logs

Selection (430 out of 640) was based on those records that were considered precise, with measured attributes, clearly geo-localized and with observations whenever a change in the stratigraphical sequence occurs and measurements exist. It was not possible to clearly identify many water points because of erroneous spatial location or associated difficulties in finding the location name, and they were rejected. Not all the oil-rig logs that existed in the area could be identified due to lack of data provision or data confidentiality.

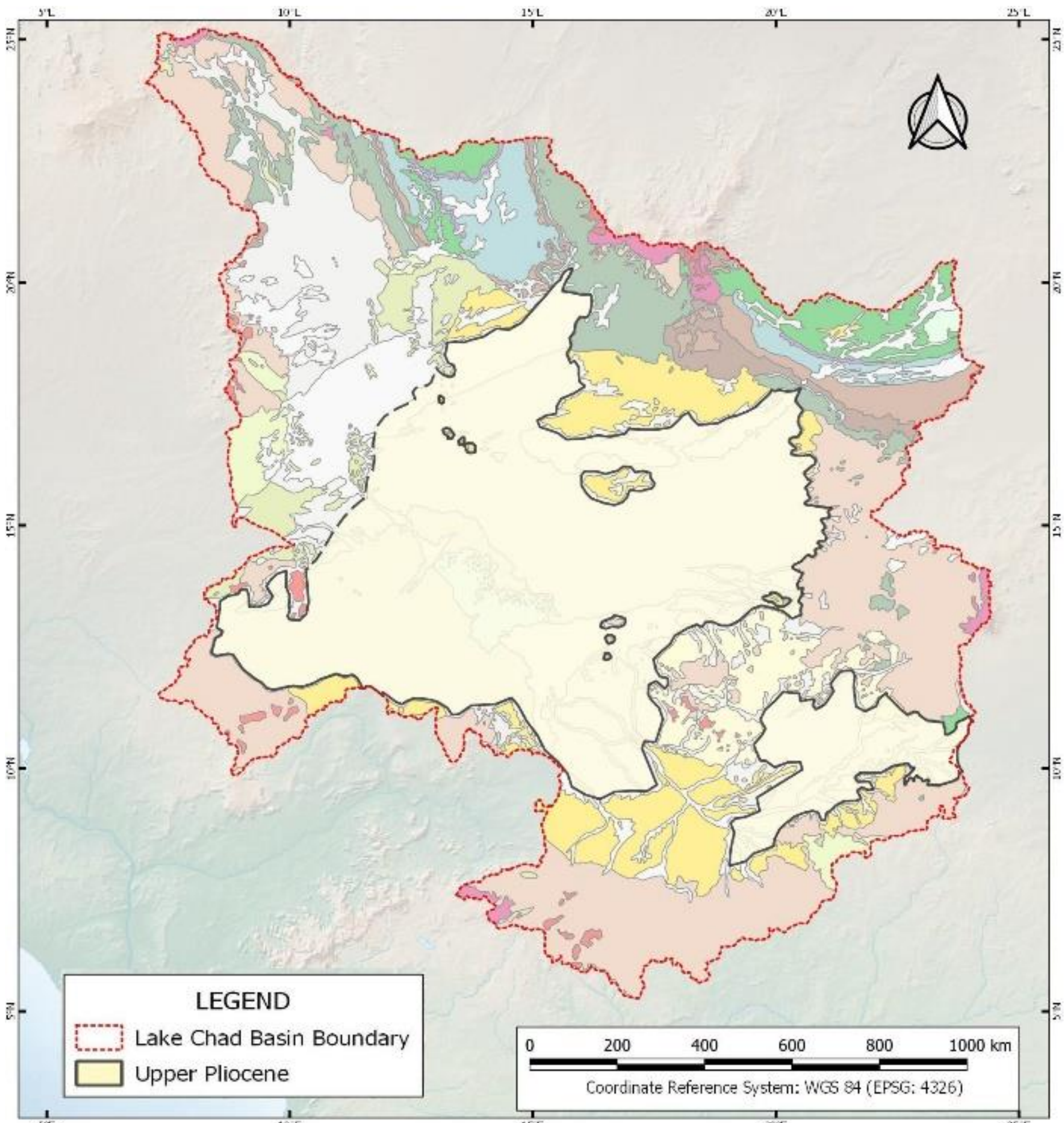

Figure B4. Surface extension for the Upper Pliocene.

Table B2. Selected boreholes with geological logs.

Campaign	Year	ID-Alias-code	Aquifer	Construction date	X (UTM)	Y (UTM)	Z (m)
Schneider	1989	1_SCH	Q, LPli, CT		588898.00	1338463.00	300.
		2_SCH	Q, LPli, CT		613273.00	1295568.00	335
		3_SCH	Q, CT		848465234.00	1448383.76	335
		4_SCH	Q, LPli		628266747.00	1325401.10	303
		5_SCH	Q, CT		576408066.00	1370631.79	295
		6_SCH	Q, CT		598348378.00	1437233.40	292
		7_SCH	Q		778357.00	1342379.00	334
		8_SCH	Q, LPli, CT		566067578.00	1321240.94	302
		10_SCH	Q, LPli		419198926.00	1497629.37	287
		11_SCH	Q		584835149.00	1294713.89	330
		12_SCH	Q, P, CT		569652881.00	1322775.09	304
		13_SCH	Q, LPli, CT		467632.54	1485526.59	282
		14_SCH	Q, LPli, CT		910016.00	1646587.00	339
		15_SCH	Q, LPli, CT		538468863.00	1267430.09	297
		16_SCH	Q, CT		1029506.00	1632371.00	395
		17_SCH	Q, LPli, CT		912214558.00	1608966.12	337
		18_SCH	Q		980116.00	1610943.00	377
		19_SCH	Q, CT		935708.00	1979612.00	241
		21_SCH	Q, CT		1007498.00	1621697.00	386
		22_SCH	Q, CT		556915904.00	1412355.86	289
		23_SCH	Q, LPli, CT		300297.00	1432945.00	295
		24_SCH	Q, LPli, CT		571361833.00	1295586.47	310
		25_SCH	Q, LPli, CT		720668.00	1652310.00	288
		26_SCH	Q, LPli, CT		503308741.00	1531690.33	322
		27_SCH	Q		323583.09	1630299.75	323
		28_SCH	Q, LPli, CT		503408214.00	1328002.40	297
		29_SCH	Q, LPli, CT		508199045.00	1303256.12	298
		31_SCH	Q		490398863.00	1198234.35	312
		32_SCH	Q, LPli		671192962.00	1325150.54	309
		34_SCH	Q, LPli		530263521.00	1381936.98	290
		35_SCH	Q, LPli, CT		463721.00	1270474.00	304

		37_SCH	Q, LPli		538667944.00	1506802.01	310
		38_SCH	Q, CT		889408.00	1494898.00	345
		39_SCH	Q, LPli		426926795.00	1575990.47	308
		40_SCH	Q, CT		889407789.00	1494897.67	345
		42_SCH	Q		603561572.00	1417200.51	288
		43_SCH	Q		481376.75	1238110.12	307
		44_SCH	Q, CT		528433702.00	1420971.51	287
		46_SCH	Q, LPli, CT		525498.00	1143124.00	333
		47_SCH	Q, LPli, CT		813994.00	1615210.00	299
		48_SCH	Q, CT		902041587.00	1577741.96	346
		49_SCH	Q, LPli, CT		494722377.00	1242509.25	306
BGRM	1992	50_BRGM	Q, CT		997041053.00	1530834.37	406
		51_ BRGM	Q		1131184.92	1535957.07	545
		52_ BRGM	Q, CT		978499914.00	1497884.96	372
		53_BRGM	Q, CT		1015795.34	1492158.94	387
		54_BRGM	Q, CT		991528.77	1468724.51	387
		56_BRGM	Q, CT		1077528.42	1225711.20	439
		57_BRGM	Q, LPli, CT		734912393.00	1375893.40	297
		58_BRGM	Q, CT		1188243.81	1242619.67	457
		59_BRGM	Q, LPli, CT		777982781.00	1342161.67	330
		61_BRGM	Q, CT		894328531.00	993772.15	367
		62_BRGM	Q, CT		682316985.00	973102374.00	381
		63_BRGM	Q		480296388.00	1665707.84	310
		64_BRGM	Q, CT		1030877.36	1594867.58	377
		65_BRGM	Q, CT		1022479.14	1585121.69	390
		66_BRGM	CT		573339086.00	1017208.96	456
		68_BRGM	CT		1052896.38	1866523.97	389
		69_BRGM	Q, CT		1005452.09	1493487.38	381
		70_BRGM	Q, CT		712508804.00	955227301.00	389
		71_BRGM	Q		796226038.00	1441511.20	298
		72_BRGM	Q, CT		704118571.00	958348097.00	385
		73_BRGM	Q, CT		1150572.92	1119140.63	417
		74_BRGM	Q, LPli, CT		951150936.00	1466522.10	364
		75_BRGM	Q, LPli, CT		811302542.00	1452177.63	302
		77_BRGM	Q, CT		1148401.38	1105367.77	421
		78_BRGM	Q, CT		1029891.95	1504290.29	399
		79_BRGM	Q, LPli, CT		399408527.00	1616393.35	323
		80_BRGM	Q, LPli, CT		399408527.00	1616393.35	319

		81_BRGM	Q		580651317.00	1652931.97	295
		82_BRGM	Q, CT		685065306.00	939445943.00	389
		83_BRGM	Q, LPli, CT		457281045.00	1574858.69	326
		84_BRGM	Q		1172074.56	1107430.96	424
		85_BRGM	Q		615036555.00	1583013.34	289
		86_BRGM	Q		638796651.00	992943911.00	429
		87_BRGM	Q, CT		1150382.38	1119745.23	436
		88_BRGM	Q, CT		673020.45	949777103.00	405
		89_BRGM	Q, CT		1047535.70	1603100.49	400
		90_BRGM	Q, CT		1007531.18	1583049.34	373
		91_BRGM	Q, CT		682855015.00	1129022.50	329
		92_BRGM	Q, LPli, CT		463683401.00	1270512.60	300
		93_BRGM	CT		788636009.00	959813229.00	378
		94_BRGM	Q, CT		1015446.21	1593898.96	395
		95_BRGM	Q, CT		1009210.17	1474610.75	393
		96_BRGM	Q, LPli, CT		459395655.00	1243647.99	304
		97_BRGM	Q		584281355.00	1640039.56	289
		98_BRGM	Q, LPli, CT		419120353.00	1583911.76	308
		99_BRGM	Q, CT		646504.72	1106737.80	338
		100_BRGM	Q, LPli, CT		740543257.00	1378071.11	297
		101_BRGM	Q, LPli, CT		481331984.00	1238099.08	300
		102_BRGM	Q		523286101.00	1665711.09	301
		103_BRGM	Q		662187759.00	1518738.72	276
		104_BRGM	Q, CT		1026446.97	1533523.87	389
		105_BRGM	Q, LPli, CT		441074515.00	1252743.80	305
		106_BRGM	Q, LPli, CT		525141.81	1143371.76	322
Nigeria	1965	107_NGR1	Q, LPli		340234914.00	1254472.03	360
		108_NGR1	Q, LPli		371187.46	1448715.19	274
		109_NGR1	Q, LPli		356154883.00	1274450.47	323
		110_NGR1	Q, LPli, CT		324366291.00	1232282.00	393
		111_NGR1	Q, LPli, CT		331132596.00	1365223.48	301
		112_NGR1	Q, LPli		369059266.00	1305237.92	306
		113_NGR1	Q, LPli		355614557.00	1283387.91	317
		114_NGR1	Q, LPli		373919018.00	1318226.00	297
		115_NGR1	Q, LPli		370564865.00	1309544.37	303
		116_NGR1	Q, LPli		380936018.00	1331682.78	293
		117_NGR1	CT		255196656.00	1236334.04	390
		118_NGR1	Q, LPli		405109527.00	1358071.38	287

		119_NGR1	Q, LPli		388993.92	1340246.29	291
		120_NGR1	Q, LPli		414019382.00	1368203.94	287
		121_NGR1	Q, LPli		363283227.00	1296811.82	308
		122_NGR1	Q, LPli, CT		356775279.00	1432411.60	276
		123_NGR1	Q, LPli		391358269.00	1349953.81	290
		124_NGR1	Q, LPli, CT		298307439.00	1310932.22	335
		125_NGR1	Q, LPli		383218771.00	1319925.92	293
		126_NGR1	Q, LPli, CT		348251359.00	1401138.71	278
		127_NGR1	Q, LPli		410029639.00	1365095.52	287
		128_NGR1	Q, CT		334326186.00	1242689.86	363
	1966-1968	129_NGR2	Q, CT		769703628.00	1346143.98	320
		130_NGR2	Q, LPli		590673065.00	1338845.66	301
		131_NGR2	Q, LPli		626781915.00	1324810.74	305
		132_NGR2	Q		779669694.00	1342966.21	332
		133_NGR2	Q, LPli		274650717.00	1312399.01	335
		134_NGR2	Q		303505222.00	1740438.70	363
		135_NGR2	Q		309483454.00	1764428.91	340
		136_NGR2	Q, LPli		226513935.00	1307576.92	350
		137_NGR2	LPli, CT		300377752.00	1486823.42	299
		138_NGR2	Q, LPli		299261869.00	1476063.08	296
		139_NGR2	Q, LPli		309641776.00	1302218.67	318
		140_NGR2	Q, LPli, CT		168339099.00	1302381.32	372
		141_NGR2	Q, LPli		380908447.00	1331641.85	295
		142_NGR2	Q, LPli, CT		303534.56	1324464.61	309
		143_NGR2	Q, LPli, CT		505191462.00	1337458.63	293
		144_NGR2	Q, LPli		285222707.00	1376894.06	300
		145_NGR2	Q, LPli		293252.62	1356693.24	300
		146_NGR2	Q, LPli		281310447.00	1438990.44	300
		147_NGR2	Q, LPli, CT		317244955.00	1278596.98	341
		148_NGR2	Q, LPli, CT		287338079.00	1413415.12	299
		149_NGR2	Q, LPli		441266029.00	1336555.22	297
		150_NGR2	Q, LPli		256841491.00	1311911.45	339
		151_NGR2	Q, LPli, CT		286976927.00	1540126.46	293
		152_NGR2	Q, LPli, CT		456025.48	1341334.34	292
		153_NGR2	Q, LPli		325111809.00	1634253.07	332
		154_NGR2	Q, LPli		189840672.00	1300568.43	390
		155_NGR2	Q, LPli		292825833.00	1465535.24	293
		156_NGR2	Q, LPli, CT		508199045.00	1303256.12	298

		157_NGR2	Q, LPli		551141327.00	1341538.02	298
		158_NGR2	Q, LPli		347453552.00	1319779.23	300
		159_NGR2	Q, CT		298411.29	1311126.28	326
		160_NGR2	Q, CT		663108728.00	1323390.98	311
		161_NGR2	Q, LPli		241332789.00	1309346.86	341
		162_NGR2	Q, LPli		306985795.00	1601794.25	302
		163_NGR2	Q, LPli		319346659.00	1663718.05	350
		164_NGR2	Q		304860321.00	1241613.35	361
		165_NGR2	Q, LPli		419514951.00	1336509.99	292
		166_NGR2	Q		305699179.00	1713685.86	338
		167_NGR2	Q, LPli, CT		308523854.00	1694429.81	358
		168_NGR2	Q, LPli, CT		296843569.00	1575912.85	287
		169_NGR2	Q, LPli		367845976.00	1329870.66	296
		170_NGR2	Q, LPli, CT		287197833.00	1388417.25	298
		171_NGR2	Q, LPli		319173374.00	1315321.35	308
		172_NGR2	Q, LPli, CT		303039186.00	1515576.14	290
		173_NGR2	Q, LPli		402013025.00	1334736.53	290
		174_NGR2	Q, LPli, CT		288677294.00	1452875.09	298
Al-Alfia II	2005-2006	284_AL05	Q		743867145.00	1274827.27	334
		295_AL05	none AQ level		930717397.00	1138887.02	443
		319_AL05	none AQ level		914494768.00	1154605.26	428
		320_AL05	none AQ level		887539422.00	1170233.14	394
Bokoro	2013-2014	334_BOK	Q	01/12/2013	740869294.00	1273939.68	334
		335_BOK	Q	01/05/2014	739522806.00	1273630.57	332
		336_BOK	Q	01/11/2013	743635149.00	1227573.60	337
		337_BOK	Q	01/03/2014	743635149.00	1227573.60	337
		338_BOK	none AQ level	01/09/2014	850176689.00	1375901.67	362
		339_BOK	Q, CT	01/12/2013	763988571.00	1248671.49	343
		340_BOK	Q	01/12/2013	802355213.00	1403671.73	306
		341_BOK	Q	01/11/2013	742357358.00	1327195.23	316
		342_BOK	Q	01/05/2014	741446748.00	1327311.83	316
		343_BOK	Q, CT	01/06/2013	924198259.00	1418802.07	363
		344_BOK	Q, LPli, CT	01/02/2014	915830139.00	1423420.37	354
		345_BOK	Q, LPli, CT	01/11/2013	759260.86	1201721.23	345
		346_BOK	Q, CT	01/12/2014	927626826.00	1372210.31	409
		347_BOK	Q, CT	01/01/2014	917534527.00	1367120.26	442

		348_BOK	CT	01/01/2014	885873805.00	1407610.57	357
		349_BOK	CT	01/01/2014	957657525.00	1330312.44	477
		350_BOK	Q, CT	01/12/2013	769962475.00	1349318.55	322
		351_BOK	Q, CT	01/05/2014	770672695.00	1347742.27	318
		352_BOK	Q	01/03/2014	863191062.00	1279074.90	482
		353_BOK	Q, CT	01/12/2013	755397105.00	1271044.75	339
		354_BOK	Q, CT	01/03/2014	888370438.00	1257774.58	486
		355_BOK	Q, LPli, CT	01/03/2014	769580004.00	1197652.05	344
		356_BOK	-	01/12/2013	792672213.00	1356299.08	337
		357_BOK	-	01/05/2014	792980531.00	1357151.25	335
		358_BOK	Q, CT	01/12/2013	761921.39	1217954.87	339
		359_BOK	CT	01/11/2013	761921.39	1217954.87	339
		360_BOK	-	01/03/2014	832129408.00	1228124.99	384
		361_BOK	-	01/01/2014	936586357.00	1228074.80	470
		362_BOK	-	01/02/2014	858122093.00	1311080.92	505
		363_BOK	-	01/01/2014	898109293.00	1414729.36	357
		364_BOK	Q, CT	01/11/2013	746928069.00	1294271.25	333
		365_BOK	Q, CT	01/12/2013	856560588.00	1355942.64	407
		366_BOK	Q, CT	01/02/2014	823578274.00	1310748.93	382
		367_BOK	Q	01/01/2014	880014755.00	1391866.45	362
		368_BOK	-	01/02/2014	812070372.00	1307716.78	381
		369_BOK	CT	01/03/2014	787672243.00	1169645.95	351
		370_BOK	-	01/02/2014	849843554.00	1287937.28	489
		371_BOK	Q, CT	01/05/2014	740273198.00	1358501.29	304
Koweit	2004-2005	380_KOW	Q, CT	10/03/2005	798147371.00	1454399.12	299
		386_KOW	Q, CT	13/12/2004	803523411.00	1567859.68	297
		400_KOW	Q, CT	06/12/2004	832211508.00	1507798.15	319
H.Pastorale	2008-2009	402_HYP	Q, LPli	01/02/2009	804136287.00	1224677.52	383
		403_HYP	LPli	01/06/2009	898864335.00	1236255.93	482
		404_HYP	-	01/04/2008	896187859.00	1409228.20	360
		411_HYP	-	01/07/2009	776705.46	1263970.86	343.00
		418_HYP	LPli	01/05/2009	935184.61	1209168.96	438
		419_HYP	Q	01/07/2009	817468681.00	1406910.45	318
		421_HYP	-	01/07/2009	819599221.00	1383865.77	333
		427_HYP	-	01/06/2009	911762.78	1153741.63	424
		429_HYP	LPli	01/01/2009	829424667.00	1264692.67	406
		430_HYP	LPli	01/06/2008	904175069.00	1302959.88	518
		432_HYP	LPli	01/05/2009	928380495.00	1313757.30	507

		435_HYP	LPli	01/04/2009	918169952.00	1293142.86	490
9FED	2012	439_FED	Q		1058735.81	1533506.21	426
		489_FED	Q		1046390.48	1509865.66	413
		497_FED	Q		1050001.76	1476694.16	405
		509_FED	Q		1068145.92	1465718.70	421
		525_FED	Q		1045150.12	1461145.51	416
		546_FED	Q		1060448.57	1533759.16	423
		552_FED	Q		1064432.68	1459687.80	422
		559_FED	Q		1062984.79	1536343.76	429
		561_FED	Q		1045083.06	1501604.43	414
		565_FED	Q		1043914.55	1467010.77	406
		576_FED	Q		1054998.61	1492094.89	423
		583_FED	Q		1058177.30	1532846.39	424
		585_FED	Q		1055530.63	1458949.70	423
		591_FED	Q		1064913.40	1533609.42	432
		592_FED	Q		1063215.93	1534035.16	431
		602_FED	Q		1055553.03	1534332.21	420
		610_FED	Q		1055465.10	1511567.08	416
		629_FED	Q		1050165.71	1512535.06	407
		630_FED	Q		1050041.23	1512717.50	408
		664_FED	Q		1047822.14	1514984.17	411
		666_FED	Q		1066251.22	1493935.87	419
		673_FED	Q		1050450.18	1510474.61	416
		678_FED	Q		1049730.41	1498678.15	413
		681_FED	Q		1041972.47	1507615.61	408
		718_FED	Q		1053803.45	1508817.79	411
Moussoro	2015	730_MUS	Q	01/06/2015	315088.16	1820998.58	408
		731_MUS	Q	01/06/2015	319623674.00	1839476.57	410
		732_MUS	Q	01/06/2015	316377385.00	1823370.65	397
		733_MUS	Q	01/06/2015	318516608.00	1834263.26	417
		734_MUS	Q	01/06/2015	315064997.00	1821929.94	423
10FED	2015-2016	736_FED10	CT		986216072.00	1282186.84	438
		737_FED10	-	14/12/2015	986040537.00	1281752.76	440
		738_FED10	CT		991763.04	1326396.13	475
		739_FED10	CT		991205251.00	1246556.01	478
		740_FED10	CT	27/01/2016	1001292.34	1243384.26	435
		741_FED10	-		1044743.78	1238202.92	430
		745_FED10	Q, CT	20/01/2016	1107979.35	1284142.47	447

		746_FED10	Q, LPli, CT		1114078.08	1252256.08	457
		747_FED10	CT	31/01/2016	1152137.86	1270151.06	470
		748_FED10	Q, LPli, CT	24/03/2016	1113959.35	1252099.52	452
		749_FED10	Q, LPli, CT	26/03/2016	1124133.15	1266156.92	455
		782_FED10	Q		1027784.43	1171372.96	412
		808_FED10	CT		760719065.00	976793477.00	380
		823_FED10	CT		791304.48	957969304.00	372
		824_FED10	CT		819321076.00	990706867.00	414
		849_FED10	Q, CT		816891231.00	915414859.00	390
		861_FED10	Q		1022363.16	1401910.82	435
		866_FED10	Q, CT		1003942.80	1366568.18	502
		909_FED10	Q, CT		796947359.00	1107708.05	356
		911_FED10	CT		836506879.00	945360985.00	386
		913_FED10	-		808785.85	1073552.76	365
		930_FED10	CT		827072633.00	1022289.81	409
		948_FED10	Q, CT		861454435.00	1089130.83	364
		949_FED10	Q, CT		908423444.00	1066478.58	406
		950_FED10	Q, CT		925546435.00	1086277.04	383
		951_FED10	CT		831401968.00	1001475.35	422
Ouaddai	2015	980_OUA	-	13/11/2015	1266040.30	1453275.00	868
		981_OUA	-	21/11/2015	1263140.40	1508022.21	880
		982_OUA	-		1262596.94	1507523.63	889
		983_OUA	-	08/07/2015	1270097.98	1487266.19	866
		984_OUA	-		1367687.43	1478440.86	833
		985_OUA	-	11/07/2015	1268727.98	1493542.07	876
		986_OUA	-	03/11/2015	1304286.90	1494652.27	788
		987_OUA	-	05/11/2015	1268564.31	1496945.73	847
		988_OUA	-	07/11/2015	1268567.78	1496951.40	847
		989_OUA	-		1269250.04	1497123.43	847
		990_OUA	-		1279981.45	1494024.91	849
		991_OUA	-	29/06,2015	1259081.33	1481278.44	822
		992_OUA	-	29/06/2015	1260208.13	1480729.00	803
		993_OUA	-	10/11/2015	1266318.70	1498660.30	855
		994_OUA	-	12/11/2015	1266318.70	1498660.30	855
		995_OUA	-		1270006.32	1496874.12	856
		996_OUA	-		1270881.81	1508588.92	846
Sila	2014-2016	997_SIL	-	03/12/2014	1280689.05	1404429.78	632
		998_SIL	-	28/10/2014	1246131.24	1410271.51	628

		999_SIL	-	25/10/2014	1250886.16	1409694.90	628
		1000_SIL	-	26/01/2015	1286630.36	1415406.58	689
		1001_SIL	-	26/06/2015	1354495.68	1265385.95	563
		1002_SIL	-	22/11/2014	1244937.63	1408758.05	628
		1003_SIL	-	28/01/2015	1280750.96	1409583.44	647
		1004_SIL	-	15/02/2015	1288891.03	1397283.19	618
		1005_SIL	-	11/12/2015	1345238.65	1238951.11	545
		1006_SIL	Q	22/11/2015	1356640.94	1226839.88	507
		1007_SIL	-	27/01/2016	1361631.77	1256778.99	535
		1008_SIL	Q	27/11/2015	1358034.38	1229418.82	509
		1009_SIL	Q	06/12/2015	1352973.17	1222180.58	500
		1010_SIL	-	23/01/2015	1277884.99	1410433.36	651
		1011_SIL	-	12/02/2015	1291880.01	1395250.75	618
		1012_SIL	-	01/11/2014	1242312.00	1409481.13	675
		1013_SIL	-	09/03/2015	1298883.65	1391676.05	607
		1014_SIL	-	21/11/2015	1357914.82	1226039.24	505
		1015_SIL	-	13/11/2014	1243814.88	1415974.45	670
		1016_SIL	-	24/06/2015	1356061.54	1266767.65	576
		1017_SIL	-	27/01/2015	1280148.40	1411919.87	649
		1018_SIL	-	05/03/2015	1307608.05	1404119.36	652
		1019_SIL	Q	08/12/2015	1362449.28	1223463.85	511
		1020_SIL	-	28/10/2015	1354024.49	1266294.06	570
		1021_SIL	-	23/06/2015	1354027.38	1266300.33	574
		1022_SIL	Q		1359960.41	1244113.98	533
		1023_SIL	Q	06/11/2015	1360310.79	1243605.50	530
		1024_SIL	-	17/06/2015	1307069.84	1291494.82	565
		1025_SIL	-	22/03/2015	1307251.91	1373534.55	605
		1026_SIL	-	05/12/2014	1276631.71	1406912.98	635
		1027_SIL	-	08/12/2014	1277826.34	1404812.60	515
		1028_SIL	Q	09/12/2014	1279538.61	1407457.10	636
		1029_SIL	-	27/05/2015	1294223.19	1360333.47	607
		1030_SIL	-	08/11/2015	1362002.68	1232261.41	512
		1031_SIL	-	06/03/2015	1307623.26	1395842.45	633
		1032_SIL	-	20/03/2015	1304530.04	1379214.34	608
		1033_SIL	-	21/02/2015	1298709.06	1400869.94	639
		1034_SIL	-	23/02/2015	1298658.71	1401580.90	640
		1035_SIL	-	25/02/2015	1302261.21	1395180.54	608
		1036_SIL	Q	31/01/2016	1357898.01	1229945.42	516

		1037_SIL	Q	29/11/2015	1359289.54	1231538.55	510
		1038_SIL	LPli	18/02/2015	1293285.19	1397900.33	621
		1039_SIL	-	17/03/2015	1302353.22	1386110.74	595
		1040_SIL	-	10/12/2015	1339922.63	1244317.14	552
		1041_SIL	-	04/06/2015	1309425.00	1276406.39	567
		1042_SIL	-	05/06/2015	1308154.29	1295342.23	573
		1043_SIL	-	30/10/2014	1249025.00	1411953.00	636
		1044_SIL	-	02/03/2015	1302869.11	1392165.16	620
		1045_SIL	-	08/06/2015	1301993.27	1287882.01	547
		1046_SIL	-	11/03/2015	1295635.37	1384561.84	643
Wadi Fira	2016	1046_WAD	-	20/06/2016	1249880.00	1608610.00	980
		1047_WAD	-	22/06/2016	1249930.00	1608735.00	983
		1048_WAD	-	25/06/2016	1251732.00	1605605.00	1007
		1049_WAD	-	02/06/2016	1254463.00	1613968.00	981
		1050_WAD	-	09/05/2016	1252669.00	1620543.00	944
		1051_WAD	-	11/05/2016	1248446.00	1620141.00	938
		1052_WAD	-	13/06/2016	1254684.00	1613755.00	968
		1053_WAD	-	16/06/2016	1249239.00	1597179.00	968
		1054_WAD	-	25/05/2016	1248701.00	1633417.00	926
		1055_WAD	-	13/05/2016	1245426.00	1621906.00	934
		1056_WAD	-	23/05/2016	1246986.00	1626667.00	922
		1057_WAD	-	17/06/2016	1250904.00	1609622.00	991
		1058_WAD	-	09/06/2016	1256667.00	1619756.00	959
		1059_WAD	-	11/06/2016	1254462.00	1619196.00	951
		1060_WAD	-	28/05/2016	1257176.00	1638116.00	948
		1061_WAD	-	31/05/2016	1257182.00	1637612.00	937
Maio Kebbi	2014-2016	1062_BAF	CT	01/07/2014	586729487.00	1028884.11	384
		1063_BAF	CT	01/05/2016	586237943.00	1016693.32	436
		1064_BAF	Q, CT	01/06/2014	596669355.00	1055445.05	354
		1065_BAF	CT	01/06/2014	555193362.00	1022991.29	391
		1066_BAF	CT	01/05/2014	566551535.00	1000435.37	425
		1067_BAF	Q, CT	01/06/2014	641429565.00	1022071.34	365
		1068_BAF	Q, CT	01/05/2014	588766691.00	1096430.02	338
		1069_BAF	Q, CT	01/06/2014	590944244.00	1078159.70	344
		1070_BAF	Q, CT	01/05/2016	594003049.00	1085231.82	342
		1071_BAF	Q, CT	01/01/2016	546120013.00	1130350.50	328
		1072_BAF	Q, CT	01/01/2016	540333313.00	1135718.11	338
		1073_BAF	Q, LPli, CT	01/07/2014	566774565.00	1163738.74	324

		1074_BAF	Q, CT	01/12/2015	559190.12	1207586.00	317
		1075_BAF	Q	01/04/2014	514685177.00	1098858.50	331
		1076_BAF	CT	01/06/2014	514686159.00	1104558.60	332
		1077_BAF	Q, CT	01/05/2014	521118489.00	1100811.79	323
		1078_BAF	CT	01/12/2015	533638481.00	1074138.47	337
		1079_BAF	Q, CT	01/05/2014	538925133.00	1238605.94	308
		1080_BAF	Q, CT	01/01/2016	545373557.00	1228687.00	306
		1081_BAF	Q, CT	01/04/2016	606002956.00	1188077.48	331
		1082_BAF	Q, CT	01/04/2016	615938623.00	1186549.90	333
		1083_BAF	Q, CT	01/04/2016	522725.34	1167075.73	319
		1084_BAF	Q, CT	01/05/2014	598736362.00	1136754.68	333
Tibesti		1085_TIB	-		653463728.00	2257902.17	747
		1086_TIB	-		653757339.00	2260896.89	752
		1087_TIB	-		653980605.00	2261596.33	755
		1088_TIB	-		654341277.00	2262097.74	760
		1089_TIB	-		662289356.00	2263655.36	793
Alkali		Alk-1	Q		69179.00	1426939.00	339

File: selected-logs.xls. It contains information about the 430 geological logs

APPENDIX C. HYDRAULIC PARAMETERS

Table C1. Hydraulic parameters (type of test not provided; * test of short duration; + spatial location unknown). Aq: aquifer**

	Region	Aq	Area	X	Y	k (m/s)	T (m^2/s)	m (%) / S	Other	Reference
NIGER-NIGERIA		Q	Komadougou (Bagara, Diffa)	13.36	12.44	_	10^{-3} - $2.8x10^{-2}$ **	20-25	thickness 80 m no info test	Genthon et al., 2015
				13.36	12.44	10^{-6} - 10^{-5}	-	-		Leblanc, 2002; Gaultier, 2004; Zairi, 2008 (from modelling)
			Ngagam borehole (F8)	13.56	12.86		$7.8x10^{-2}$ **	24.5	(48 h pumping F8)	Descloitres et al., 2013 (based on MRS and TDEM)
	Komadougou valley		Kadzell	+	+		$4.5x10^{-2}$ - $1.6x10^{-1}$ (mean $7.2x10^{-2}$)			
		CT	West Niger	+	+		$2.4x10^{-4}$ - $2x10^{-2}$			
		Q	Assaga	13.30	12.71		$2.8x10^{-2}$ *			after OFEDES and FORACO (1983-1989); Gaultier, 2004
			Dagaya	13.55	13.06		$8x10^{-3}$ *			
			Blabrim (Blabrine)	13.46	12.76		$4.7x10^{-1}$	32 (31 -32.8)		Kemgang et al., 2015 (based on MRS data)
			Ngagam	13.57	12.86		$7.0x10^{-2}$ **	24 (24 - 27)		
	Komadougou -Yobé Hadeija-Jama'are river		Harbo	12.15	9.54	$8x10^{-4}$** (average)	$2x10^{-3}$ - $3.5x10^{-3}$**	$9x10^{-5}$ - $2x10^{-4}$**		after Schulz, 1975; Hassan, 2002
			Hago	12.36	10.05	$2.5x10^{-4}$** (average)	$1x10^{-3}$ - 2.1.3x10^{-3}**	$3.4x10^{-4}$ - $6.2x10^{-4}$**		
			Hadejia	12.45	10.04	$9.2x10^{-4}$ - $2.7x10^{-3}$**	$2.7x10^{-3}$ - $8.2x10^{-3}$**	$1.4x10^{-4}$ - $4.4x10^{-4}$**		
	Komadougou Yobé Hadeija river	Q?	Kasaga	+	+	$1.1x10^{-3}$**	$7.5x10^{-3}$**	$8x10^{-5}$ - $9x10^{-4}$**	Alluvial? Piedmont? Bedrock?	after Diyam, 1987

			Masari	11.64	7.69	$5.4x10^{-4}$**	$2x10^{-3}$**	$2x10^{-4}$ - $4x10^{-3}$			
			Madachi	12.58	10.2	$1.6x10^{-3}$**	0.01	$2x10^{-4}$ - $5x10^{-2}$			
			Jama'ar	9.24	12.41	$9.1x10^{-4}$**	$6x10^{-3}$**				
			Kuka	11.66	9.92						
			Tabasha	+	+	$2.8x10^{-4}$**	$2.5x10^{-3}$**				
			Hantsu	12.21	9.57	$1.6x10^{-3}$ - $3.6x10^{-3}$**	$8.7x10^{-7}$**				
			Gunka	12.14	9.36	$1.2x10^{-3}$ - $1.8x10^{-3}$**	$9.9x10^{-3}$**				
	Jama'are-Yobé rivers		Ganuwa	12.63	7.66	$1.5x10^{-3}$**	$7.5x10^{-3}$**			after water surveys (1986)	
			Zubuki	11.83	10.00	$3.1x10^{-3}$**	0.01				
			Sakwa	12.12	10.29	$1.3x10^{-3}$**	$3.4x10^{-3}$**				
			Tarabua	+	+	$1.3x10^{-3}$**	$7.8x10^{-3}$**				
		CT	Middle zone Dalori	11.88	14.16		$8.5x10^{-5}$	$1.4x10^{-3}$		after Millet et al., 1968	Offodile, 2002
			Ngala	12.34	14.19		$1.8x10^{-3}$	1.2 $x10^{-3}$			
			Sabsawa	+	+		$1.1x10^{-2}$	$1.8x10^{-3}$			
		Q	Maiduguri GRA	11.83	13.15		$9.7x10^{-5}$	$9x10^{-3}$			
			Maiduguri Gwange 2	11.83	13.15		7.1 $x10^{-5}$	8 $x10^{-3}$			
			Maiduguri 3	11.83	13.15		1.4 $x10^{-4}$	6 $x10^{-3}$			
	Bornou		Maiduguri	11.83	13.15		$6.3x10^{-5}$ **			after WAR DROP Engineering, 1993	Zairi R, 2008
	Komadougou Gana		Damboa	11.22	12.73		$1.3x10^{-2}$ **				
			Komadugu	12.10	15.00	$1.0x10^{-3}$ - $4x10^{-2}$		16-25	valley	LCBC-IRD, 2016 (based on MRS and TDEM)	
			Kadzell	+	+	$3x10^{-4}$ - 1.0x10-3		8-13			
			North of lake	13.71	14.08	$1.0x10^{-3}$ - $1.0x10^{-2}$		10-35			
CAMEROON		CT	Logone-Chari	+	+	$4x10^{-3}$ - $2x10^{-2}$			Yaeres?		
			Ouroungoulmo	14.62	12.29		$4.1X10^{-4}$ **		No information		
			Gouloundouma	14.73	11.50		$1.1x10^{-2}$ **				
		Q	Maroua	14.31	10.59				Piedmont and yaeré	Kemgang et al., 2015 (MRS data)	
			Ouroungoulmo	14.64	12.28		$4.1x10^{-4}$	20 (16-20)			

		Q	Abirou	14.58	10.93		$2.5x10^{-4}$	16.5 (16-19.2)			
			Kourouang	15.00			$7.2x10^{-4}$			UNESCO-BMZ-LCBC, 1997 (after BRGM/LCBC, 1993)	
			Maham	10.69	5.01		$9x10^{-4}$				
CHAD	Kanem Ogolian		Mao (GKW data)	14.12	15.31		$6.9x10^{-2}$ **		(oeolian sands)		Schneider and Wolf, 1992
			Moussoro	13.64	16.49		$1.2x10^{-2}$ **		(oeolian sands)		
	Bol (river-lake)		Ogolian layer	13.47	14.73		$2.5x10^{-3}$ - $3.5x10^{-3}$		Polder. + from Kanem1 and 2		
			Mid-Pleistocene sands	13.47	14.73		$1.6x10^{-2}$ - $2.2x10^{-2}$	35			
	Borkou	CT	Faya (F2, F3)	17.92	19.10	$3x10^{-4}$ **	$1.21x10^{-1}$ **				
	Chari-Baguirmi	Q	Massakori	12.10	15.73	$4x10^{-4}$ - $1.0x10^{-3}$ **	$3.2x10^{-3}$ - $6.6x10^{-3}$ **		6 tests (global)		
			Am Tchokoro (HP13)	12.10	15.91	$4.7x10^{-4}$ *	$7x10^{-3}$ *	$5x10^{-2}$	2 tests	after Schneider (1967)	
			Dapkaraye (HP17)	10.79	16.29	$1.4x10^{-4}$ *	$2.5x10^{-3}$ *	$1x10^{-3}$			
			Goz Dibek2	12.77	15.52	$1.4x10^{-4}$ **	$1.1x10^{-3}$ **	$3x10^{-5}$		after Schroeter et al, 1973	
			Abou Guern	11.72	16.04	$6.5x10^{-4}$ **	$5.8x10^{-3}$ **			after Schroeter et al (1973)	Schneider, 2001
			Koundoul	11.97	15.15		$1.7x10^{-3}$ **			after Zaubousky (¿)	
			Atron	13.36	16.24		$2.7x10^{-3}$		step-down; reinterpretation	UNESCO-BMZ-LCBC, 2000	
			Am Kounoio	13.67	21.57		$5.5x10^{-3}$				
			N'Djamena	12.14	15.01		$3.2x10^{-3}$ **	$4x10^{-4}$ **		after BRGM/LCBC, 1993	UNESCO-BMZ-LCBC, 1997
			N'Djamena	12.14	15.01		$6.6x10^{-3}$ **	$1x10^{-3}$ **			

	Massaguet	Q	Massaguet F1	12.43	15.44	$1.5x10^{-5}$ **	$3x10^{-4}$ **	$7.2x10^{-3}$		After Schroeter et al., 1973. FAO	Schneider and Wolf, 1992
			Massaguet F2	12.43	15.44	$1.6x10^{-4}$ **	$3.2x10^{-3}$ **			after Lohou, 1964	
		LPli	Maigana (HP8)	11.98	16.57	$9.3x10^{-5}$ *	$7x10^{-4}$ *	$1x10^{-3}$ *		after Schneider, 1967	
			Am Boung (FED 1991)	12.31	15.01		$1.1x10^{-3}$ **	$1x10^{-4}$ **			
			Bout el Fil (FED 1991)	12.57	14.95		$5.2x10^{-3}$ **	$1x10^{-4}$ **			
			Kaga (FED 1991)	+	+		$2.8x10^{-3}$ **	$1x10^{-4}$ **			
	Mayo Kebbi East	Q	Kandoul (1964)	+	+	$1.3x10^{-4}$ **	$1.7x10^{-3}$ **	$2x10^{-3}$ **			
			Bongor (GKW, 1969)	10.28	15.37		$2.5x10^{-2}$ **				
		Pli	Bokoyo (1963)	11.97	15.58		$4x10^{-3}$ *	$3x10^{-3}$ *			
	Mayo Kebbi	Bed rock	Tianga (GKW, 1970)	+	+		$3.5 x10^{-3}$ **				
		Cr	Garua	9.30	13.40		$3.5x10^{-5}$ - $2.5x10^{-2}$ **	10^{-4} - $2.5x10^{-2}$ **		after Martin, 1978; Beriat, 1984	
	Koros	CT	Bédoko	8.73	16.38		$5.5x10^{-2}$ **			after Garin, 1987	
			Beboni	8.79	16.66		$6x10^{-2}$ **				
			Bére	9.32	16.15		$1.5x10^{-4}$ *	$1.5 x 10^{-4}$ *		after Garin, 1987; Barbut, 1991	
			Gore Nord	12.86	14.81		$2x10^{-4}$ *	$1.6x10^{-5}$ *			
			Maikane	+	+		$3.9x10^{-4}$ *	$4x10^{-4}$ *			
			Draï Ngolo	9.57	16.15		$7.5x10^{-4}$		step-down; reinterpretation	UNESCO-BMZ-LCBC, 2000	
			Baloungou	+	+		$6.7x10^{-4}$				
			Dogbara	+	+		$1.1x10^{-3}$				
			Kariadeboum	9.18	16.70		$2.4x10^{-3}$				
			Dar Modelngar	+	+		$3x10^{-3}$				
			Tchere Ayba	9.41	16.73		$3.2x10^{-4}$				
	Batha	CT?	Banga	13.38	19.68		$8.9x10^{-4}$				

***File: parameters.xls. Collected and reviewed information on aquifer tests.**

APPENDIX D. GROUNDWATER MAPPING FOR THE 2008-2011 PERIOD

The selection of water points for mapping was based on information from different sources with unknown accuracy or data collection method. It is worth mentioning that: *i)* as some water level measurements found in the databases could not be definitively attributed to a specific aquifer unit (*Q* or *CT*), they were rejected; *ii*) no new data were found for the upper areas that lie north of Lake Chad.

After reviewing the reports presented in Table D1, they consist of records of groundwater level data in wells and related information (i.e. aquifer, well screen location, etc.). Some water points considered to be quite accurate are plotted in Fig. D1.

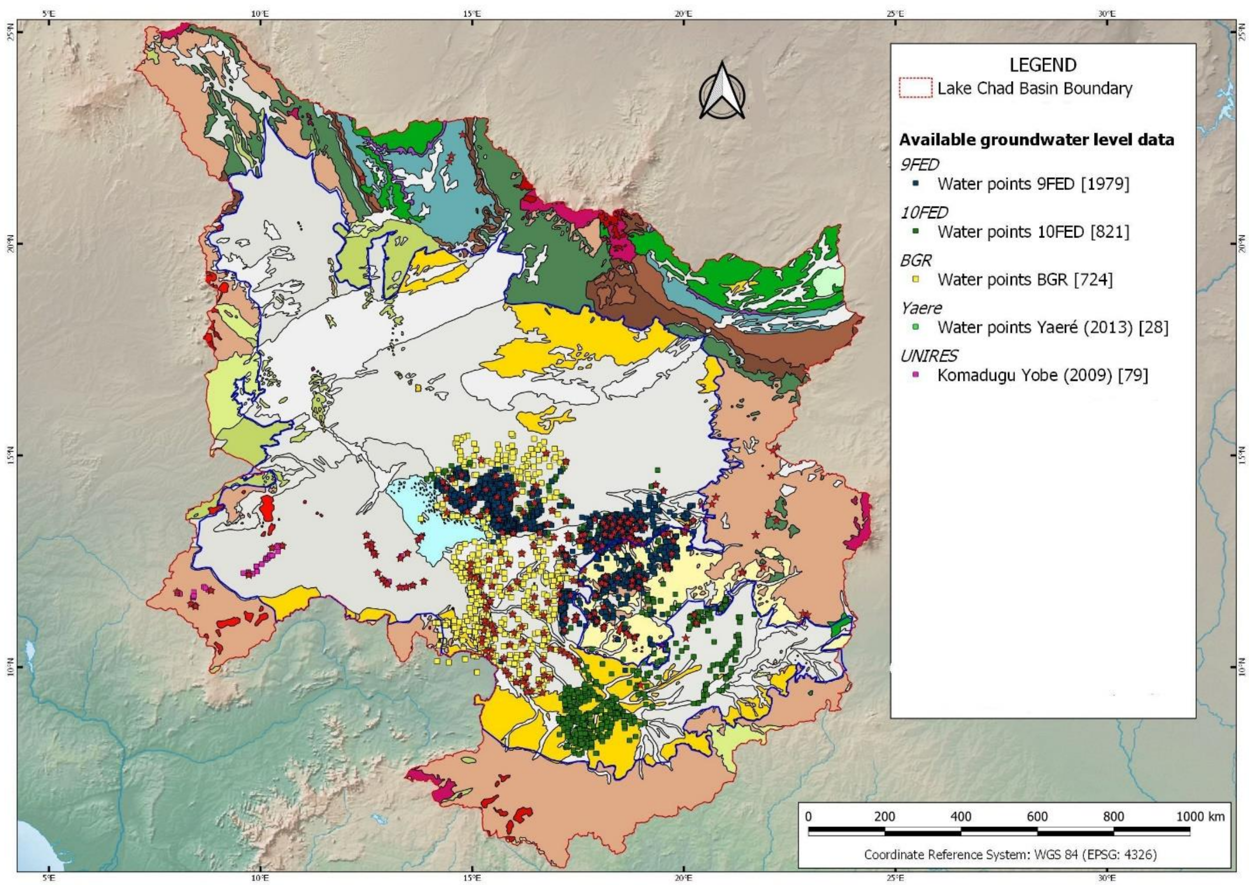

Figure D1. Spatial distribution of the total water points exploiting the aquifer system in the study area (from databases RESOPIEZ, SUIVPIEZ and SITEAU). UNIRES: (year) and [number of data] for the UNIRES campaign.

Of a total of 9,356 bores (traditional wells, piezometers, wells, Table 3, Table D2), a subset of 239 irregularly spaced data points, along with water level data (both aquifers), was selected for the regional flow description of both surface (unconfined) and deep (confined) aquifers (Table D3). Several years of groundwater measurements (from 2008 to 2011) were simultaneously drawn to build the piezometric map. Shallow wells or water wells with uncertain information were discarded.

To build the groundwater contour map, the water level depths of the wells and piezometers collected during the 2008-2011 period were converted from the measured data into relative levels (m.a.s.l.). A graphic construction of groundwater contours and flow direction was created by trial-and-error by plotting the dataset information on a topographic map on the 1:1,200.000 scale. Estimates of the surface water elevations along the riverbed that borders the site were estimated from the values reported from the DEM applied in the project.

Table D1. Availability of water points (boreholes, wells, piezometers).

Program/Inventory	Number of water points*	Coverage	Owner
5-8 FED	5,140	1987-2008	Direction de l'Hydraulique (Chad) (Includes Almy Nadif project co-financed by FED, KFW (German Cooperation) and AFD (Agence Française de Développement).
9FED	2,918	2008-2014	Direction de l'Hydraulique (Chad)
10FED	1430	2014-2017	Direction de l'Hydraulique (Chad)
11FED		2014?-2020	Direction de l'Hydraulique (Chad)
Projet Almy_Al_Afia	123	2005-2006	Programme d'Hydraulique Pastorale au Tchad Central (PHTC). Projet de la Direction de l'Hydraulique (Chad)
BGR	516	2008-2011, 2103	LCBC and Direction de l'Hydraulique (Chad)
UNIRES	80	2009	Univ. of Kansas Missouri-USA (Prof. Jejung). Komadougou-Yobé (Nigeria).
UNHCR/OXFAM GB	101	2009-2010	Refugees-Camps (Chad). Ministère de l'Hydraulique Villageoise et Pastorale. Direction de l'Alimentation en Eau potable LCBC
UNHCR	288	2004-2014	Refugees-Camps (Chad). Ministère de l'Hydraulique Villageoise et Pastorale. Direction de l'Alimentation en Eau potable LCBC
UNICEF	312	2009-2016	IAS (International Aid Services). LCBC
IAEA (RAF/7/011)	73	2010	LCBC
PHPTO	263	2004-2008	Project Almy-Bahaim LCBC; Direction de l'Hydraulique (Chad). (financed by AFD - Agence Française de Développement)
BD Forages (SITEAU)	59,045	1994, 1998-2009, 2011	LCBC; Direction de l'Hydraulique (Chad)
PHPTC	82	2006-2007	Project Almy_Al Afia LCBC; Direction de l'Hydraulique (Chad) (financed by AFD -Agence Française de Développement)
PRODALKA_GTZ	230	2005-2007	Mayo-Kebi (Chad). LCBC

Table D2. Table of all the water points with groundwater level (2008-2011). Only a small dataset is presented.

Campaign	Year	ID-Alias-code	Aquifer	Construction date	X (UTM)	Y (UTM)	Z (m)	Level measurement	Water level (m)	Gw level (masl)
9FED	2011	ABDA036		08/06/2011	190019.00	115028.00	522.51	10/06/2011	5.00	517.51
9FED	2011	ABDA038		16/03/2011	190217.00	114438.00	509.07	17/03/2011	7.88	501.19
9FED	2011	ABDC068		22/03/2011	191738.00	111835.00	468.01	23/03/2011	4.38	463.63
9FED	2011	ABDC069		12/06/2011	192933.00	111417.00	479.37	14/06/2011	10.02	469.35
9FED	2011	ABDC071		28/03/2011	191339.00	111414.00	483.00	29/03/2011	5.26	477.74
9FED	2011	ABEA090		29/03/2011	201314.00	134900.00	432.00	29/03/2011	38.29	393.71
9FED	2011	ABEA091		02/04/2011	200949.00	134901.00	426.00	02/04/2011	18.36	407.64
9FED	2011	ABEA093		18/03/2011	200154.00	133156.00	414.00	18/03/2011	55.52	358.48
9FED	2011	ABEA097		16/03/2011	200648.00	133544.00	411.00	16/03/2011	21.28	389.72
9FED	2011	ABEA100		08/03/2011	200458.00	133640.00	416.00	08/03/2011	37.20	378.80
9FED	2011	ABEA105		28/05/2011	200808.00	134713.00	428.00	28/05/2011	10.14	417.86
9FED	2011	ABEA106		15/03/2011	200235.00	133613.00	407.00	15/03/2011	22.54	384.46
9FED	2011	ABEA107		12/03/2011	200331.00	133840.00	411.00	12/03/2011	37.97	373.03
9FED	2011	ABEA108		28/03/2011	200015.00	133515.00	408.00	28/03/2011	45.84	362.16
9FED	2011	ABEA110		04/04/2011	200925.00	134857.00	422.00	04/04/2011	32.58	389.42
9FED	2011	ABEA111		13/03/2011	200446.00	133753.00	408.00	13/03/2011	23.97	384.03
9FED	2010	ABEC070	Quaternary	29/11/2010	200129.00	131004.00	416.00	29/11/2010	46.11	369.89
9FED	2010	ABEC073	Quaternary	30/11/2010	200052.00	131315.00	406.00	30/11/2010	40.72	365.28
9FED	2010	ABEC075	Quaternary	09/12/2010	200420.00	131825.00	405.00	09/12/2010	12.25	392.75
9FED	2010	ABEC077	Lower Pliocene	12/12/2010	201330.00	132733.00	419.00	12/12/2010	22.12	396.88
9FED	2011	ABEC081		04/06/2011	200703.00	124720.00	421.00	04/06/2011	24.22	396.78
9FED	2011	ABEC082		04/12/2010	201413.00	131217.00	412.00	04/02/2011	41.70	370.30
9FED	2011	AMDA049		06/05/2011	200426.00	133018.00	443.75	14/05/2011	31.26	412.49
9FED	2011	AMDA050		05/05/2011	201002.00	124832.00	436.93	16/05/2011	21.35	415.58
9FED	2008	AMJA036		25/10/2008	170445.00	134925.00	294.29	26/10/2008	26.81	267.48

File: water-points.xls. It contains information on the 2198 water points and groundwater levels for the 2008-2011 period

Table D3. Water points selected for the piezometric map.

Campaign	Year	ID_Alias Code	ID	Aquifer	X	Y	Z (m)	Level measurement	Water level (m)	Groundwater level (m.a.s.l)
BGR	2008	AH21	1	Quaternary	16.7077	10.7977	336.00	11/12/2008	34.75	301.25
BGR	2008	AH27	2	Basement	17.0962	10.3882	342.00	13/12/2008	18.1	323.90
BGR	2009	AH63	3	Quaternary	16.4503	12.8648	288.00	01/01/2009	35.3	252.70
BGR	2009	AH66	4	Quaternary	17.0667	11.7092	326.00	01/01/2009	28.6	297.40
BGR	2009	AH68	5	Quaternary	17.0697	11.9121	320.00	01/01/2009	31.8	288.20
BGR	2009	AH72	6	Quaternary	16.4700	11.6560	326.00	01/01/2009	39.6	286.40
BGR	2009	AH76	7	Quaternary	16.4282	11.4018	327.00	01/01/2009	29.3	297.70
BGR	2009	AH84	8	Quaternary	15.9934	10.8076	332.00	01/01/2009	36.5	295.50
BGR	2009	AH88	9	Quaternary	15.9531	11.2452	333.00	01/01/2009	45.75	287.25
BGR	2009	AH90	10	Quaternary	15.3596	11.4485	306.00	01/02/2009	7.5	298.50
BGR	2009	AH91	11	Quaternary	15.4298	11.5556	307.00	01/02/2009	30.3	276.70
BGR	2009	AH96	12	Quaternary	15.8884	11.8524	322.00	01/02/2009	51.15	270.85
BGR	2009	AH97	13	Quaternary	16.0683	12.0174	305.00	01/02/2009	40.35	264.65
BGR	2009	AH104	14	Quaternary	15.4657	11.9069	298.00	01/02/2009	30	268.00
BGR	2009	AH107	15	Quaternary	15.2220	12.0062	298.00	01/02/2009	12.85	285.15
BGR	2009	AH112	16	Quaternary	15.5621	12.1691	297.00	01/02/2009	42.7	254.30
BGR	2009	AH114	17	Quaternary	15.4063	12.5342	290.00	01/02/2009	42.4	247.60
BGR	2009	AH117	18	Quaternary	14.9616	12.1404	298.00	01/02/2009	12.31	285.69
BGR	2009	AH118	19	Quaternary	14.9412	12.2969	293.00	01/02/2009	15.15	277.85
BGR	2009	AH119	20	Quaternary	14.9710	12.4333	292.00	01/02/2009	25.52	266.48
BGR	2009	AH136	21	Quaternary	16.7885	11.5284	333.00	01/03/2009	6.5	326.50
BGR	2009	AH139	22	Quaternary	15.8644	12.4317	293.00	01/03/2009	51.7	241.30
BGR	2009	AH141	23	Lower Pliocene	17.3987	12.0432	332.00	01/03/2009	3.5	328.50

BGR	2009	AH145	24	Quaternary	17.3662	12.4130	304.00	01/03/2009	5.1	298.90
BGR	2009	AH147	25	Quaternary	17.1152	12.7993	292.00	01/03/2009	33	259.00
BGR	2009	AH148	26	Quaternary	17.2021	12.4109	297.00	01/03/2009	64.3	232.70
BGR	2009	AH152	27	Quaternary	16.6834	11.2191	335.00	01/03/2009	3.1	331.90
BGR	2009	AH155	28	Quaternary	17.6262	12.2882	326.00	01/03/2009	4.75	321.25
BGR	2009	AH157	29	Lower Pliocene	17.5651	11.9618	345.00	01/03/2009	5.1	339.90
BGR	2009	AH162	30	Lower Pliocene	16.9863	12.6713	292.00	01/03/2009	43.2	248.80
BGR	2009	AH167	31	Quaternary	17.2094	12.6328	293.00	01/04/2009	21.25	271.75
BGR	2009	AH168	32	Quaternary	15.9739	13.1611	290.00	01/04/2009	19.4	270.60
BGR	2009	AH169	33	Quaternary	16.1732	12.6807	292.00	01/04/2009	45.3	246.70
BGR	2009	AH170	34	Quaternary	15.2744	11.6755	304.00	01/04/2009	12.8	291.20
BGR	2009	AH173	35	Quaternary	16.1708	10.9494	329.00	01/04/2009	46	283.00
BGR	2009	AH177	36	Quaternary	15.6705	12.7009	290.00	01/04/2009	39.72	250.28
BGR	2009	AH187	37	Quaternary	15.3322	11.3678	312.00	01/04/2009	11.9	300.10
BGR	2009	AH192	38	Quaternary	15.1828	11.9172	300.00	01/04/2009	11.8	288.20
BGR	2009	1	39	Quaternary	15.0879	12.1080	298.00	01/11/2009	16.3	281.70
BGR	2009	2	40	Quaternary	16.4724	13.8722	279.00	01/11/2009	19.8	259.20
BGR	2009	3	41	Quaternary	16.4298	14.1082	287.00	01/11/2009	27.5	259.50
BGR	2009	4	42	Quaternary	16.5119	14.2773	284.00	01/11/2009	26.8	257.20
BGR	2009	11	43	Quaternary	16.7499	15.0487	293.00	01/11/2009	31.3	261.70
BGR	2009	14	44	Quaternary	17.2174	14.8483	266.00	01/11/2009	18.4	247.60
BGR	2009	18	45	Quaternary	16.2026	13.6582	290.00	01/11/2009	20.3	269.70
BGR	2009	26	46	Quaternary	16.0630	14.3285	291.00	01/11/2009	18.2	272.80
BGR	2009	28	47	Quaternary	16.0337	14.0838	287.00	01/11/2009	17.8	269.20
BGR	2009	29	48	Quaternary	15.9029	13.9808	286.00	01/11/2009	14.4	271.60
BGR	2009	38	49	Quaternary	16.7847	13.3747	307.00	01/11/2009	4	303.00
BGR	2009	40	50	Quaternary	17.2155	13.4522	299.00	01/11/2009	6.6	292.40
BGR	2009	42	51	Quaternary	16.8924	13.6903	289.00	01/11/2009	11.6	277.40
BGR	2009	46	52	Quaternary	17.2158	13.9262	290.00	01/11/2009	13.5	276.50

BGR	2009	63	53	Quaternary	15.3319	14.1898	330.00	01/11/2009	8.9	321.10
BGR	2009	64	54	Quaternary	15.5570	14.5063	360.00	01/11/2009	13.9	346.10
BGR	2009	77	55	Quaternary	15.3558	13.6931	298.00	01/12/2009	8.5	289.50
BGR	2009	81	56	Quaternary	16.2589	13.2815	308.00	01/12/2009	9.2	298.80
BGR	2009	82	57	Quaternary	16.9360	13.0633	288.00	01/12/2009	27.6	260.40
BGR	2009	84	58	Quaternary	16.6003	13.1634	295.00	01/12/2009	19.3	275.70
BGR	2009	85	59	Quaternary	15.7172	13.1786	289.00	01/12/2009	14.5	274.50
BGR	2009	102	60	Quaternary	15.1882	13.5754	301.00	01/12/2009	4.8	296.20
BGR	2009	171	61	Quaternary	14.4024	13.6450	294.00	01/12/2009	5.8	288.20
BGR	2009	172	62	Quaternary	14.3897	14.2285	313.00	01/12/2009	4.8	308.20
BGR	2009	173	63	Quaternary	14.3954	13.9778	303.00	01/12/2009	2.2	300.80
BGR	2009	176	64	Quaternary	15.2110	14.8865	350.00	01/12/2009	22	328.00
BGR	2009	177	65	Quaternary	14.7508	14.5355	343.00	01/12/2009	5.7	337.30
BGR	2009	179	66	Quaternary	15.8174	14.3006	321.00	01/12/2009	22	299.00
BGR	2009	181	67	Quaternary	15.5878	14.0143	318.00	01/12/2009	14.3	303.70
BGR	2009	184	68	Quaternary	14.5308	14.4356	337.00	01/12/2009	12.7	324.30
BGR	2010	AH203	69	Quaternary	14.3083	14.3638	315.00	01/03/2010	19.5	295.50
BGR	2011	A3	70	Continental Terminal	17.4704	10.0911	346.00	01/01/2011	17.37	328.63
BGR	2011	A4	71	Continental Terminal	17.4310	10.1654	349.00	01/01/2011	8.7	340.30
BGR	2011	A5	72	Continental Terminal	17.2954	10.2716	350.00	01/01/2011	21.35	328.65
BGR	2011	A6	73	Continental Terminal	17.1857	10.3356	343.00	01/01/2011	18.5	324.50
BGR	2011	A9	74	Quaternary	16.8456	10.4352	335.00	01/01/2011	26	309.00
BGR	2011	A19	75	Quaternary	15.5387	10.7964	316.00	01/01/2011	36.2	279.80
BGR	2011	A22	76	Quaternary	15.4509	10.3929	325.00	01/01/2011	9.75	315.25
BGR	2011	A25	77	Quaternary	15.4751	10.9932	315.00	01/01/2011	19.15	295.85
BGR	2011	A28	78	Quaternary	15.3321	11.3678	312.00	01/01/2011	10.17	301.83
BGR	2011	A34	79	Quaternary	15.4083	10.2472	331.00	01/01/2011	4.04	326.96
BGR	2011	A37	80	Quaternary	15.7859	9.9119	339.00	01/01/2011	4.2	334.80

BGR	2011	A38	81	Quaternary	15.8594	9.8154	346.00	01/01/2011	3.9	342.10
BGR	2011	A40	82	CT	16.0410	9.6403	346.00	01/01/2011	2.1	343.90
BGR	2011	A42	83	Quaternary	16.2019	9.6551	347.00	01/01/2011	4.49	342.51
BGR	2011	A43	84	CT	16.2671	9.7602	352.00	01/01/2011	4.82	347.18
BGR	2011	A48	85	Quaternary	16.3326	10.0134	341.00	01/01/2011	13.44	327.56
BGR	2011	A49	86	Quaternary	15.4933	10.8992	320.00	01/01/2011	21.9	298.10
BGR	2011	A50	87	Quaternary	16.3048	10.2931	336.00	01/01/2011	14.2	321.80
BGR	2011	A59	88	Quaternary	15.7510	10.2030	335.00	01/01/2011	12	323.00
BGR	2011	A65	89	Quaternary	15.8938	10.5249	324.00	01/01/2011	3.1	320.90
BGR	2011	A70	90	Quaternary	16.1979	10.5798	328.00	01/01/2011	23.6	304.40
BGR	2011	A75	91	Quaternary	16.6742	10.1794	338.00	01/01/2011	20	318.00
BGR	2011	A77	92	Continental Terminal	16.7099	9.7953	345.00	01/01/2011	7	338.00
BGR	2011	A80	93	Continental Terminal	16.8398	9.7385	345.00	01/01/2011	8.65	336.35
BGR	2011	A83	94	Continental Terminal	16.5884	9.5964	351.00	01/01/2011	4.2	346.80
BGR	2011	A86	95	Continental Terminal	16.6588	9.3918	360.00	01/01/2011	10.9	349.10
BGR	2011	A89	96	Continental Terminal	16.3997	9.4226	357.00	01/01/2011	7.8	349.20
BGR	2011	A90	97	Continental Terminal	16.2946	9.4102	356.00	01/01/2011	5.1	350.90
BGR	2011	A91	98	Continental Terminal	16.2793	9.5828	352.00	01/01/2011	3.57	348.43
BGR	2011	A94	99	Quaternary	15.3177	10.3756	324.00	01/01/2011	2.7	321.30
BGR	2011	A97	100	Quaternary	15.2316	10.5702	318.00	01/01/2011	11.1	306.90
BGR	2011	A98	101	Quaternary	15.2349	10.6764	319.00	01/01/2011	5	314.00
BGR	2011	A101	102	Quaternary	15.2705	10.8592	314.00	01/01/2011	3	311.00
BGR	2011	A103	103	Quaternary	15.3476	11.0264	313.00	01/01/2011	12.15	300.85
BGR	2011	A104	104	Quaternary	15.2960	11.0934	313.00	01/01/2011	2.8	310.20
UNIRES	2009		105	Quaternary	12.7654	12.2200	318.00		318.00	253.00
UNIRES	2009		106	Quaternary	12.7115	12.6450	306.00		306.00	242.00

UNIRES	2009		107	Quaternary	12.8816	12.0733	329.00		329.00	272.61
UNIRES	2009		108	Quaternary	12.6724	12.7107	303.00		303.00	246.61
UNIRES	2009		109	Quaternary	12.9490	12.0009	337.00		337.00	287.00
UNIRES	2009		110	Quaternary	12.6204	12.8201	308.00		308.00	259.00
UNIRES	2009		111	Quaternary	13.0018	11.9553	327.00		327.00	278.28
UNIRES	2009		112	Quaternary	13.4441	11.8836	305.00		305.00	257.30
UNIRES	2009		113	Quaternary	13.8614	12.0172	294.00		294.00	256.00
UNIRES	2009		114	Quaternary	12.6171	12.9175	312.00		312.00	274.50
UNIRES	2009		115	Quaternary	13.5996	11.9272	297.00		297.00	261.50
UNIRES	2009		116	Quaternary	12.5303	12.8761	308.00		308.00	273.00
UNIRES	2009		117	Quaternary	13.2934	11.8780	304.00		304.00	269.40
UNIRES	2009		118	Quaternary	13.3048	12.5699	288.00		288.00	253.86
UNIRES	2009		119	Quaternary	13.4720	12.6829	290.00		290.00	265.80
UNIRES	2009		120	Quaternary	13.7282	13.0018	281.00		281.00	266.00
UNIRES	2009		121	Basement	8.8313	11.8042	417.00		417.00	406.00
UNIRES	2009		122	Quaternary	13.7990	13.0790	282.00		282.00	273.60
UNIRES	2009		123	Basement	8.0279	11.7707	522.00		522.00	513.71
UNIRES	2009		124	Quaternary	10.2742	12.8078	344.00		344.00	337.50
UNIRES	2009		125	Quaternary	12.5037	13.1127	303.00		303.00	297.00
UNIRES	2009		126	Basement	8.3589	11.4840	537.00		537.00	531.00
UNIRES	2009		127	Basement	8.4644	11.4319	552.00		552.00	547.60
UNIRES	2009		128	Quaternary	9.7237	12.1723	368.00		368.00	363.90
UNIRES	2009		129	Quaternary	10.5179	12.8587	342.00		342.00	340.00
9FED	2010	ABEC070	130	Quaternary	20.0247	13.1678	416.00		416.00	369.88
9FED	2010	ABEC073	131	Quaternary	20.0144	13.2208	406.00		406.00	365.28
9FED	2010	ABEC075	132	Quaternary	20.0722	13.3069	405.00		405.00	392.75
9FED	2010	ABEC077	133	Lower Pliocene	20.2250	13.4592	419.00		419.00	396.88
9FED	2010	AMJC065	134	Quaternary	17.2694	13.1253	336.00		336.00	307.34
9FED	2010	AMJD094	135	Quaternary	17.5803	13.1128	300.00		300.00	266.15

9FED	2010	AMJD105	136	Quaternary	17.6658	13.1344	344.00		344.00	306.37
9FED	2010	AMJD111	137	Quaternary	17.2744	13.0278	300.00		300.00	267.40
9FED	2010	AMJD117	138	Quaternary	17.8989	13.4928	343.00		343.00	290.20
9FED	2010	ATIA047	139	Quaternary	18.2606	13.5269	332.00		332.00	270.85
9FED	2010	ATIB111	140	Quaternary	18.5886	13.5494	335.00		335.00	279.22
9FED	2010	ATIC257	141	Quaternary	18.3647	13.1856	336.00		336.00	328.62
9FED	2010	ATIC278	142	Quaternary	18.1703	13.3114	342.00		342.00	297.48
9FED	2010	ATIC292	143	Quaternary	18.0975	13.4056	326.00		326.00	268.78
9FED	2010	ATIC297	144	Quaternary	18.3186	13.3706	337.00		337.00	286.74
9FED	2010	ATIC314	145	Quaternary	18.1381	13.1386	338.00		338.00	301.08
9FED	2010	ATIC330	146	Quaternary	18.2867	13.0911	344.00		344.00	315.90
9FED	2010	ATIC362	147	Quaternary	18.4961	13.4300	332.00		332.00	278.74
9FED	2010	ATIC367	148	Quaternary	18.4592	13.2767	330.00		330.00	294.76
9FED	2010	ATID128	149	Lower Pliocene	18.5989	13.0542	345.00		345.00	337.03
9FED	2010	ATID140	150	Quaternary	18.7275	13.0772	343.00		343.00	323.21
9FED	2010	ATID156	151	Quaternary	18.7736	13.4953	348.00		348.00	289.49
9FED	2010	ATID158	152	Quaternary	18.7217	13.3931	349.00		349.00	289.97
9FED	2010	ATID159	153	Quaternary	18.7642	13.2053	345.00		345.00	293.67
9FED	2010	ATID160	154	Quaternary	18.9772	13.4328	358.00		358.00	296.97
9FED	2010	ATID163	155	Quaternary	18.8678	13.2803	362.00		362.00	298.57
9FED	2010	ATID168	156	Lower Pliocene	18.7231	13.0392	343.00	06/06/2010	343.00	333.00
9FED	2010	ATID174	157	Quaternary	18.5586	13.2061	337.00		337.00	309.51
9FED	2010	ATID175	158	Quaternary	18.6800	13.4053	337.00		337.00	281.00
9FED	2010	BOKB129	159	Lower Pliocene	17.9931	12.7567	311.00		311.00	307.06
9FED	2010	BOKB137	160	Quaternary	17.9439	12.7983	311.00		311.00	278.23
9FED	2010	BOKB141	161	Quaternary	17.5228	12.9822	310.00		310.00	289.50
9FED	2010	BOKB145	162	Quaternary	17.6119	12.9864	303.00		303.00	281.00
9FED	2010	BOKB153	163	Quaternary	17.8606	12.9422	342.00		342.00	319.31

9FED	2010	DAGA031	164	Lower Pliocene	18.1056	10.9006	410.01		410.01	401.04
9FED	2010	DAGA033	165	Lower Pliocene	18.1169	10.9506	416.00		416.00	407.30
9FED	2010	DAGB031	166	Lower Pliocene	18.6428	10.8003	429.86		429.86	418.53
9FED	2010	DAGB032	167	Lower Pliocene	18.7125	10.7364	413.72		413.72	400.32
9FED	2010	DAGB033	168	Lower Pliocene	18.8431	10.6908	450.04		450.04	422.50
9FED	2010	GUEA078	169	Lower Pliocene	18.1525	11.9558	423.83	14/04/2010	423.83	415.71
9FED	2010	GUEA085	170	Lower Pliocene	18.0631	11.9889	411.02		411.02	405.80
9FED	2010	GUEB029	171	Lower Pliocene	18.9353	11.8631	508.61		508.61	500.33
9FED	2010	GUEB040	172	Lower Pliocene	18.7692	11.9186	604.95		604.95	594.36
9FED	2010	MANA070	173	Quaternary	19.0286	12.9006	355.00		355.00	328.54
9FED	2010	MANB050	174	Lower Pliocene	19.7150	12.6786	416.68		416.68	382.70
9FED	2010	MANB098	175	Quaternary	19.7575	12.9803	413.00		413.00	381.19
9FED	2010	MANC045	176	Lower Pliocene	19.0761	12.0719	484.47		484.47	477.20
9FED	2010	MAND045	177	Quaternary	19.6261	12.3194	501.15		501.15	497.56
9FED	2010	MAND051	178	Quaternary	19.5769	12.4136	508.84		508.84	502.20
9FED	2010	MELB020	179	Lower Pliocene	17.9103	11.6847	395.00		395.00	380.81
9FED	2010	MELD084	180	Lower Pliocene	17.7731	11.2000	386.21		386.21	371.43
9FED	2010	MELD098	181	Lower Pliocene	17.8947	11.2736	380.94		380.94	356.73
9FED	2010	MELD101	182	Lower Pliocene	17.9464	11.0839	396.93		396.93	381.00
9FED	2010	MGOA226	183	Lower Pliocene	18.4372	12.8092	349.00		349.00	310.87
9FED	2010	MGOA238	184	Quaternary	18.0789	12.8586	329.00		329.00	301.61

9FED	2010	MGOB243	185	Lower Pliocene	18.9375	12.9867	350.00		350.00	325.67
9FED	2010	MGOB251	186	Lower Pliocene	18.8072	12.9811	349.00		349.00	340.00
9FED	2010	MGOB252	187	Lower Pliocene	18.6069	12.9711	345.00		345.00	321.15
9FED	2010	MGOB253	188	Lower Pliocene	18.8089	12.8733	355.00		355.00	335.70
9FED	2010	MGOB254	189	Lower Pliocene	18.8422	12.9261	344.00		344.00	328.45
9FED	2010	MGOC160	190	Lower Pliocene	18.1522	12.1336	413.36		413.36	401.14
9FED	2010	MGOC180	191	Quaternary	18.4431	12.1072	469.02		469.02	456.34
9FED	2010	MGOD193	192	Quaternary	18.9292	12.1489	601.00		601.00	571.11
9FED	2010	MGOD213	193	Lower Pliocene	18.7872	12.0497	457.93		457.93	442.45
9FED	2010	MGOD223	194	Quaternary	18.9458	12.4119	393.55		393.55	364.51
9FED	2010	MGRC030	195	Quaternary	19.3397	14.3014	364.00		364.00	299.04
9FED	2010	MGRD040	196	Quaternary	19.5231	14.1586	367.00		367.00	298.14
9FED	2010	OMJC077	197	Lower Pliocene	19.0792	13.2861	364.00		364.00	299.88
9FED	2010	OMJD034	198	Lower Pliocene	19.6278	13.1603	381.00		381.00	353.14
9FED	2010	OMJD039	199	Lower Pliocene	19.5417	13.1194	379.00		379.00	353.09
9FED	2010	OMJD040	200	Lower Pliocene	19.5178	13.1622	376.00		376.00	360.73
9FED	2009	BOLB233	201	Quaternary	14.7411	13.9217	317.10		317.10	305.82
9FED	2009	BOLB242	202	Quaternary	14.8917	13.6692	298.83		298.83	290.29
9FED	2009	MELA083	203	Quaternary	17.0992	11.5158	326.50		326.50	306.97
9FED	2009	MELA114	204	Quaternary	17.3247	11.6936	334.74		334.74	289.18
9FED	2009	MELC034	205	Quaternary	17.2175	11.1286	337.94		337.94	311.02
9FED	2009	MELC036	206	Lower Pliocene	17.4656	11.2006	342.93		342.93	297.43
9FED	2009	MELC037	207	Lower Pliocene	17.4294	11.1014	342.99		342.99	305.77

9FED	2009	MILA009	208	Quaternary	17.1756	10.8678	342.33		342.33	325.18
9FED	2009	NGRA415	209	Quaternary	15.0517	13.9683	327.09		327.09	313.49
9FED	2009	NGRB158	210	Quaternary	15.6833	13.7750	305.14		305.14	270.62
9FED	2009	NGRD267	211	Quaternary	15.6344	13.4903	305.15		305.15	276.78
9FED	2009	NOKD041	212	Quaternary	14.9139	14.1694	337.81		337.81	305.41
PHPTO	2008		213	Quaternary	22.1950	13.4564	811	04/04/2008	38.45	772.55
PHPTO	2008		214	Quaternary	21.7025	13.1225	647	01/05/2008	20.86	626.14
PHPTO	2008		215	Quaternary	21.6964	13.1183	648	02/05/2008	19.76	628.24
PHPTO	2008		216	Quaternary	22.0086	13.6253	872	06/05/2008	28.2	843.8
PHPTO	2008		217	Quaternary	20.5122	13.5053	470	20/08/2008	20.95	449.05
PHPTO	2008		218	Quaternary	20.7615	14.0090	530	21/01/2008	29.72	500.28
PHPTO	2008		219	Quaternary	20.4211	13.8222	451	26/01/2008	32.26	418.74
PHPTO	2008		220	Quaternary	20.6681	13.8433	574	28/01/2008	13.65	560.35
PHPTO	2011		221	Basement	12.4150	21.5656	607	26/06/2011	607	594.58
UNHCR (Chad)	2010	Kounougou	222	Basement	14.7747	22.5747	911	26/04/2010	28.2	892.45
UNHCR (Chad)	2011	IRIDF006	223	Quaternary	22.2124	15.1986	959	2010	18.45	940.55
UNICEF	2009		224	Basement	22.8183	11.2628	559	03/11/2009	16.79	542.21
UNICEF	2009		225	Basement	22.9233	11.2356	578	06/11/2009	35.25	542.75
UNICEF	2009		226	Lower Pliocene	22.7758	11.0472	510	04/11/2009	27.62	482.38
UNICEF	2011		227	Quaternary	21.8681	12.3608	581	20/10/2011	18.43	562.57
UNICEF	2011		228	Quaternary	12.4150	21.5656	607	26/06/2011	607	594.58
UNHCER	2009	DJAB F001	229	Basement	21.3798	12.2433	582	2009	31.37	550.63
UNHCER	2009	DJAB F002	230	Basement	21.3895	12.2195	584	2009	584	584
UNHCER	2010		231	Basement	14.5094	22.0723	983	2010	983	980.04
UNHCER	2010		232	Basement	14.4628	21.9399	976	2010	976	956.85
UNHCER	2010	GUER F002	233	Quaternary	22.0723	14.5094	983	2010	2.96	980.04
UNHCER	2010	IRID F012	234	Quaternary	22.1160	15.1155	937	2010	17.35	919.65
BD Forages/	2008	SARB078	235	Quaternary	18.9800	9.5700	433	09/06/2008	56.91	376.09

Direction Hydraulique										
BD Forages/ Direction Hydraulique	2008	IROA017	236	Quaternary	19.4800	10.5000	405	10/04/2008	11.18	393.82
BD Forages/ Direction Hydraulique	2008	AMTC123	237	Quaternary	20.3000	11.0400	436	12/05/2008	25.11	410.89
BD Forages/ Direction Hydraulique	2008	DJOA044	238	Quaternary	20.0500	10.6800	420	15/05/2008	16.46	403.54
BD Forages/ Direction Hydraulique	2009	AMTC146	239	Quaternary	20.2500	11.2300	439	18/01/2009	37.41	401.59

File: selected-water-points.xls

APPENDIX E. NATURAL RECHARGE ESTIMATION

Groundwater recharge is a complex nonlinear process function of meteorological conditions, soil, vegetation, physio-graphic characteristics and geological material properties. Quantification of the natural groundwater recharge rate is a basic prerequisite for efficient groundwater resources management (Lerner et al., 1990; Stephenson et al., 1981).

Recharge estimation was obtained through the open source VISUAL-BALAN V2.0 model, which computes sequential daily water balances in soil, the unsaturated zone and the aquifer by a distributed approach. The main soil water processes of the balance include precipitation and irrigation input, where output is water interception, surface runoff, evapotranspiration, interflow and groundwater flow, soil water variation and water level in the aquifer. The soil-water budget is simply an accounting scheme used to predict soil-water storage, evapotranspiration and water surplus (including deep infiltration, overland flow and stream losses). Multiplying the rate (mm/yr) by the recharge zone areal extension gives the volumetric recharge (m^3).

To define the recharge zones in the region, different layers of information (DEM, land use/land cover, soil types, rainfall and geomorphology) were defined (Table E1, Fig E1). RS data and GIS tools were used to overlay the different layers. The existing meteorological stations with daily data from TAHMO used for recharge estimation are found in figure E2.

Table E1. The layers with information used for recharge estimation.

Layer	Source	Remarks
Digital Elevation Model (DEM)	The United States Geological Survey (USGS) Global Data Explorer (GDEx) website (https://gdex.cr.usgs.gov/gdex/)	A 30*30 m resolution ASTER global DEM (ASTER GDEM), version 2.0
Land Use and Land Cover	The European Space Agency (ESA)	Defining the rain-fed and irrigated areas from groundwater for millet, sorghum, maize and rice crops
Soil type	European Soil Data Centre (https://esdac.jrc.ec.europa.eu/content/soil-map-soil-atlas-africa#tabs-0-description=0)	
Precipitation and temperature	TAHMO: www.tahmo.org; CHADFDM:http://stream.CHADFDM.edu/CHADFDM/WEBPAGE/interface.php?locale=en	Daily data
Climate classification	The Köppen–Geiger climate classification system	Subdividing the area into three zones according to rainfall and temperature.

Seventeen natural recharge zones were defined and assumed as being homogeneous in relation to soil parameters, land use (forest, urban, irrigated and rain-fed), aquifer and meteorological data.

Recharge was calculated for all these zones for the 2005–2014 period. The lack of wells hydrographs (groundwater level time series for this period did not allowed model calibration.

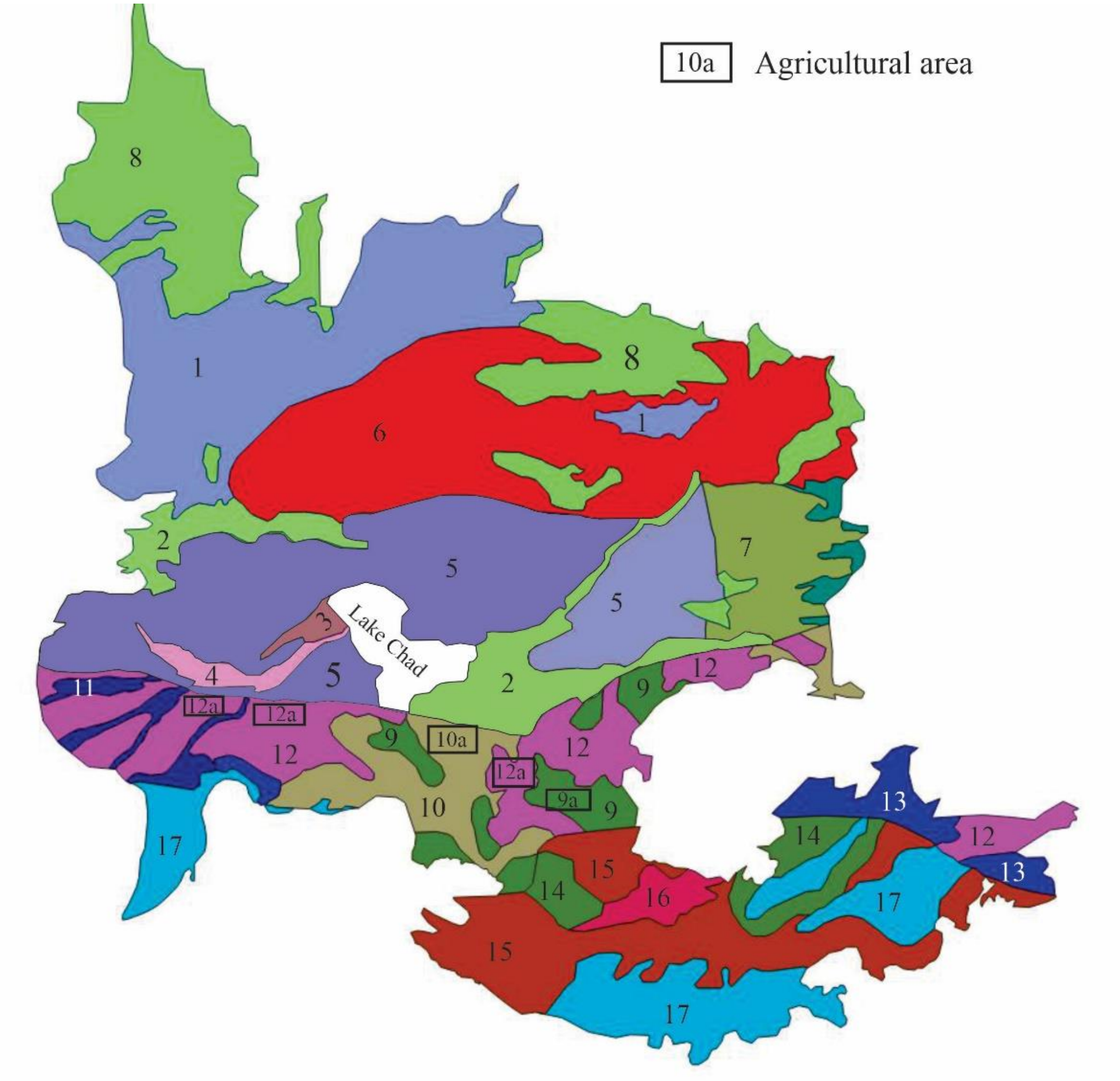

Figure E1. Zonation of recharge areas for the surface aquifer. Numbers in squares indicate areas that have undergone agricultural development in the zone.

Meteorological conditions analysis

To calculate natural recharge, the quantitative data of meteorological records, mainly precipitation and temperature measurements, were retrieved and analyzed from three open platforms (SIEREM, TAHMO and ResEau), an online data repository. Most records present gaps, are discontinuous or only had several years of quality data.

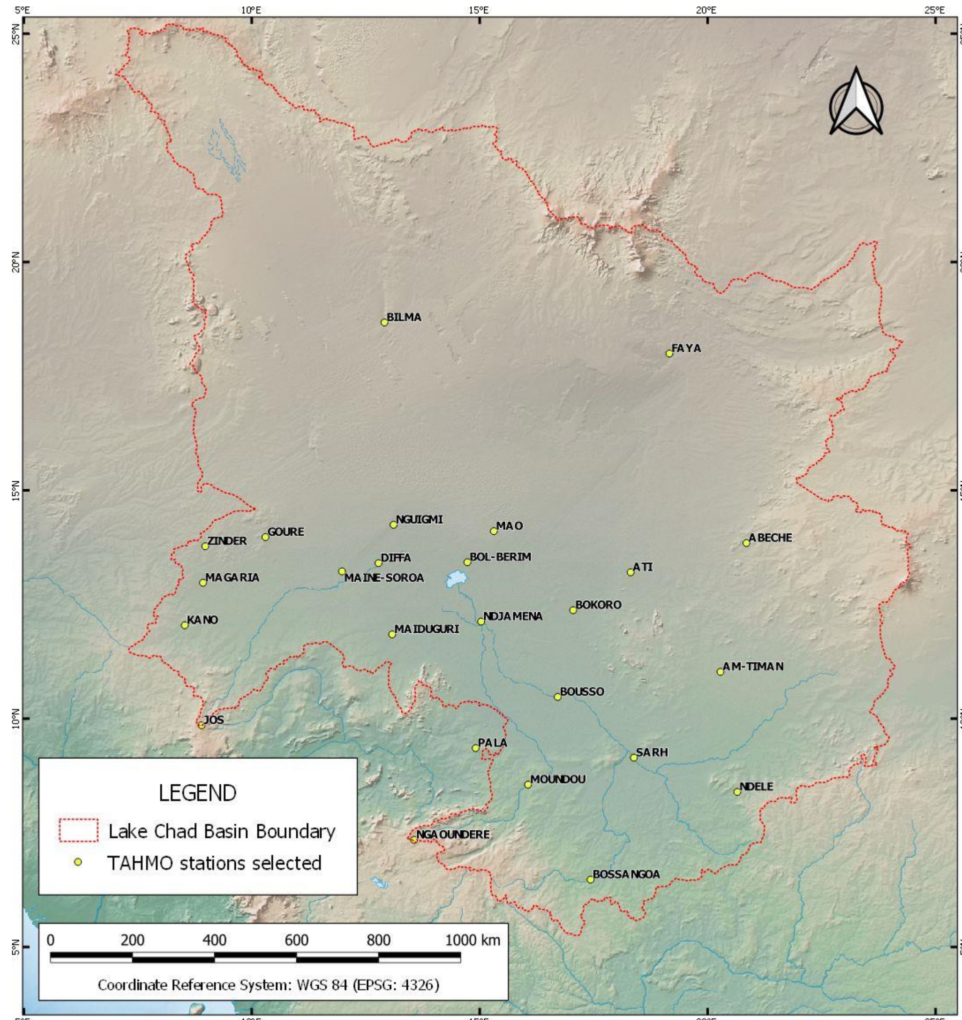

Figure E2. The TAHMO meteorological stations in the LCB with daily data.

Table E2. The meteorological data available on open platforms.

Parameters	TAHMO	SIEREM	ResEeau
Number of ground-based stations	32	332	52
Time period	1973 - 2018	1940-1990	1998-2012
Type of data	daily	daily	mean
Continuous data series	yes	relevant gaps	no
Precipitation (P)	yes	yes	yes
Temperature (T)	yes	no	no
Wind	yes	no	no
Other parameters	yes	no	no

TAHMO (Trans-African Hydro-Meteorological Observatory) database storage has continuous daily time series available (P and T), and was the most appropriate for this study (Table E2). As many years and stations present gaps in data, the daily rainfall data from 2005 to 2014 were collected from the 25 rainfall ground stations presented Fig. E2.

The 2005-2014 period had the highest percentage of available data and the fewest gaps (less than 20%) in the time series. The 10-year dataset length allowed a robust amount of daily rainfall variability in the region to be captured.

Satellite rainfall products (datasets) were also downloaded from the Lake Chad's Flood and Drought Monitoring and Forecasting System (CHADFDM), Multi-Source Weighted-Ensemble Precipitation (MSWEP). For the 2005-2014 period, gridded rainfall estimates were compared with the TAHMO datasets for the same period and locations. A visual observation of the rainfall datasets indicated that the wet and dry conditions during the 2005-2014 period presented different trends on both platforms and satellite data sets overestimated the ground-based values in some specific locations.

Results

The results of the final recharge from precipitation and irrigation are presented in Table E3; similar results have been obtained by other authors (Leblanc, 2002; Babamaaji et al., 2012). Apparently in the areas with low precipitation and high temperature, irrigation was a major source of recharge to aquifers, regardless of them using groundwater or surface water (Lerner et al., 1990). Previous compilations made in the study into recharge in irrigated zones in a semiarid environment on the global scale showed that irrigation increased recharge by between 1% and 25%, with an average of ~15% (Scanlon et al., 2006).

Table E3. The 17 recharge zones and average recharge estimations for 2008-2011 (see also Fig. E3).

Zones	Area (km^2)	Mean precipitation (mm/yr) (2008-2011)	Mean recharge (rainfall) (mm/ yr) (2008-2011)	Total recharge (mm) (2008-2011)
1	155,000	7	0	0
2	80,854	250	0	0
3	4,261	156	0	0
4	10,340	240	12	36
5	97,283	184	7	21
6	189,000	30	0	0
7	155,389	267	19	57
8	160,000	7	0	0
9*	34,541	716	26	977
10*	50,143	743	38	1,028
11	15,463	365	39	117

12*	106,058	591	61	1,117
13	27,434	1,200	153	460
14	28,898	1,200	140	419
15	101,472	1,187	123	369
16	11,814	1,187	161	483
17	96,723	1,433	193	580

**Irrigated areas (data taken from www.fao.org/aquastat)*

Visual Balan makes a number of simplifying assumptions; for example, water moves vertically and not laterally, although recharge may not be purely diffused, but may also occur more as a preferential flow. Assumptions, inputted information, along with the vast area, could lead to different estimates to the 'considered true' values.

The Visual Balan model outputs were directly exported to the Modflow model. However, outputs were used as first inputs to calculate recharge for Modflow by considering that the results were based on a physically robust estimation process.

APPENDIX F. THE PROJECT'S DATABASE

Data Archiving

The data used to develop the groundwater hydrology and model conceptualization were introduced into an open source geographical information system (QGIS), which allows create, edit, visualize, analyze and map geospatial information gathered from existing literature for monitoring or site investigation purposes. This serves as a repository for all the data, information and knowledge that accumulated through the project to facilitate future analyses of the aquifer system. This information wealth provides a framework to obtaining the data needed for further numerical model development. The developed data inventory includes data source lists and references.

Data are stored on a spreadsheet, QGIS, or even in a Geo-model. The DB design allows information to be retrieved, such as the inventory of: borehole location and associated data (owner, data, geological description, etc.); water point (owner & campaign, water level observations or tests). Basic understanding of QGIS is necessary.

This section describes the archive structure and the all data to support the hydrogeological interpretations and the associated metadata, e.g. data source, capture date, etc.

Data collection, analysis and checking

The available data, based on measurements and interpretations of observations, come mainly from a number of hydrogeological studies and reports conducted for site research purposes. A wide variety of additional data is generally available (including descriptive data), which can be split into three different groups:

i) geographical, which refers especially to location coordinates, elevation or depth; *ii)* geological, composed of boreholes and lithological, hydrostratigraphical and pretrographical descriptions; *iii)* hydrologic-hydrogeological information made up of *in situ* tests, hydrological parameters, observation heads, climate, etc. A full list is presented below.

In order to avoid erroneous information, the analysis stage (data collection and assessment) included: *i)* confirming the location, availability and verification of the obtained data; *ii)* assessing the spatial/temporal distribution and validity of all the parameters and observations; *iii)* the quantification of flow processes or stresses (e.g. recharge, abstraction; *iv)* developing data inventories, including data source lists and references.

The units used

The MKS system, the international standard system of units, is applied to the different data used in modeling. Table G1 presents the parameters and units applied while the project was underway.

Table F1. Parameters and units.

Temperature	**ºC**
Precipitation	mm
Time	day (d)
Depth	meter (m)
Length	meter (m)
Elevation	meter (m)
Coordinates	UTM (Rockware & MODFLOW) Geographical (QGIS)
Hydraulic conductivity (K)	meter/second (m/s)
Transmissivity (T)	$meter^2/second$ (m^2/s)
Storage coefficient (S)	dimensionless
Porosity (m)	%
Recharge	millimeter/year (mm/yr)
Flow	$meter^3/day$ (m^3/day)
Evapotranspiration	millimeter/year (mm/yr)
Groundwater allocation and use	million cubic meter/year (Mm^3/yr)
Pumping rates	cubic meter/day (m^3/d)
Head potential	meter (m.a.s.l)

Data storage and display

Input data

The geological information from boreholes was analyzed and coded to be stored in a DB. Each borehole is defined by its geographical coordinates (latitude and longitude), depth and elevation. The depth of the hydrostratigraphical/lithological changes (hydrogeological layers) is retrieved from the information stored in the geological logs DB. This approach facilitates further possible changes in the system's geometry. Finally, 430 randomly distributed geological logs with descriptive data were used to set up the system.

Regarding elevation, the topographical surface (upper limit of the quaternary aquifer) is based on the SRTM 30m data (https://lpdaac.usgs.gov/dataset_discovery/measures/measures_products_table/srtmgl1_v003). To obtain top soil elevation, Multi-resolution Terrain Elevation Data 2010 (GMTED2010) (USGS) data were used. The employed dataset is 30 arc-seconds (resolution of about 1 km). There are more datasets with higher resolutions but, due to computational limitations, this dataset was the best solution for the project's objective.

For the purpose of this report, a location code index was established that provides each location with a unique code. The unique code used in this report is included in Appendix D, along with the corresponding codes used by others (Alias-CODE). This systematic approach is beneficial because nonunique location codes exist from previous work and can lead to confusion.

The hydraulic parameters of the different aquifers (*Q* and *LPli-CT*) were retrieved from technical reports, PhD and MSc theses provided by LCBC, IRD, ResEau, or from existing repositories. After analyzing the test procedure, data quality and the obtained values, the selected results were stored in the DB (with the corresponding geographical coordinates, aquifer and data sources). The assessment included comments on the uncertainty of values. The piezometric information includes the geographical location and the groundwater level of the selected water points after quality assurance checks. The piezometric data went from 2008 to 2011, and only one datum per water point was used.

Output data

The database output permits the total or partial retrieval, and the display, of the information stored by output devices (screen and printer) following QGIS system procedures.

Graphic outputs include maps with the spatial location of geological boreholes, water points or hydraulic parameters for the defined aquifers. The files resulting from the stored information data search are also produced by user demand following the QGIS procedure (https://qgis.org/en/docs/index.html). Some examples of exploitation are presented in Figs. F1 to F4.

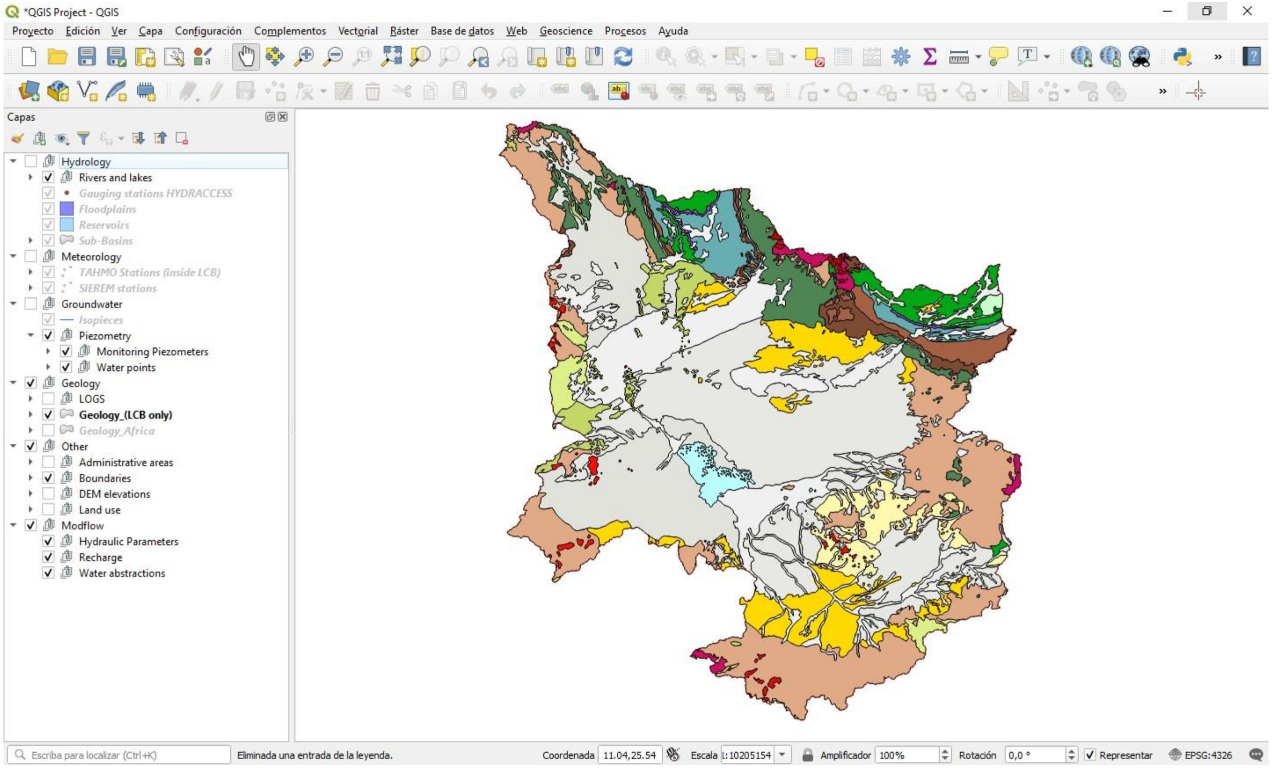

Figure F1. The GIS database overview.

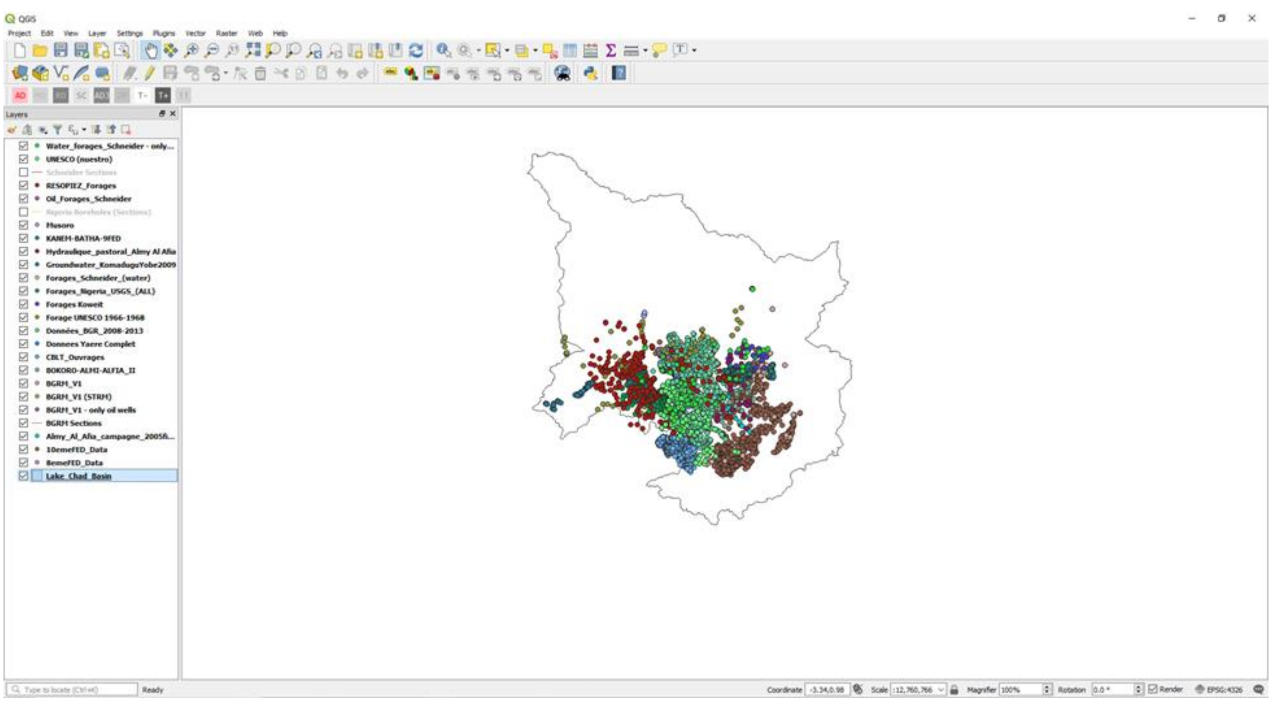

Figure F2. Water points.

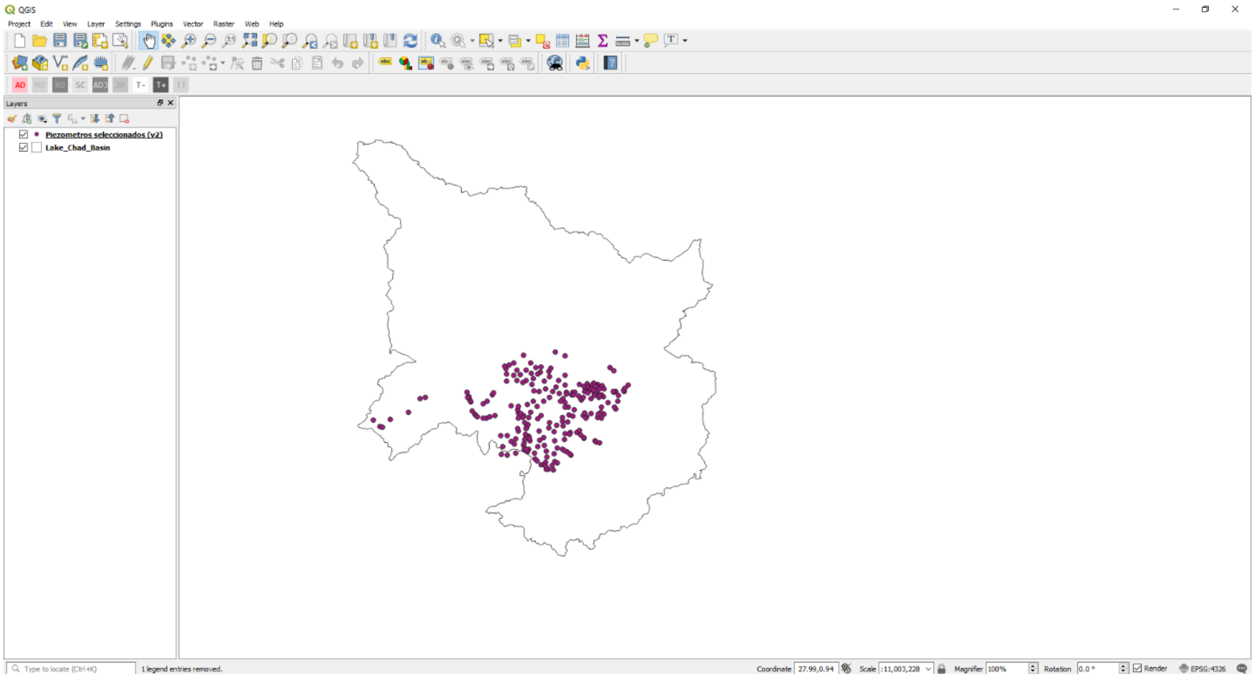

Fig F3. Selected wells.

	Campaign	Year	ID-Alias code	village	Construction date	X (GCS)	Y (GCS)	Z(m)	Well depth	Water Level (m)	GW level (masl)
1736	BGR	2009	AH67	GAMA	01/01/2009	17.1598	11.78417	329.00	24.50	22.20	306.80
1737	BGR	2009	AH68	ALDEHERE	01/01/2009	17.06967	11.9121	320.00	30.90	31.80	288.20
1738	BGR	2009	AH69	ABRAYE	01/01/2009	17.01743	11.99873	316.00	43.00	28.10	287.90
1739	BGR	2009	AH70	DJOUKHA	01/01/2009	16.92975	12.04188	313.00	38.50	33.70	279.30
1740	BGR	2009	AH71	DOULILIO	01/01/2009	16.90897	11.91202	321.00	55.00	40.80	280.20
1741	BGR	2009	AH72	ADELEBE	01/01/2009	16.47002	11.65603	326.00		39.60	286.40
1742	BGR	2009	AH73	BADJODA	01/01/2009	16.30175	11.6801	333.00	60.00	48.50	284.50
1743	BGR	2009	AH74	BIDRI	01/01/2009	16.22782	11.56112	332.00	51.00	37.80	294.20
1744	BGR	2009	AH75	MOUDOU	01/01/2009	16.41628	11.49678	335.00	49.00	35.60	299.40
1745	BGR	2009	AH76	OUALDI	01/01/2009	16.42823	11.40175	327.00	27.30	29.30	297.70
1746	BGR	2009	AH77	SEITE	01/01/2009	16.51942	11.36595	333.00	40.00	27.22	305.78
1747	BGR	2009	AH78	BODORO	01/01/2009	16.47403	11.22023	329.00	16.50	12.40	316.60
1748	BGR	2009	AH79	GOUGOUM	01/01/2009	16.36023	11.36545	333.00	30.00	27.25	305.75
1749	BGR	2009	AH80	MAIMERE ADAM	01/01/2009	16.34955	11.4196	330.00	46.00	31.90	298.10
1750	BGR	2009	AH81	TCHOUE	01/01/2009	16.30957	11.45897	330.00	33.10	33.50	296.50
1751	BGR	2009	AH82	MASSENYA	01/01/2009	16.23257	11.41455	332.00	25.36	20.50	311.50
1752	BGR	2009	AH83	BOURAM ECOLE	01/01/2009	15.75663	11.01115	324.00	70.00	45.40	278.60
1753	BGR	2009	AH84	BOUGOUMORO	01/01/2009	15.9934	10.80755	332.00	26.23	36.50	295.50
1754	BGR	2009	AH85	DARADJA TIDJANI	01/01/2009	16.1125	10.84383	329.00	48.00	34.80	294.20
1755	BGR	2009	AH86	MODORIO	01/01/2009	15.76252	11.12558	326.00	80.00	43.25	282.75
1756	BGR	2009	AH87	ORGNON	01/01/2009	15.68347	11.04568	319.00	13.30	5.20	313.80

Figure F4. Information about water points in Excel.

APPENDIX G. NUMERICAL MODEL. LAYERS AND SEMICONFINED AQUIFER SIMULATED GROUNDWATER LEVEL

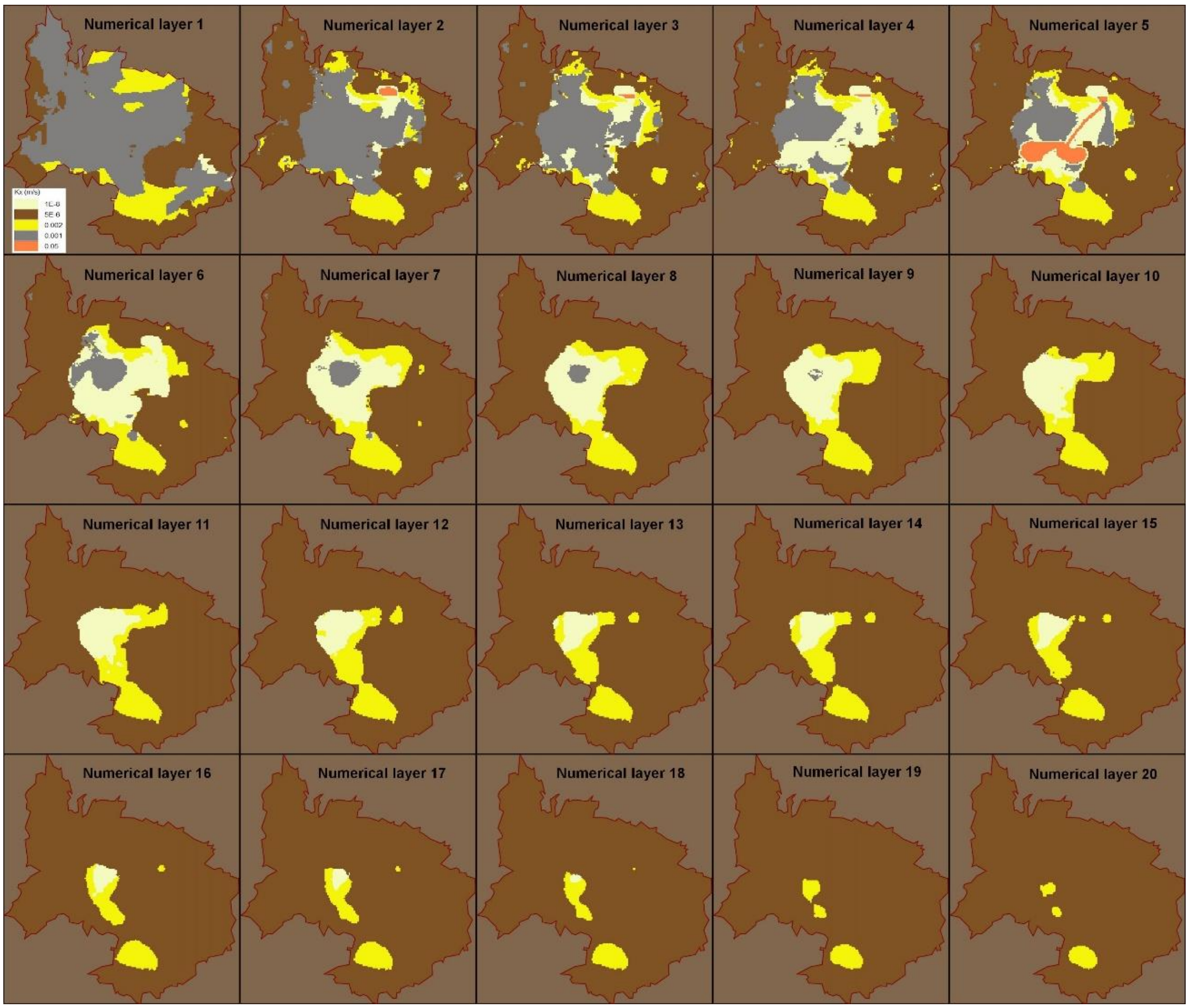

Figure G1. Numerical model. The defined hydrostratigraphical layers extension along basin depth and K (m/s; red maximum, pale yellow minimum) distribution. Gray: Quaternary; Brown: bedrock; Dark yellow: CT+LPli.

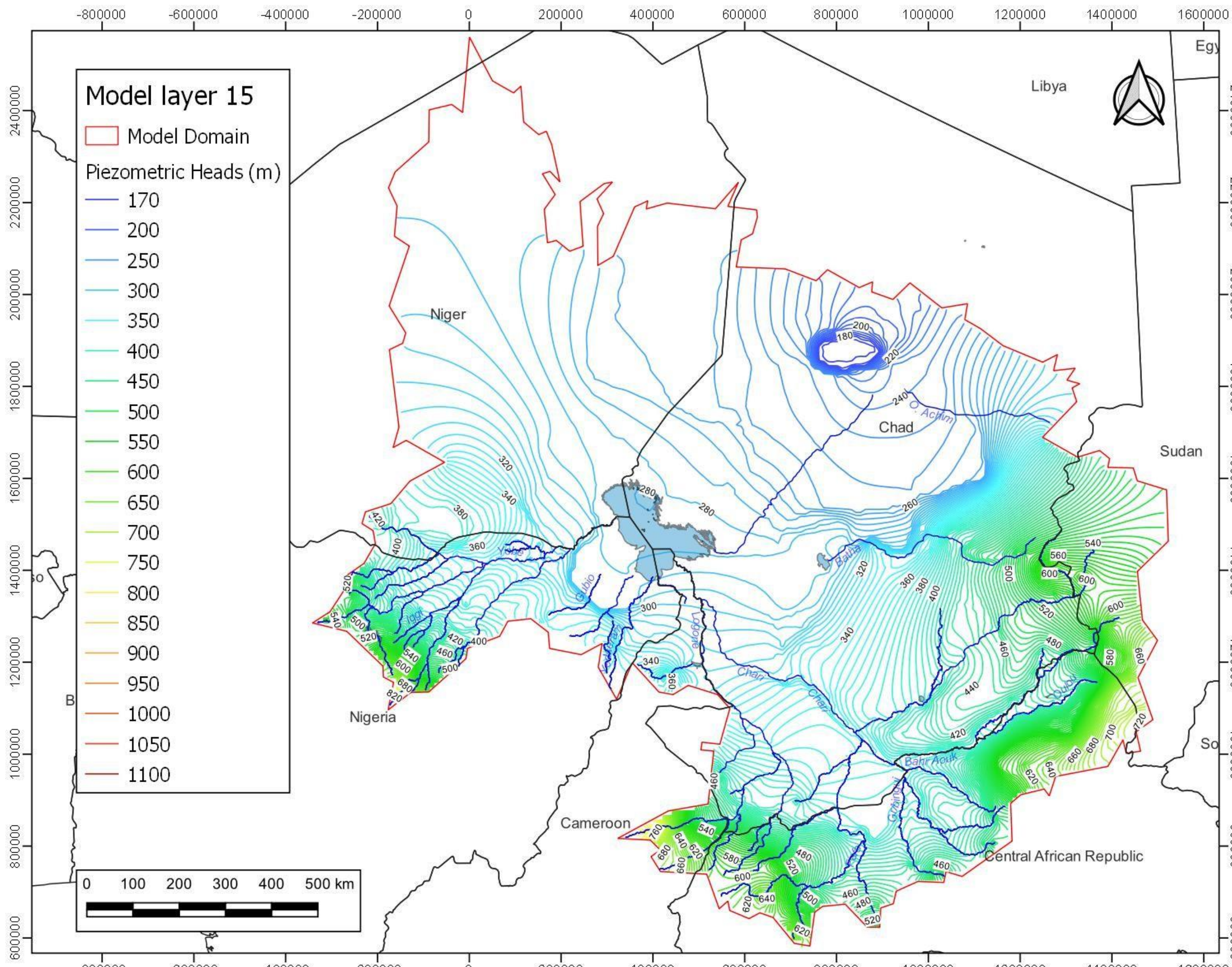

Figure G2. Semiconfined aquifer: the simulated piezometric level.

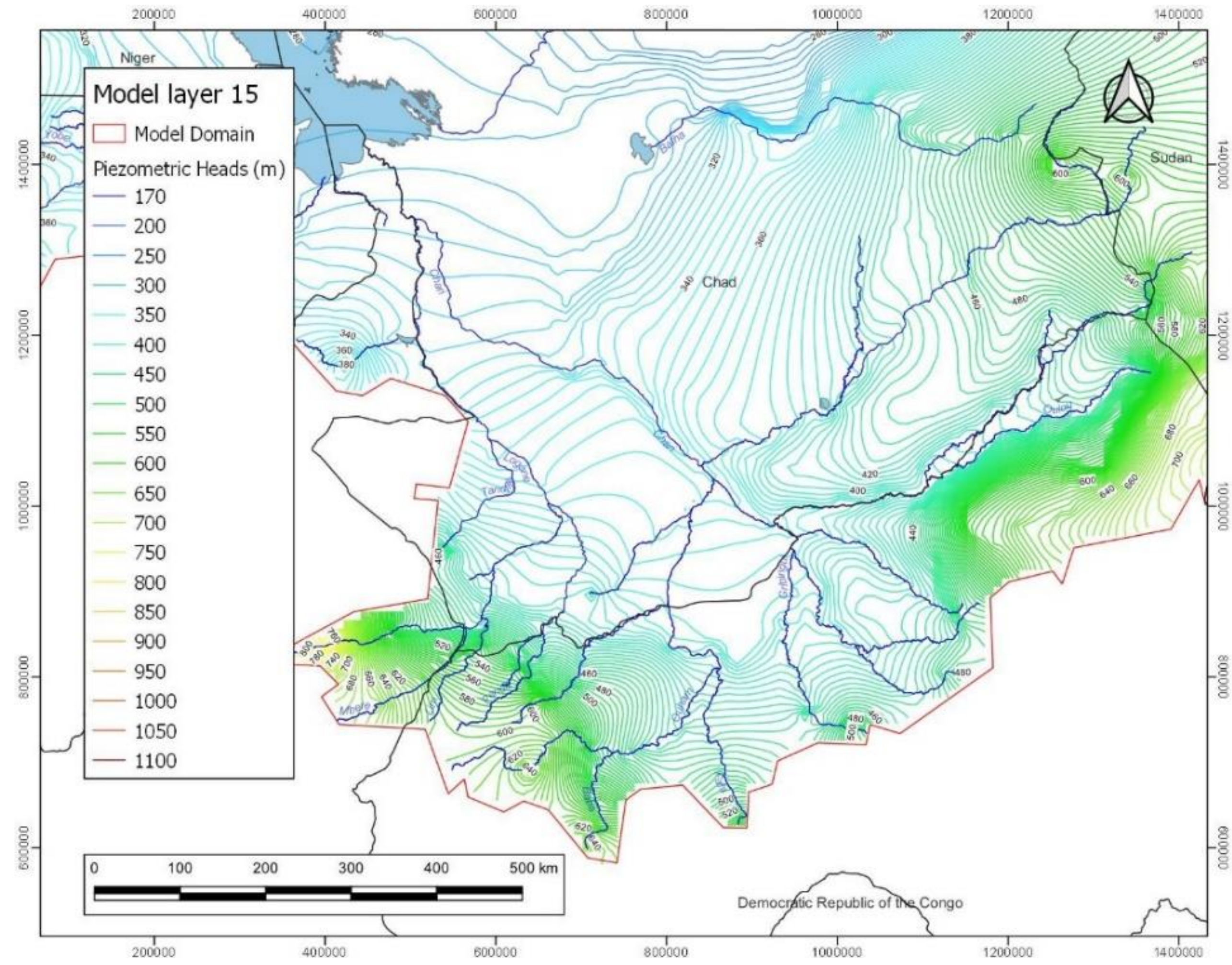

Figure G3. The Chari-Logone area semiconfined aquifer. The simulated piezometric level.

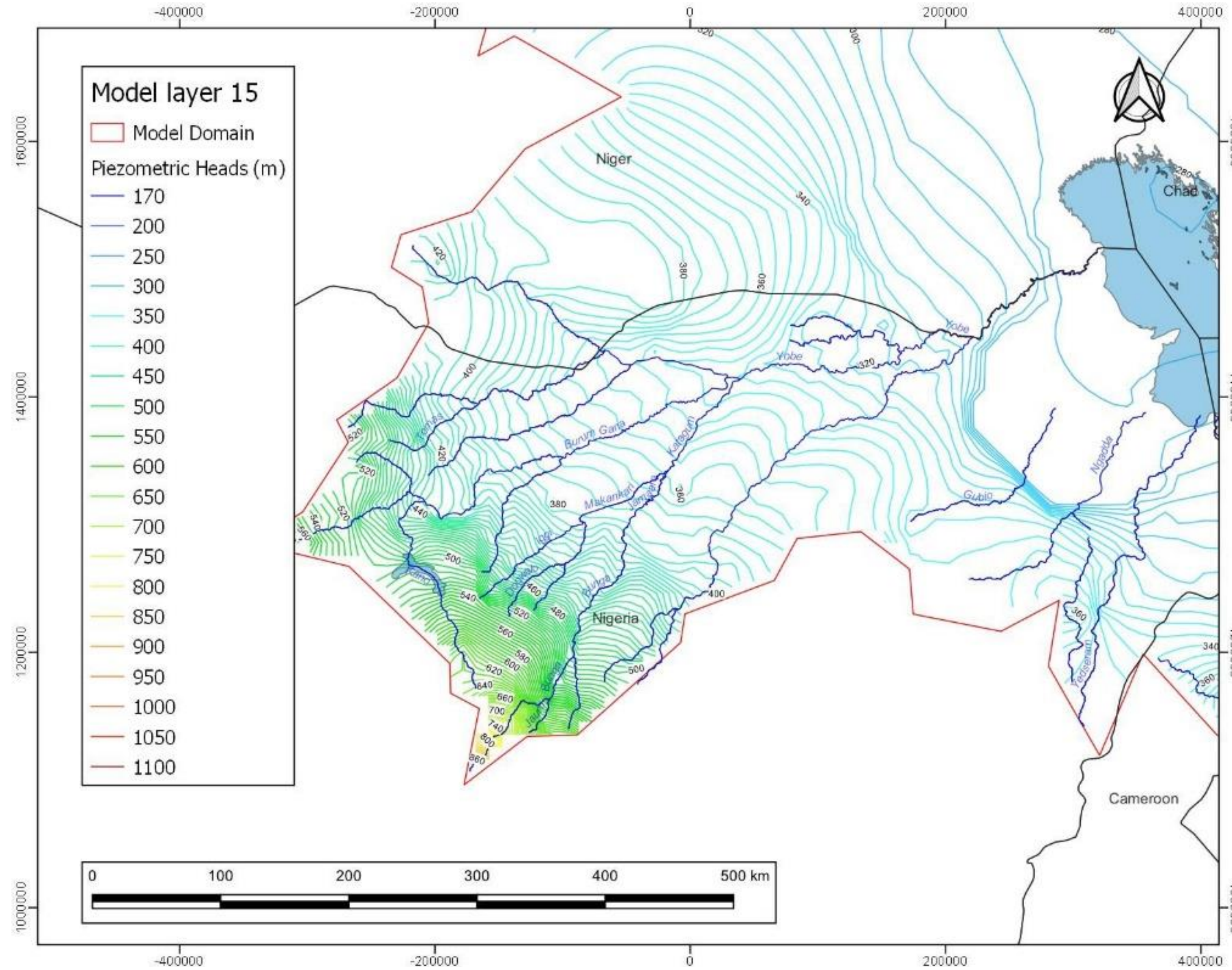

Figure G4. The Komadougou-Yobé area semiconfined aquifer. The simulated piezometric level.