Assessment of groundwater hydrology of the Quaternary aquifer of Lake Chad Basin

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“Make everything as simple as possible, but not simpler.”

Albert Einstein

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Abstract

This thesis aims to update and improve the Lake Chad Basin quaternary aquifer conceptual model, previously established in the final 60's of last century. To achieve this, gathering relevant and high-quality data to fill this gap with updated hydrological, geological, meteorological, and groundwater information constitutes the first step to update and revising the existing conceptual model. The specific objectives of the study include studying the dynamics of the Quaternary aquifer by analyzing natural recharge-discharge, analyzing exchanges between surface and groundwater systems, and constructing a conceptual model for the Quaternary based on hydro-stratigraphic units and water budget.

Located in Chad graben region, the sedimentary Chad Aquifer Formation-CAF (Quaternary, Pliocene and Continental deposits) extends along the entire basin and is one of the largest transboundary aquifers of the world. The studied region, characterized by three main climate types, including hot desert, hot semi-arid, and tropical wet and dry, which is located West-Central Africa and stretching over 2,381,000 km^2 is home to one of the largest existing aquifers in the region. It is composed by three aquifer systems: the Quaternary, Lower Pliocene, and Continental Terminal. The basin is underlain by a Precambrian crystalline basement and Late Cretaceous, Tertiary, and Quaternary sandy or sandstone formations. The regional Quaternary aquifer plays a crucial role in the water balance of the basin and outcrops over an estimated surface of 1,014,000 km^2. It serves as a crucial source of freshwater for the area and plays an essential role in the region's socio-economic development. The Lake Chad Basin is a large arid and semi-arid area with limited data availability; regional information mostly refers to developed studies during 2004-2008. The study area is.

The current research is divided into two parts: data gathering and storage of new geo-hydrological information, and analysis and data assessment from collected information for the hydrogeological update based on scientific publications, ground data, and also remote sensing data, and more than 10,000 digital files, provided by national and international institutions working in the Lake Chad Basin.

The applied methodology also involves storage of new geo-hydrological information, including updated basin geometry from subsurface geological information provided by 430

lithological well logs and further generation of the 3D description from the RockWare code. Based on new collected information hydro-stratigraphic units were established at basin scale. The research independently quantifies the rate of daily natural groundwater recharge in the CAF based in a soil-plant water numerical model (Visual Balan) for the 2005-2014 period. The study also discusses the methods and tools used to analyze climatic data, estimate recharge, and model the unsaturated zone in the Chari-Baguirmi groundwater depression by modelling processes in the unsaturated zone. The study utilizes various sources of hydrological and geological data, including remote sensing platforms for climatic data.

The CAF, generally exploited throughout the basin, comprises the following hydrostratigraphical units from top to bottom: *-)* upper phreatic aquifer, of Quaternary (*Q*) deposits; Upper Pliocene aquitard; *-)* Lower Pliocene (*LPli*), intermediate confined aquifer, in some areas artesian; *-)* the deep confined or unconfined aquifer of Continental Terminal (*CT*, Oligocene-Miocene). The hydrogeologic system is constituted by deep confined-unconfined aquifers (Lower Pliocene, and *CT*, of Tertiary age) and a Quaternary unconfined shallow aquifer with considerably lateral variability, sediment type and varying hydraulic parameters. Hydraulic connectivity exists between the two aquifers in the southern part of the area where the Continental Terminal outcrops and with the main rivers. CAF basin boundaries are mainly crystalline rocks.

The 2008–2011 potentiometric surface (water table aquifer: *Q* and *LPli-CT*) indicates regional groundwater flow toward the central and northern basin zones (Bodel´e, north of Kanem); however, very little information is available for this area. Due to lack of data for the deep confined aquifer (*LPli-CT*) only groundwater contours can be displayed in the southern part. The groundwater level generally lowers toward Lake Chad and to the upper northern basin part (the Lowlands). The lowest values are always observed in piezometric depressed zones (Bornou and Kazdell, SW of the lake) and Ya´er´e and Chari-Baguirmi ,E of the lake) with a minimum value of at Chari Baguirmi.

Groundwater recharge is primarily controlled by precipitation in the southern part of the Basin and in the dune systems to the north, accounting for between 0% and 13% of total precipitation. Important surface water-groundwater interactions take place during flood periods in the Komadougou-Yobe and Chari Logone River systems. Vertical leakage from the aquitard through the Q (south of Manga) and lateral inflow from the weathered crystalline bedrock or from the northern boundary, Nubian sandstone, may also take place. Discharge is through pumping wells, mainly from the Quaternary aquifer to surface water and to the Lowlands northern region at the Bodel´e depression, the lowest topographic point of the basin (approx. 165 m). To date, Lake Chad constitutes an in-transit hydrologically open system lake, ensuring removal of dissolved salts. The exchanges between Lake and the Quaternary aquifer are not significant due to the limited hydraulic aquifer connection and only up to a distance of around 50 km from the lake's shore, according to isotopic data. The quantitative attempt of water budget estimate of the system highlights the largely uncertain assessment due to numerous data gaps and information.

Results from unsaturated zone numerical modelling at the natural piezometric depression of Chari Baguirmi, indicates the rainfall effect is only observed at the upper soil layers. It may accumulate on the soil surface and does not infiltrate deeply into the ground, which all lead to low aquifer recharge. The effect of the past drying climate over millennia, when the depressing process should have appeared, could create an upward flux regime throughout the unsaturated zone that could reach the groundwater level. No upward water flux (positive outputs) is observed under the present climate conditions.

The research findings contribute to the understanding of the hydrogeology of large arid and semi-arid areas, where limited and low-quality data are a challenge in developing an accurate conceptual model of the groundwater system. By fulfilling the planned objectives, the study provides an updated and improved conceptual model of the Chad Aquifer Formation in the Lake Chad Basin, contributing to a better understanding of the hydrogeology of large arid and semi-arid areas. The results will have important implications for groundwater management and will provide a better understanding of the water balance and flow systems in the region. The outcomes of this study will also be of great interest to decision-makers, stakeholders, and water resource managers in the Lake Chad Basin, as they will help to ensure sustainable use and management of groundwater resources in the region.

Resumen

La Cuenca del Lago Chad con una superficie de 2,381,000 km^2 y situada en África occidental central, se extiende a lo largo de tres tipos climáticos: desierto cálido, semiárido cálido-húmedo y tropical seco. Constituye una gran zona árida-semiárida, con limitada disponibilidad de datos y donde la información hidrológica regional existente consiste principalmente en estudios desarrollados durante los años 2004-2008.

Parte del denominado graben Chadiano (República del Chad), la Chad Aquifer Formation-CAF (Cuaternario, Plioceno y Continental Terminal), compuesta por materiales sedimentarios sobre el basamento fundamentalmente cristalino,. se extiende sobre toda la cuenca y constituye uno de los mayores acuíferos transfronterizos del mundo compartido por Chad,Nigeria, Niger, Camerún y República Centroafricana.

La CAF está constituida por tres sistemas acuíferos: Cuaternario, Plioceno Inferior y Continental Terminal. El acuífero cuaternario, cuyo modelo conceptual fue establecido en los años 60 del siglo pasado aflora sobre una superficie estimada de 1,014,000 km^2, constituye un elemento fundamental de la cuenca hidrológica, es la mayor fuente de agua dulce en la zona y desempeña un papel esencial para el desarrollo socioeconómico de la región.

El objetivo de esta tesis es actualizar y mejorar el modelo conceptual existente del acuífero cuaternario de la Cuenca del Lago Chad mediante la incorporación de nueva información hidrogeológica generada. Para ello, se ha realizado una recopilación y posterior evaluación de información hidrológica, hidrogeológica, geológica y meteorológica. Los objetivos específicos del estudio incluyen evaluar la geometría a nivel regional del acuífero cuaternario y analizar su dinámica a partir del análisis y definición de las unidades hidroestratigráficas, recarga-descarga natural, piezometría y conexión hidráulica agua superficial-agua subterránea a partir de los nuevos datos incorporados.

En esta Tesis, se deben destacar dos aspectos de la investigación llevada a cabo, consistentes en la recopilación y almacenamiento de nueva información geo-hidrológica y su posterior análisis y evaluación. La información, generalmente proporcionada por instituciones nacionales e internacionales con trabajos en la Cuenca del Lago Chad, consiste

fundamentalmente en publicaciones científicas e informes y datos locales de aproximadamente 10,000 archivos digitales.

La CAF, explotada en toda la cuenca, comprende las siguientes unidades hidroestratigráficas de superficie a profundidad: -) acuífero freático superior, constituido por depósitos cuaternarios (Q); acuitardo del Plioceno Superior; -) acuífero intermedio del Plioceno Inferior (LPli), confinado y en algunas zonas artesiano; -) el acuífero profundo del Terminal Continental (CT, Oligoceno-Mioceno), confinado o libre . A nivel hidrogeológico la CAF está constituida por acuíferos profundos confinados-no confinados (LPli y CT, de edad terciaria) y un acuífero superficial Cuaternario no confinado con importante variabilidad lateral, y diversos tipos de sedimento y parámetros hidráulicos. Los límites de la CAF son principalmente rocas cristalinas Existe conexión hidráulica entre los dos acuíferos en la parte sur del área de estudio, donde el Terminal Continental aflora y con los principales ríos.

Para la actualización de la geometría geológica del modelo conceptual, a nivel tridimensional en toda la extensión de la cuenca, se han utilizado en 430 registros litológicos de pozos y el código RockWare. A partir del análisis de los registros se han establecido las unidades hidroestratigráficas existentes a nivel regional.

La superficie piezométrica establecida para el periodo 2008-2011 (acuífero superficial libre: Cuaternario y LPli-CT) indica que el flujo regional es hacia la zona central y norte de la cuenca (Bodelé, norte de Kanem), aunque se debe destacar la escasa información existente en esta última zona. La profundidad del agua subterránea generalmente disminuye hacia el lago Chad y hacia la parte norte superior de la cuenca (Lowlands). Los valores piezométricos más bajos se observan siempre en las depresiones piezométricas naturales de Bornou y Kazdell (suroeste del Lago) y Ya'er'e y Chari-Baguirmi, (este del Lago) siendo el valor mínimo detectado en Chari Baguirmi.

El Lago Chad es un sistema hidrológicamente abierto y en tránsito, que elimina las sales disueltas. Según datos isotópicos los intercambios entre el Lago y el acuífero cuaternario no son significativos debido a la limitada conexión hidráulica con el acuífero y solo apreciables hasta una distancia de alrededor de 50 km de la orilla del lago,.

La recarga natural del acuífero superficial para el periodo 2005-2014, independientemente estimada mediante un modelo distribuido agua-suelo-planta (VisualBalan), constituye entre el 0% y el 13% de precipitación. Está controlada principalmente por la precipitación en la parte sur de la cuenca y en los sistemas de dunas del norte. Durante los periodos de inundación existe una importante interacción agua superficial-agua subterránea y sistemas fluviales de Komadougou-Yobe y Chari Logone. También es posible una recarga por ascenso vertical al Cuaternario a través del acuitardo (al sur de Manga) y flujo lateral procedente del macizo cristalino o areniscas nubias directamente en contacto con el acuífero en el Norte de la cuenca.

La descarga del acuífero se realiza a través de pozos de bombeo, principalmente del acuífero cuaternario, hacia las cuencas fluviales y hacia el Norte de la cuenca- 'Lowland' en la depresión de Bodelé, el punto topográfico más bajo de la cuenca (aprox. 165 m). El intento cuantitativo de estimación del presupuesto de agua del sistema destaca la evaluación en gran medida incierta debido a numerosas brechas de datos e información.

La investigación cuantifica de manera independiente la tasa de recarga natural diaria de aguas subterráneas en CAF basada en un modelo numérico distribuido que calcula el balance agua-suelo-planta (Visual Balan) para el período 2005-2014.

Los resultados de la simulación de la zona no saturada en la depresión piezométrica natural de Chari Baguirmi indican ausencia de flujo ascendente desde el nivel piezométrico del acuífero (exfiltración) bajo las condiciones climáticas actuales. El efecto de la precipitación solo es observable en las capas superiores del suelo, donde puede acumularse y al no infiltrarse produce una recarga al acuífero muy limitada. Se estima que el proceso que dio origen a estas depresiones se debe a la existencia de periodos climáticos a nivel geológico de mayor aridez, donde la posible presencia de un régimen de flujo ascendente a través de toda la zona no saturada alcanzando el nivel freático podría haberse producido.

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Chapter 1

Introduction and state of the art

1.1. Introduction

This chapter presents information of the Basin provided by different authors from a hydrogelogic standpoint. It needs to be mentioned that the lake and surface hydrology does not constitute a specific objective of this research and field campaings have not been conducted for sampling or aquifer monitoring. In this chapter, there is a presentation of outcomes at the hydrogeological and geological level, of a number of local studies, publications or PhD dissertations analyzing diverse aspects of the basin covering from geology, hydrology, remote sensing, or numerical modelling. Most information is available only for the Southern part of the basin and fewer changes are foreseen for the rest of the area from the geological and hydrogeological point of view.

The Lake Chad Basin is an inland hydrologic basin situated in West-Central Africa, and extends from Algeria, Sudan and to a small area of Libya, in addition to Cameroon, Central African Republic, Chad, Niger, and Nigeria (Member States of the Lake Chad Basin Commission). Conformed by de Chari- Logone and the Komadugu-Yobe as the most important river basins and the Lake Chad it is an important freshwater resource for neighboring countries; from the groundwater point of view, it also constitutes one of the largest existing aquifers. The system is a transboundary basin (Chad Aquifer Formation-CAF) shared by Algeria, Cameroon, Central African Republic, Chad, Libya, Niger, Nigeria and Sudan to a greater or lesser extent (TWAP, 2012).

The size of the lake has varied considerably over time (Lemoalle, 2014) from the single Mega Chad Lake dated betewwn 15-11.5 Ka up to recent times: in the 1960s, the area of the lake was 25,000 km^2, but now, it is approximately 2,000 km^2 after severe droughts. Previous studies have demonstrated that the water balance in the lake reflects the interactions among rainfall, evaporation, lateral inflow, and groundwater, with the inundated area varying substantially according to the amount of annual rainfall and run-off. At present, Lake Chad is an in-transit hydrologically open system lake ensuring removal of dissolved salts. Discharge from tributary rivers has also reduced, partly resulting from the construction of dams and an increasing demand for water from the local population. More than two thirds of the basin is situated in an arid zone that does not actively contribute to the surface flow into Lake Chad; only humid tropical climatic zone of the S-SW contributes to water resources (S of Chad and E of Nigeria).

Since the initial works by Isiorho (1989) and Schneider (1989), a number of local studies, publications or PhD dissertations have examined diverse aspects of the basin covering from geology, hydrology, remote sensing or modelling. In Table 1 most relevant works are summarized. The summary is also included several institutions and organizations (e.g., Fonds Européen de Développement (FED), Lake Chad Basin Commission (LCBC), Global Environmental Facility (GEF), oil companies, Member States, international agencies, and academic institutions) and organizations working in the Lake Chad basin in specific aspects (conceptual model, recharge, depressions). Most information is available only for the Southern part of the aquifer.

Table 1. A summary of works carried out

Geology	**Groundwater hydrology/hydrogeology**	**Hydrochemistry**	**Recharge**	**Modelling**
Wolff (1964) Servant (1973) Gear and Schroeter (1973) BRGM-CIEH (1979) Isiorho (1989) Schneider (1989) Schneider and Wolff (1992) Eberschweiler (1993a,b) Vicat et al. (2002) Ganwa et al. (2009) Mbowou et al. (2012) ReSeay (2016) ResEAU (2017)	UNESCO (1969) Schneider (1989) Eberschweiler (1993a,b) Ngounou Ngatcha (1993) BGRM/LCBC (1993) Alkali (1995) Bonnet and Murville (1995) Birkett (2000) Djoret (2000) Massuel (2001) Hassan (2002) Leblanc (1997, 2002 and 2007) PNUD (2003) Gaultier (2004) Zaïri (2008) BGR-LCBC. (2009 ; 2010 ; 2012) Le Coz (2010) ANTEA/EGIS/BCEOM/CIAT (2012) Hamit (2012) Ibrahim (2013) Bouchez (2015) Buma et al. (2016) BGR-LCBC (2017)	UNESCO/LCBC (2002) UNESCO (2004) BGR/LCBC (2017) IAEA, 2017	Carter et al. (1994) Njitchoua & Ngounou Ngatcha, (1997) Edmunds et al., (1998) Djoret & Travi, (2001) Massuel, (2001) Edmunds et al. (2002) Hassan, (2002) Leblanc et al. (2002, 2007) Gaultier, (2004) Goni, (2006) Aranyossy, et al., (2007) Ngounou Ngatcha et al., (2007a) Zairi, (2008) Babama'aji et al. (2012) Buma et al. (2016) IRD-LCBC, (2016) Tewolde et al., (2019)	Coe and Foley (2001) Massuel (2001) Hassan (2002) Gaultier (2004) Boronina and Ramillien (2008) Delclaux et al. (2008) Zaïri (2008) Le Coz et al. (2009, 2010) Bader et al. (2011) Abderamane (2012) Descloitres et al. (2013) Moussa (2013) Candela et al. (2014) Bouchez (2015) Buma et al. (2016)

From the geological point of view, the Basin is composed of both Late Cretaceous volcanic and Cenozoic to Quaternary sedimentary formations (Vicat et al., 2002; Ganwa et al., 2009), underlain by a Precambrian basement (Gear and Schroeter, 1973). According to the exploratory drilling at Logone-Birni and Bol (Lake Chad Basin), this basement is located at a depth of about 600 m (Mbowou et al., 2012). The tectonic movements that affected Africa and South America contributed to the formation of the Agadem and Bornu troughs in the Lake Chad Basin (Vicat et al., 2002; Mbowou et al., 2012).

Regional groundwater systems comprise different geological and hydrogeological zones. Groundwater represents one of the most important available resources in the region, being the Chad formation (Quaternary) the most important aquifer. At regional scale, aquifer system definition and characterization are based in the works of Isiorho (1989) and Schneider from early 1980s. Three aquifers of interest of sedimentary origin are defined for the Lake Chad basin (Schneider, 1989; Eberschweiler, 1993, FAO, 1973): The Chad aquifer formation, the confined Continental Hammadien and the Continental Intercalaire. Precambrian crystalline rocks (schists, granite, etc.) compose the bedrock and outcrop on the southern edge of the basin. The Chad Formation (Quaternary-Miocene) has received most of the research interest and is composed by: 1) the upper phreatic aquifer, present throughout the basin and made up of Quaternary deposits; 2) the lower Pliocene materials comprise the intermediate confined aquifer; 3) a deep confined aquifer made up of the Continental Terminal (CT) deposits (Oligocene-Miocene).

Since UNESCO (1969) carried out the first systematic study of groundwater and surface water by using hydrograph records and groundwater dating methods with isotopes, local and regional studies have been developed to examine diverse aspects of the basin hydrology and water resources. Reports addressing the sustainable water resources management at the basin or regional scale include: (BGR-LCBC, 2009, 2010, 2012, and 2017); UNESCO-PNUD-CBLT, (1972) for study of water resources in the Lake Chad Basin 1966-1970; UNESCO-BMZ-LCBC (2000); UNESCO. (2004) and UNDP (2006 and 2016) among them. Local studies EU financed for water supply (FED funds) have been also developed specially in the northern areas of Chad (among the studies for the refugee camps water supply). Lately, during the 2012-2019 period and later, an important research program is being developed by the Swiss Cooperation in all basin extent. First phase published only covers the N-NE area of Chad (ReSeau, 2016).

Research Objectives

One of the main challenges in understanding the hydrogeology of large arid and semi-arid areas is the limited availability and low quality of relevant data. The data available varies between zones (and countries) and are often spatially and temporally inconsistent, resulting in inadequate data coverage for assessing the groundwater system as a whole. Under these circumstances, developing (& updating) a groundwater conceptual model requires the simplification of a complex groundwater system.

Most available regional information only refers to developed studies during 2004-2008, and an update of the groundwater hydrology is not available so far. The conceptual model of the aquifer system (Quaternary and Continental Terminal) needs to be revised and assessed with the new information in order to accurately represent the hydrologic system at a regional scale. The overall objective of present thesis is the 'assessment of groundwater hydrology of the regional quaternary aquifer of Lake Chad basin', with the goal to provide reliable and updated results of the conceptual groundwater model. The approach will be also based in remote sensing products.

To fulfill the project objectives, planned specific objectives are:

- Update existing conceptual model with new hydrological, geological, meteorological and groundwater information from the area, including the existing natural groundwater depression processes. Further analysis and data base creation from collected information.
- Study of the Quaternary aquifer dynamics (including water balance) by natural recharge-discharge from rainwater, Lake Chad, flooded areas and rivers.
- Analysis of exchanges between surface and groundwater systems
- Establishing the conceptual model. Constructing a conceptual model for the Quaternary will be done based in hydro-stratigraphic units, water budget and defining the flow system following the obtained information.

1.2. The State of art

1.2.1. Geological aspects

To date, very few newly published geological regional data has been found (e.g. Moussa, 2013) most of the research has been carried out during the end of last century basically by French organisations and oil companies; however as data from oil companies are confidential, new deep geological contributions cannot be assessed. Major works on regional geology which constitute the core of the geological knowledge, have been mainly developed by Wolff (1964), Servant (1973), Gear and Schroeter, 1973, Schneider (1989), Schneider and Wolff (1992), Eberschweiler (1993a,b), Vicat et al., (2002), Ganwa et al., (2009) but do not provide adequate coverage throughout the study area. They concentrate mainly in the basin's central part. According to authors, the Basin is composed of both Late Cretaceous volcanic and Cenozoic to Quaternary sedimentary formations, underlain by a Precambrian basement. Also new digital maps (shapefiles) have been produced by BGR-LCBC (2012) based on the already existing geology by Schneider and Wolff (1992). Only updated geology knowledge for the northern/eastern parts of Chad is being developed under the Swiss cooperation project (ResEAU, 2017). This project is still under development in the southern parts of the Basin.

1.2.2. Surface hydrology

As the Lake is not the objective of this work a brief introduction to changes in lake level is here presented. There exists several works documenting the rainfall changes since more than 15 ka ago and their impact in the Lake extension. A single Lake (Mega Chad, extending over 350,000 km^2) was formed when lake water level exceeds an elevation of 325 m (Schuster et al. 2005). Since the last wetter period (6000 year AD, Kröpelin, 2008), a significant reduction of rainfall has been produced, leading to the actual extension. Based on remote sensing and satellite data studies applied to the Lake Chad region, some of which focused on the changes in stream flow patterns connected to the lake, reported on the existence of a mega-lake Chad (Leblanc, 2006, 2007).

Regarding aspects related to Lake hydrology, Coe and Foley (2001) used an integrated biosphere model and a hydrological routing algorithm model. The simulations suggest that the 30% decrease of the lake area observed between the decades of 1956- 1965 and 1966-1975 was attributed primarily to long-term climate variability and about 45% of the lake area decrease between 1960s -1970s. The studies carried out by Birkett (2000) and BGR/LCBC (2017) have demonstrated that the water balance in the lake reflects the interactions among rainfall, evaporation, lateral inflow, and groundwater, with the inundated area varying according to the amount of annual rainfall and run-off. Exchanges between Lake and the Quaternary aquifer (CAF) are not significant and, according to isotopic data (Zaïri, 2008; LCBC-IRD, 2016), are limited up to around 50 km from the lake's shore. LeCoz et al., (2009) conducted a study using six algorithms to simulate the water balance of the Lake Chad basin (2.5Mkm^2).

Nkiaka et al. (2017) used standardized indicators to analyze dry/wet conditions and their application for monitoring drought/floods in the Logone catchment, Lake Chad basin. The results revealed that the catchment has a low response to rainfall at short time scales, though this progressively changed as the time scale increased, with strong correlations.

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). Some previous studies tried to quantify surface water–groundwater connectivity at a basin scale (Leduc et al., 1998; Massuel, 2001; Hassan, 2002; Gaultier, 2004; Zairi, 2008). The exchange flows between the surface and groundwater 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. In order to recreate the water balance of the Lake Chad basin, LeCoz et al. (2009) conducted a study employing six algorithms to aggregate the Shuttle Radar Topography Mission (SRTM) DEM. It is suggested that the nearest neighbor approach is also the best approach for the level-volume relationships, with an RMSD of 2.8 percent, while the median approach is the least accurate (aside from the minimum a priori).

1.2.3. Groundwater Hydrology

At regional scale, aquifer system definition and characterization are based in the initial works from early 1980s. Following the initial works at regional level of Isiorho (1989), Schneider, (1989), Eberschweiler, (1993) and Leblanc (2002), three aquifers of interest of sedimentary origin are defined for the Lake Chad basin: The Chad aquifer formation (FAO, 1973), the confined Continental Hammadien and the Continental Intercalaire. Precambrian crystalline rocks (schists, granite, etc.) compose the bedrock and outcrop on the southern edge of the basin. The Chad Formation (Quaternary- Miocene, FAO, 1973) has received most of the research interest. Aquifer formations constitute transboundary aquifers and aquifers may receive local names in the different sharing countries, they may present changes of facies and different hydraulic conditions. Most studies focus on the Chad Formation and mainly in the Quaternary aquifer.

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) are the authors of the majority of regional hydrogeological research reports and research projects. The aquifer geometry definition of the Chad Formation Aquifer System (Quaternary and Lower Pliocene/Continental Terminal) to the basin's boundaries is still lacking and there is not an updated understanding to represent basin wide aquifer system behavior more accurately on the basin scale.

A variety of hydrogeological conceptual models have been established since the prior regional efforts by Schneider and Eberschweiler (1993b). Conceptual model developed in the 60's is still accepted; however, explanation of hydrologic mechanisms explaining aquifer deep drainage and piezometric depressions is still not fully understood. Aspects related to the aquifer water budget (recharge, discharge, exfiltration, effects of droughts, lake-aquifer interaction) in recent times, jointly with new lithostratigraphic information incorporation, are still not fully investigated.

Main findings indicate maximum recharge values occur in the southern part of the Lake Chad Basin (South of 14th parallel) and in northern boundary part of the Lake, while it is almost inexistent in the northern part of the Basin. According to Leblanc (2002); Leblanc et al. (2007); Ngounou Ngatcha,2007; Goni, 2008 and Vaquero et al., (2021) in some areas recharge does not exist. 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. At the basin level Leblanc (2002) and Leblanc et al. (2006; 2007) by combining satellite imagery GRACE data and GIS methods identify surface indicators of recharge and discharge areas for groundwater/surface water interaction and paleohydrological settings; and to 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. They estimated the values of the recharge areas to range from -1 to 3 mm/yr, the delineation of the recharge and discharge areas, and some key parameters, such as: infiltration, evapotranspiration and ‘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.

Local-scale elements of research (recharge, river-aquifer exchanges, modelling, naturally existing depressions) have also received attention, with substantial specific contributions on the characterization of existing aquifers. For the Nigerian side, similar 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), as listed in the references section. In 2015, Bouchez (2015) and Bouchez et al. (2015) proposed a detailed study of the interactions between Chad Lake water and Quaternary groundwater using isotopes and geochemistry. They also attempted to estimate the residence time of the Continental Terminal aquifer groundwater using ^{36}Cl in the Chadian region of Bahr El Gazal.

Applied methods for recharge estimation in local scale mainly include isotopic studies (Djoret & Travi, 2001; Edmunds et al., 1998; Gaultier, 2004; Goni, 2006; Leduc et al., 2000; Ngounou Ngatcha, Mudry, Aranyossy, et al., 2007; Njitchoua & Ngounou Ngatcha, 1997; Tewolde et al., 2019) and mathematical modelling for different hydrologic objectives (Babama'aji, 2013; Leblanc, 2002). Zaïri (2008) studied the water table in the Kadzell (eastern Niger) and Bornou districts of the Lake Chad Basin by geochemical and hydrodynamic analysis. His studies mainly and most exclusively focused on the shallow Quaternary aquifer. Carter et al., (1994) conducted a study in the northeast of Nigeria, in which groundwater recharge of 30-60 mm/yr was estimated. The result of the study done by Edmunds et al. (2002) in northern Nigeria, shows that the annual recharge rate ranges from 14 - 49 mm/yr on the basis of unsaturated zone chloride mass-balance values and rainfall chemistry measured over eight years at three local stations.

Boronina and Ramillien (2008) developed a model using NOAA AVHRR and GRACE data to study the regional hydrogeology of the Quaternary aquifer in the Lake Chad Basin (LCB); nevertheless, few information on modelling has been found. They estimated the mean annual recharge in the ranges of 1 to 4 mm, or one percent of the mean annual precipitation for the dunes of the Kanem in the north of the Lake Chad, and 0.3 to 1 mm or 0.1 percent of the mean annual precipitation, for south of the Lake Chad.

To date, several mechanisms (overexploitation, subsidence, structurally conditioned deep drainage, changes in seawater level and evapotranspiration loss) have been suggested to explain the origins of extended piezometric depressed areas in Bornou and Kazdell (SW of the lake) and Yaere and Chari-Baguirmi (SE of the lake), with groundwater level at a depth of 40–60 m below the soil surface (e.g. Aranyossy and Ndiaye, 1993; Dieng, et al., 1990; Durand, 1982, Leblanc et al., 2003). Its presence has been generally explained by exfiltration processes, along with lack of recharge. According to Aranyossy and Ndiaye (1993), and Dieng, et al. (1990), evaporation and transpiration losses were often considered as insufficient to generate deep piezometric depressions and only this hypothesis seems to fit the whole of the hydrogeologic and climatic Sahelian conditions. From 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. However, the exfiltration mechanism is difficult to explain naturally with a groundwater depth of about 40 m (Leblanc et al., 2007; Vaquero et al., 2021). Up to now, a comprehensive model on their existence cannot explain their formation and the most accepted approach is based on insignificant recharge (natural infiltration) due to low permeability materials presence, along with considerable evapotranspiration rates (Aranyossy and Ndiaye, 1993); nonetheless, the scientific community has reached no unanimous agreement, A deep drainage mechanism to the northern zone has been here proposed (Vaquero et al., 2021).

Geophysical, chemical and isotopic aspects are not an specific objective of this research, however existing information has been accordingly analyzed to support outputs. Updated hydrochemical information are 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). Descloitres et al. (2013) carried out geophysical study in the Komadougou-Yobé region, using two distinct geophysical approaches to examine the geometry of the Quaternary aquifer and to support the hydrogeological characteristics for a numerical groundwater model data.

1.2.4. Modelling

Previous groundwater modeling work and activities have focused on extremely narrow local aims and locations, namely in the basin's central-southern region and the Quaternary aquifer (Abderamane, 2012; Hassan, 2002; Gaultier, 2004; Massuel, 2001; Zairi, 2008). Few are on a regional scale (Leblanc, 2007; Boronina and Ramilien, 2008), but they do not cover the complete hydrogeologic basin and hydrostratigraphic units of the Chad Formation. These works will be explained in detail and by topic in the following sections:

Eberschweiler (1993a) created a numerical model for the Quaternary aquifer, as well as the Lower Pliocene and Continental Terminal in the center section of the LCB, in the early 1990s. Existing lithological logs, pumping experiments, piezometric data, and rainfall from early 1960s reports are among the data. Piezometric depressions (e.g., Chari Baguirmi and Kazdell) were replicated by considering a lack of recharge infiltration and significant evapotranspiration, in addition to groundwater exfiltration from deeper zones.

Boronina and Ramillien (2008) to study the regional hydrogeology of the Quaternary aquifer in the Lake Chad Basin did an analysis based on the NOAA-AVHRR and GRACE data. 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. 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.

Based on hydrodynamic and isotopic data, Massuel (2001) created a groundwater flow model for the Chari Baguirmi region to explain the occurrence of piezometric depressions. The primary model produced data that revealed Lake Chad's limited contribution to the Quaternary aquifer, seasonal inputs from the Chari River, and the lengthy residence time of deep groundwater in some regions, which was most likely replenished during the last pluvial era. Exfiltration was the essential parameter used in this model to explain piezometric depressions.

Hassan (2002) conducted a modeling study of the Yobé River Basin in 1998. The goal was to evaluate the impact of several hydrologic factors in the overall balance of the hydrogeological system, especially assessing river-aquifer interactions and exploring the consequences of aquifer pumping. The water balance revealed that river-to-aquifer flow outweighed recharge in terms of rainfall and overland floods.

Gaultier (2004) modeled the Quaternary aquifer of the Kazdell plain (Niger) by taking precipitation fluctuations over the previous 30 years into account. The research also analyzed geochemical and isotopic data to estimate groundwater salinity and water provenance. The influence of a drying lake on the aquifer, according to the findings, was restricted to the nearest region of the lake coast with up to 10 m of groundwater depletion. The Komadougou River supplied the greatest water to the aquifer.

To analyze historical and current hydrogeochemical processes, Zaïri (2008) constructed a transient hydrodynamic model in the Quaternary aquifers of Kazdell (Nigeria) and Bornu (Nigeria). Evapotranspiration was the important parameter in both depressions, according to the modeling results. Non-point recharge from Manga and the Komadugou-Yobé River were the most major aquifer inputs, whereas Lake Chad had little effect on balance.

In Le Coz, (2010), a multiple-point statistics was used to represent facies heterogeneities in the vadose zone of the Komadougou-Yobé River valley (SE Niger), which is undergoing extensive agricultural expansion. HYDRUS findings (2003-2009) were related with the defined lithologic facies and demonstrated considerable variability for point recharge, based on a produced hydrogeologic model based, in turn, on hydrodynamic parameters acquired from the density of probability.

Abderamane (2012) presented a steady-state Quaternary aquifer numerical flow modeling of the Chari Baguirmi depression (Chad) for the 2008 period. 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.

Candela et al. (2014) created a groundwater model to predict the hydrodynamic performance of the Quaternary aquifer in the Chari-Logone region. To compensate for the absence of data, a dynamical downscaling method modeling was used. The goal of this model was to determine the boundary conditions of the local-scale model, as well as to evaluate flow direction, discharge and recharge areas, and the defining of exfiltration/infiltration zones. The Chari-Logone region was the subject of the second modeling process. The simulation specifically addressed three different scenarios of natural recharge and groundwater extraction in medium, humid, and dry climates.

Bouchez (2015) developed Lake Chad water level modeling and Chari-Logone floodplain between 1955 and 2011, based on hydrological, chemical and isotopic data. 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 (east of Lake) was the natural overflow channel of Lake Chad, while the geochemical patterns of deep piezometric depressions indicated that recharge was produced during the last old humid recharge period.

Buma et al. (2016) examined changes in the hydrological behavior of the Lake Chad Basin under severe climatic and environmental circumstances in their most recent study. The goal was also to estimate the influence of rainfall on water storage, explore subsurface water changes, and compare groundwater outputs. The findings revealed variations in groundwater content in depth for the Komadougu-Yobé, Kazdell, and Bornou depressions, with a reduced water content plainly seen in both depressions.

To depict how the system functions generally, Massuel (2001) tried to model the study area. According to his simulations, under complex circumstances, hydrodynamic modeling is risky. All the calibration characteristics, such as recharge and permeability, become significant and can balance one another out while still falling within a range of acceptable values, similar to field data.

The regional modeling results from Vaquero et al., (2021) and data from Gonçalves et al. (2020) indicate the major contribution of natural recharge together with existing surface water-groundwater exchanges (losing and gaining rivers), mainly with the Chari-Logone Rivers. This contribution is especially important for the deep semiconfined aquifer, where most of the river basin extends). The most important discharge is to rivers. This last modelling is also based in the establishment of new conceptual model, later presented, where exfiltration is not considered as the main driver for extended aquifer depressions.

Chapter 2

The Chad Basin study area

2.1. Introduction

The study region, also known as the Lake Chad hydrologic Basin (Figure 1), occupies about 2,381,000 km^2 and is located between 6°N and 24°N latitude and 8°E and 24°E longitude (www.cblt.org/en). In addition to the five Lake Chad Basin Comission (LCBC) member nations (Cameroon, Central African Republic, Chad, Niger, and Nigeria), it stretches as far as Algeria and Sudan, as well as a limited part of Libya.

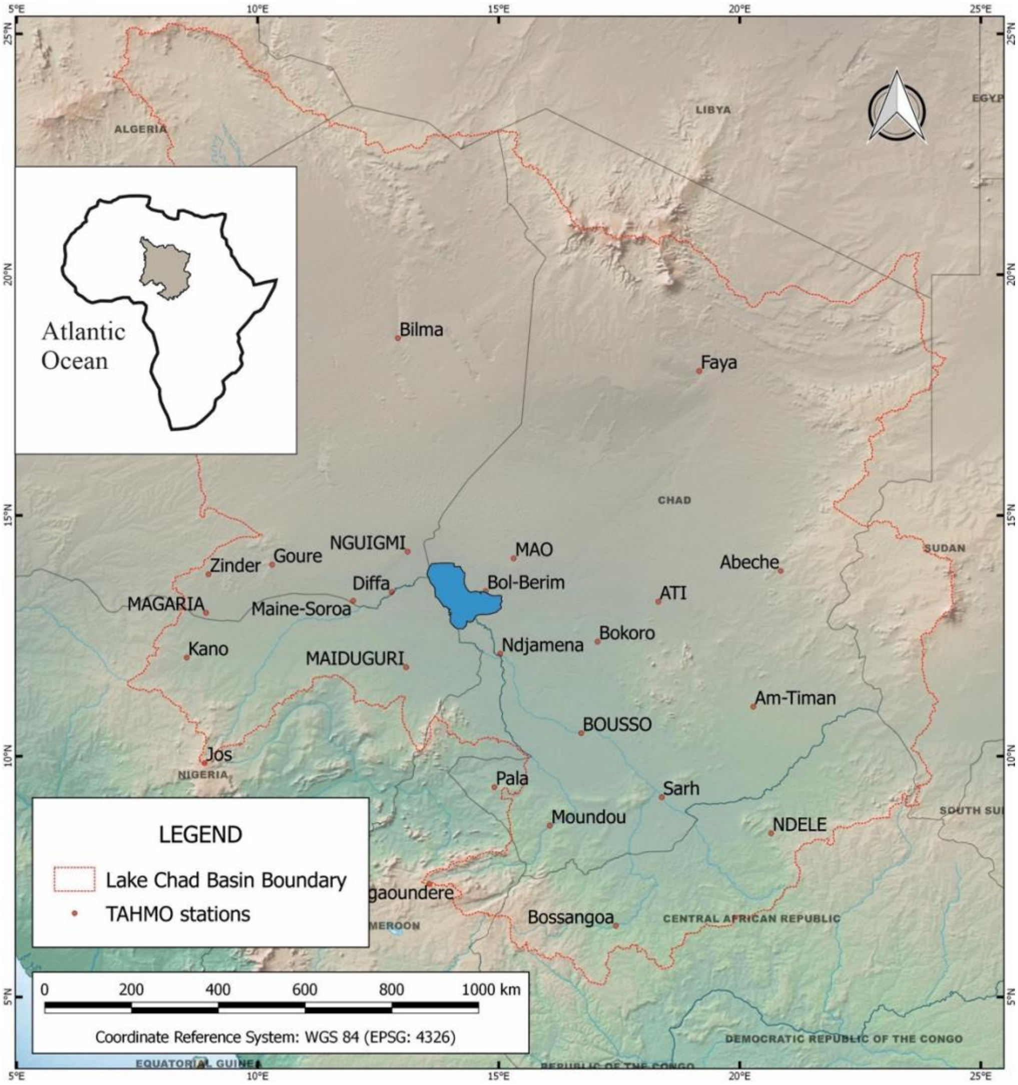


Figure 1. The Lake Chad Hydrologic Basin. Present day Lake Chad boundary and field based meterological stations

From the forested savannah in the south to the spiny shrubbed savannah in the middle and the dessert areas in the north, the region is diverse. Intensive agriculture is also practiced in parts of Nigeria and Cameroon. The climate is marked by significant spatial variations, with an arid climate to the north, a subhumid climate to the middle, and a humid climate to the south, with the majority of rainfall falling between April and October.

Figure 2 illustrates the Conventional Basin which is the intervention zone of the (LCBC) between Cameroon, Chad, Niger, Nigeria, Libya and the Central African Republic. The observer status is held by Sudan and admits Egypt, the Republic of Congo and the Democratic Republic of Congo. In 2012, it covered an area of 967,000 km² (Table 2).

Table 2. The lake Chad Basin countries - Libya is not considered here because of the absence of water contribution from its territory (FAO-RAF/7/011).

Country	**Country area (km^2)**	**Area within the basin (km^2)**	**Total area of basin (%)**	**Total country area (%)**	**Average annual rainfall (mm)**		
					min	**max**	**mean**
Nigeria	923,770	179,282	7.5	19.4	285	1,330	670
Niger	1,237,000	691,473	29	54.6	0	635	105
Algeria	2,381,740	93,451	3.9	3.9	0	135	20
Sudan	2,505,810	101,048	4.2	4.0	70	1,155	585
CAR	622,980	219,410	9.2	35.2	760	1,535	1,215
Chad	1,284,000	1,046,196	43.9	81.5	0	1,350	400
Cameroon	475,440	50,775	2.1	10.7	365	1,590	1,010
Lake Chad Basin		2,381,635	100		0	1,590	415

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

The Lake Chad is one of the largest sedimentary groundwater basins in Africa. From the hydrogeological point of view is composed by three aquifer formations (Schneider, 1989; Eberschweiler, 1993): The Chad aquifer formation (Quaternary-Miocene), the confined Continental Hammadien (Middle Cretaceous-Maestrichtian) and the Continental Intercalaire (Diantien-Lower Cretaceous).

The hydrogeologic basin is an extended plain that is mostly covered by medium- to fine-grained sand. Surface height varies from 3,300 m in the north (Tibesti Mountains), 3,000 m in the NW and 3,300 m in the SW to 180 m in the center (Figure 3). The central part of the basin is characterized by two different landscapes subdivided by the 14°N parallel: sand dunes and absence of surface water sources are typical for the northern part (Kanem), while the south is composed of a superposition of sandy and clay richly soil watered by two main rivers that discharge into the lake: the Chari-Logone River system (Chad), which supplies about 95% of the annual volume of water that reaches the lake, and the Komadougou-Yobé River system (Niger), which provides about 3% of the annual inflow to the lake (RAF/7/011). Soil types are mainly fluvisols, vertisols and aeolian sands (Figure 4, after FAO, 2016).

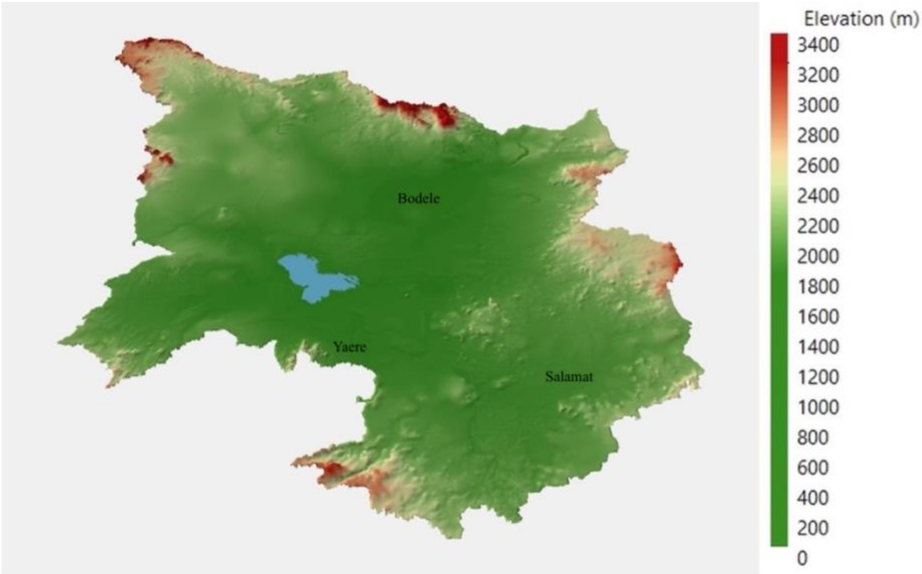


Figure 3. Elevation map of the study area (A Multi-resolution Terrain Elevation Data 2010 (GMTED2010; USGS) of 30 arc-seconds, resolution of about 1 km).

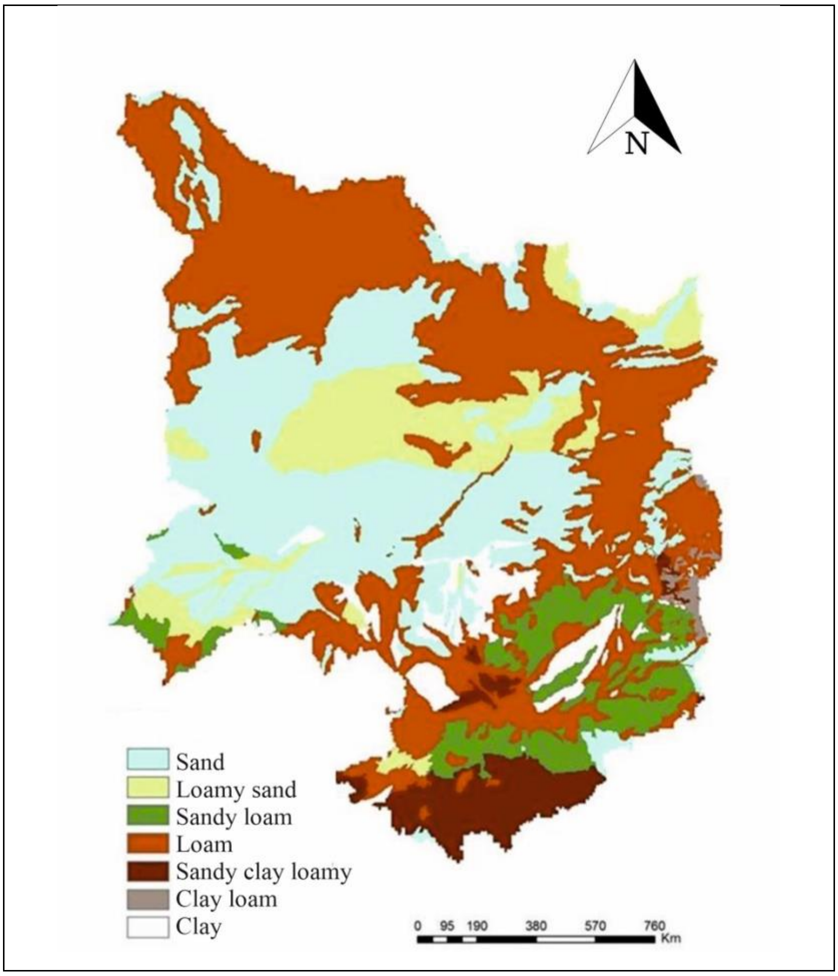


Figure 4. Type of soil and soil distribution (FAO, 2016)

Water supply for population is mainly covered from a number of shallow wells exploiting the upper aquifer. More than 20,000 wells have been identified (BGR, 2010). The water supply source for agricultural irrigation, livestock and market gardens is generally provided from existing dams and also from groundwater in the Chari-Logone (Chad-Cameroon) and the Komadugu-Yobe (Nigeria) basins. In most schemes, surface water is conveyed from existing dams via a main canal for land distribution in existing irrigation zones. Generally, no account is taken of the amount of volume being drained from dams, the applied dose or the timing involved.

2.2. Socio-economic data

About 44 million people live in the Conventional Basin, with 3,090,000 in Cameroon, 3,200,000 in Niger, 26,090,000 in Nigeria, 10,670,000 in Chad, and around 1,080,000 in the Central African Republic (Figures 4 and 6, LCBC-GIZ, 2016). The birth rate growth is expected to be between 2.5 and 3.0% (UN Population Division 2015). The lake's residents have access to less than 550 m^3 of water each year, and they are rapidly facing water shortages (Mekonnen, 2016). Agriculture, as well as nomadic and semi-nomadic animal husbandry and fisheries, are practiced by the majority of people. Water shortage is exacerbated by a rapid population growth rate (ranging from 1.5 percent to 3.7 percent each year) and the practice of irrigated agriculture, which leads to decreased seafood supply, increased food shortages, migrations, civil tensions, and hunger, among other things (LCBC-GIZ, 2016).

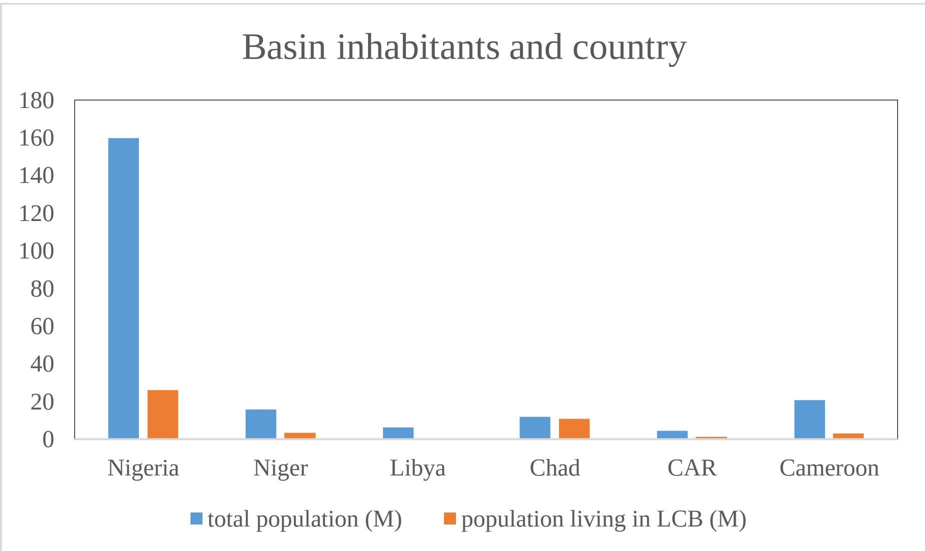


Figure 5. distribution of population in the basin by shared countries (LCBC-GIZ, 2016)

The population is dispersed across the basin's geographical region (Figure 5). In the arid north of Chad (0.1 to 1 inhabitant per km^2), where inadequate rainfall has driven agro-pastoralists to migrate southward, densities are smaller (0.1 to 1 inhabitant per km^2) (LCBC-GIZ, 2016). The indices of human growth in the Lake Chad region are significantly smaller than national averages, which are still poor by international standards. Basic public social services and amenities, such as education, health, water, highways, and electricity, are generally lacking in the region (Lemoalle et al., 2014; Magrin et al., 2015) (Figure 7).

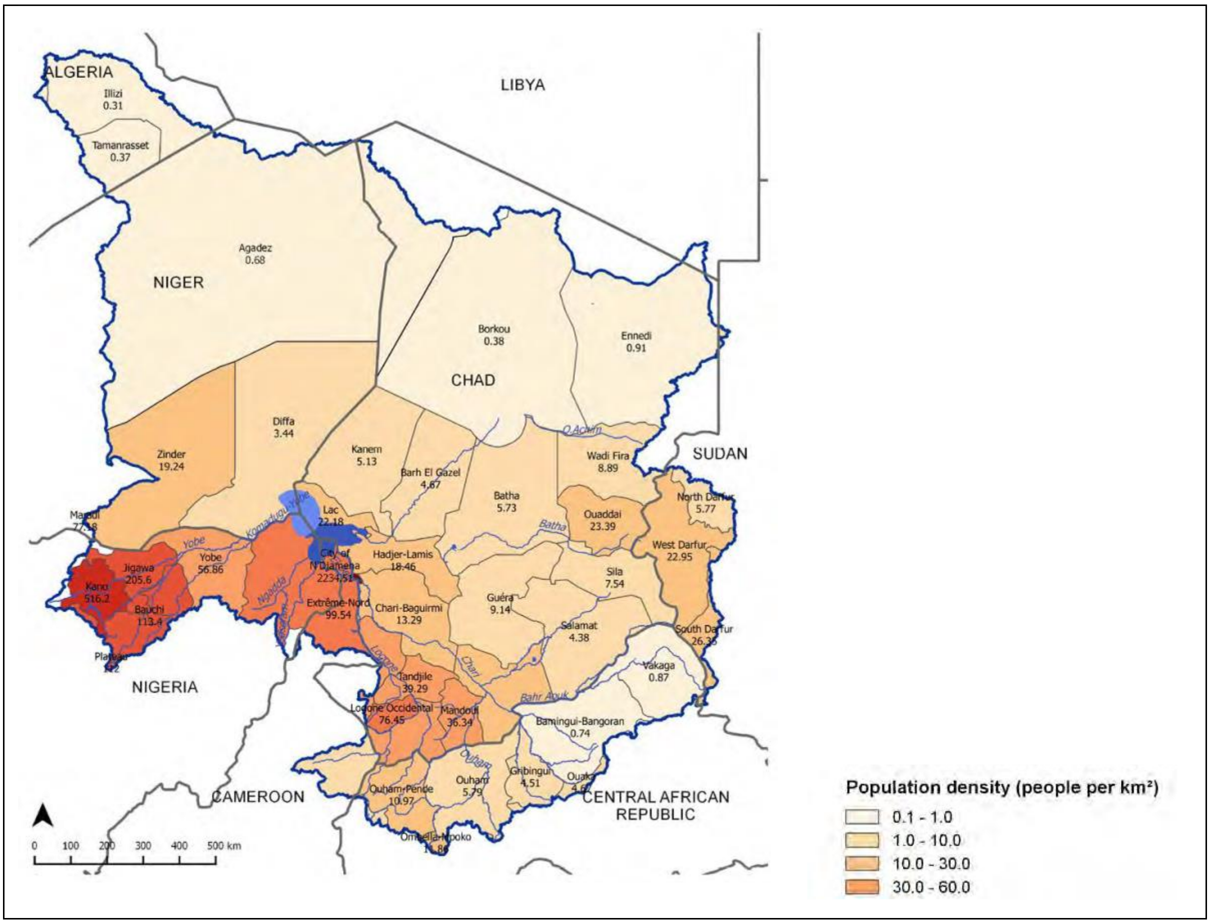


Figure 6. Population density in the Lake Chad basin (LCBC-GIZ, 2016; http://www.citypopulation.de)

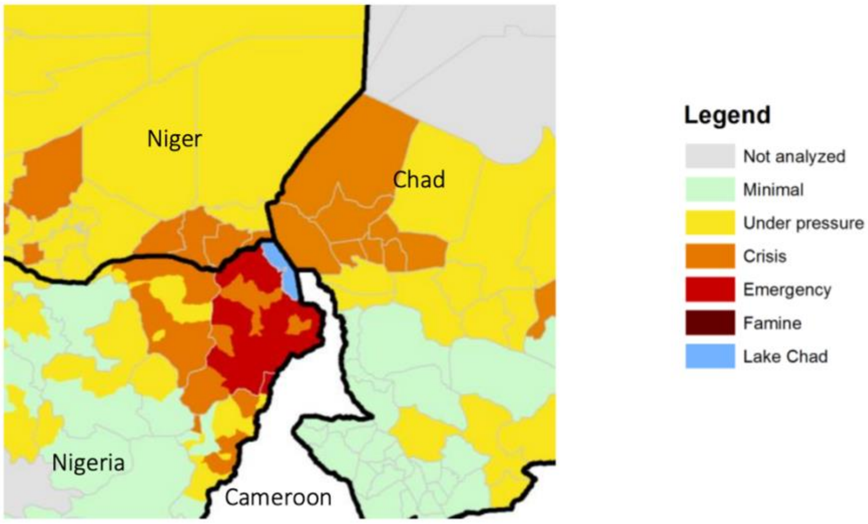


Figure 7. Projected food security situation in the Lake Chad Basin, Cadre Harmonisé, June–August 2017 (FAO, 2017).

2.3. Agriculture and farming

Irrigated agriculture is the first water user since agriculture remains the most significant occupation for over 60% of the basin's population (Figure 8). Irrigation with groundwater is becoming more common, especially for dry-season irrigation of seasonal grazing grounds (The Lake Chad Basin Aquifer System, 2013).

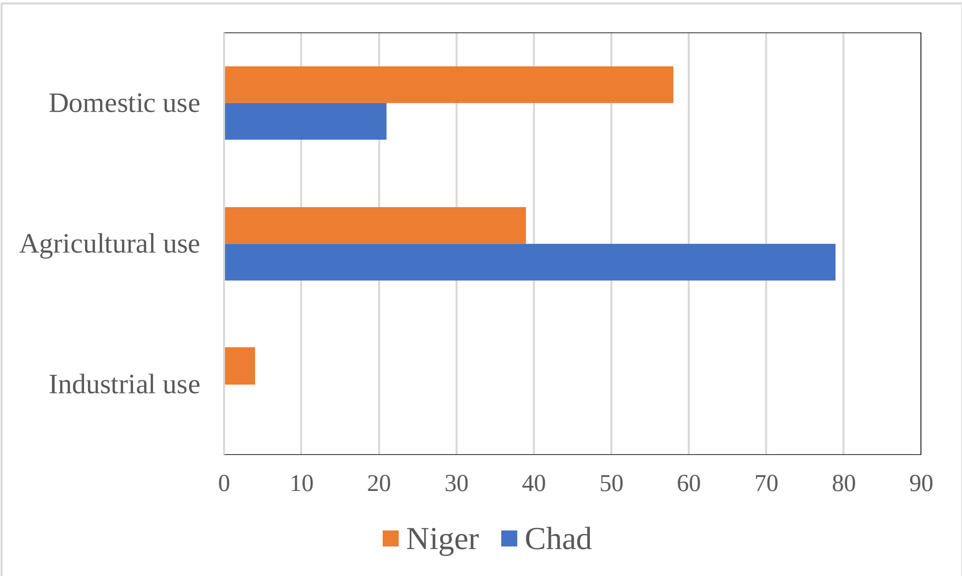


Figure 8. Sectoral groundwater uses in percentage in Chad and Niger (Marianne Alker, 2008, German development Institute)

The major way for irrigation is mostly rain-fed in the south or flooded areas. In river courses, though, cash-crop irrigation (mostly rice and cotton) exists. Demand for irrigation increased by 200 percent between 1983 and 1994, resulting in overexploitation of water supplies that were still under stress due to extreme droughts (UNDP, 2006). The FAO estimated the actual and future water volumes used for irrigation in each riparian country (Table 3). Groundwater irrigation is becoming more common in areas with irregular precipitation (marginal lands), which is a cause for concern due to poor irrigation quality (BGR-LCBC, 2012).

The Lake's wildlife and riparian species often move throughout the basin in search of habitat, and this water scarcity has a significant impact on their existence. Vulnerable human populations are forced to escape to the countryside and cross-national boundaries to survive as climate refugees (FAO Water, 2009).

Table 3. Estimated current and potential water volumes used for irrigation. Source FAO (The Lake Chad Basin Aquifer System, 2013).

Country	Irrigated area (ha)	Irrigation potential in the basin (ha)	Irrigation needs (km^3/year)	
			Per ha (m^3/ha x year)	Total (km^3/year)
Nigeria	82,821	304,000	1,000	3,040
Niger	2,000	11,000	0.21	2,000
Algeria	0	18,000	0	0
Sudan	500	4,000	75,000	0.03
Central Africa	135	16,500	16,500	8.25
Chad	14,020	277,500	15,500	4.16
Cameroon	13,820	66,700	12,500	0.83

2.4. Socioeconomic and political conditions

The socioeconomic dynamics in this area are complicated by a number of problems. Slow and insecure economic structures define riparian countries. Poverty is pervasive and serious. Niger was ranked 186th out of 186 countries in the 2013 United Nations Human Development Report, with Chad 184th, Nigeria 153rd, and Cameroon 150th (UNDP, 2016). These countries have poor labor productivity, a stagnant private sector, an overburdened informal sector, and insufficient infrastructure (GIWA, 2004). Civil wars, along with increased military spending, have slowed economic growth even further, especially in Chad and Niger (Hall, 2009; Okapara, et al., 2015). Prior to its current condition, the Lake waters assisted mass agricultural production, including fishing, animal husbandry, and the cultivation of crops and foods (such as cotton, groundnut, cassava, millet, onions, corn, maize, and sorghum), all of which benefited the region's economy (Odada et al., 2006). Agricultural productivity has been declining since the 1970s and 1980s droughts (GIWA, 2004; Okapara, et al., 2015). Water scarcity has triggered improvements in subsistence trends. Herders in some areas have moved from rearing grazing animals (cattle and camels) to rearing browsing animals (sheep and goats) as the amount of grazing land for animals has declined (Onuoha, 2009). As a result of this activity, the amount of forest cover removed has grown (Okapara, et al., 2015).

2.5. Land use-Land cover (LU-LC)

The flora of the Chad Lake basin ranges widely from the dry north to the humid south (Figure 9). The northern Sahara zone, the central Sahel zone, and the southern Sudan zone are the three regions that make up the land. The Sahara Desert can be found in the basin's northern reaches. In the southern region, tropical vegetation predominates (UNDP, 2006). A significant part of the basin, however, is made up of sand dunes with xerophytic scrubland fringes. A major seasonal wetland is the convergence region between the southern Sahel and northern Sudan-Guinea. Sudanese forest dominates the Sudan Savanna region, with edaphic grassland and acacia plants interspersed (UNDP, 2006).

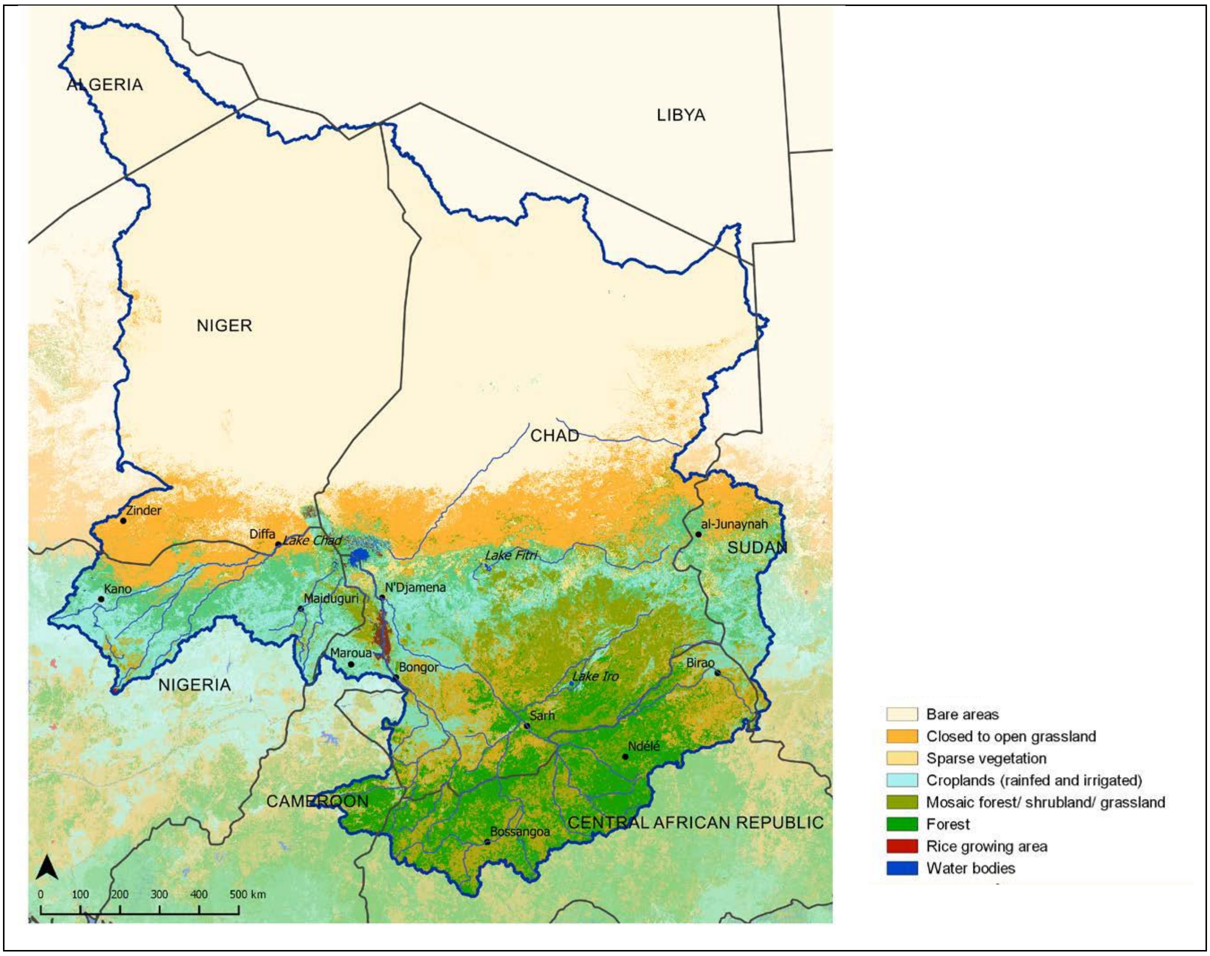


Figure 9. Land cover in the Chad basin (LCBC-GIZ, 2016).

While it has steadily shrunk in size over the last century, the Lake Chad region remains one of the richest regions of the basin's flora. The area's well-drained soils once supported thick woodlands of ebony and kapok trees, but due to soil erosion and deforestation, this has deteriorated. Acacias, baobabs, desert dates, palms, African myrrh, and Indian jujube are among the plants found in the region (UNDP, 2006).

2.6. The climate

Characterized by wide spatial variability of climate, with an arid climate North of N'Djamena, sub humid in the central part and humid in the South, most of the rainfall occurs between April and October. Across the basin, mean annual rainfall ranges between 10 and 1900 mm (Figure 10) and temperature between 41 and 18°C from North to South. In the central-southern part, minimum temperatures are reached in December and January increasing to maximum values in March and April, after which temperatures decrease due to the presence of rainy season. From July to December, the numerous plains (Yaéré, Dérésia, Massenya, Salamat, Komadugu-Yobe) are periodically flooded (after FAO and LCBC-GIZ, 2016).

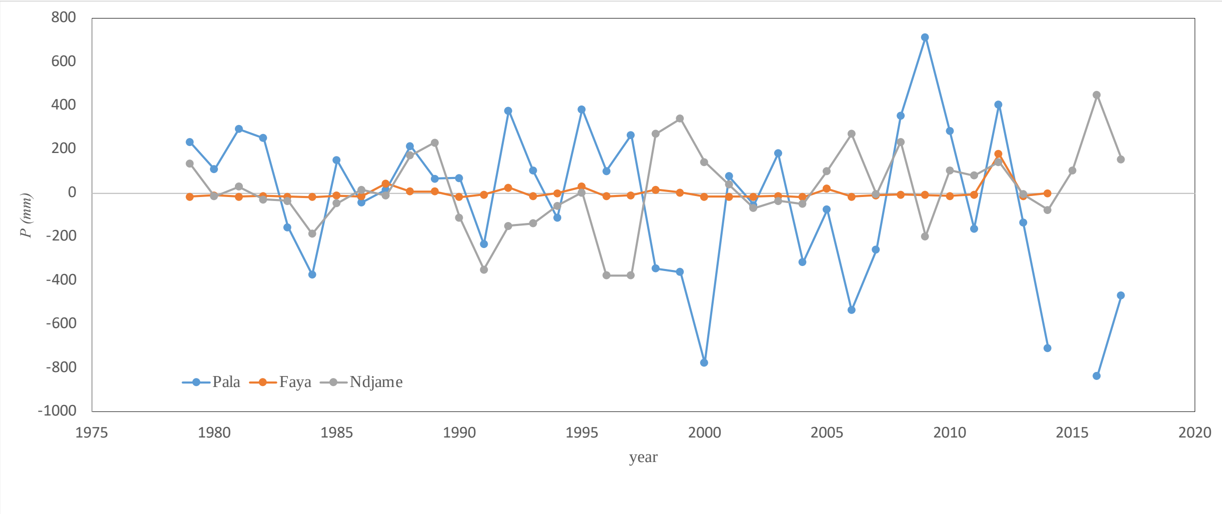


Figure 10. Comparison of yearly rainfall to average amount during the study 1978- 2017 period for three meteorological stations (Pala, Faya and N'Djamena). See Fig. 11 for locations.

The study area extends over different climatic zones that range from desert climatic to the tropical regime and it is characterized by great variability of spatial climatic conditions (rainfall and temperature). The Lake Chad Basin's climate is classified into three subtypes (from north to south, Köppen–Geiger climate classification system, Figure 11):

- The hot desert climate (BWh) characterized by less than 180 mm of rainfall per year ;
- The hot semi-arid climate (BSh) has an average annual rainfall of between 300 mm and 1100 mm;
- The tropical wet and dry or savanna climate (Aw) with an average annual rainfall greater than 1300 mm.

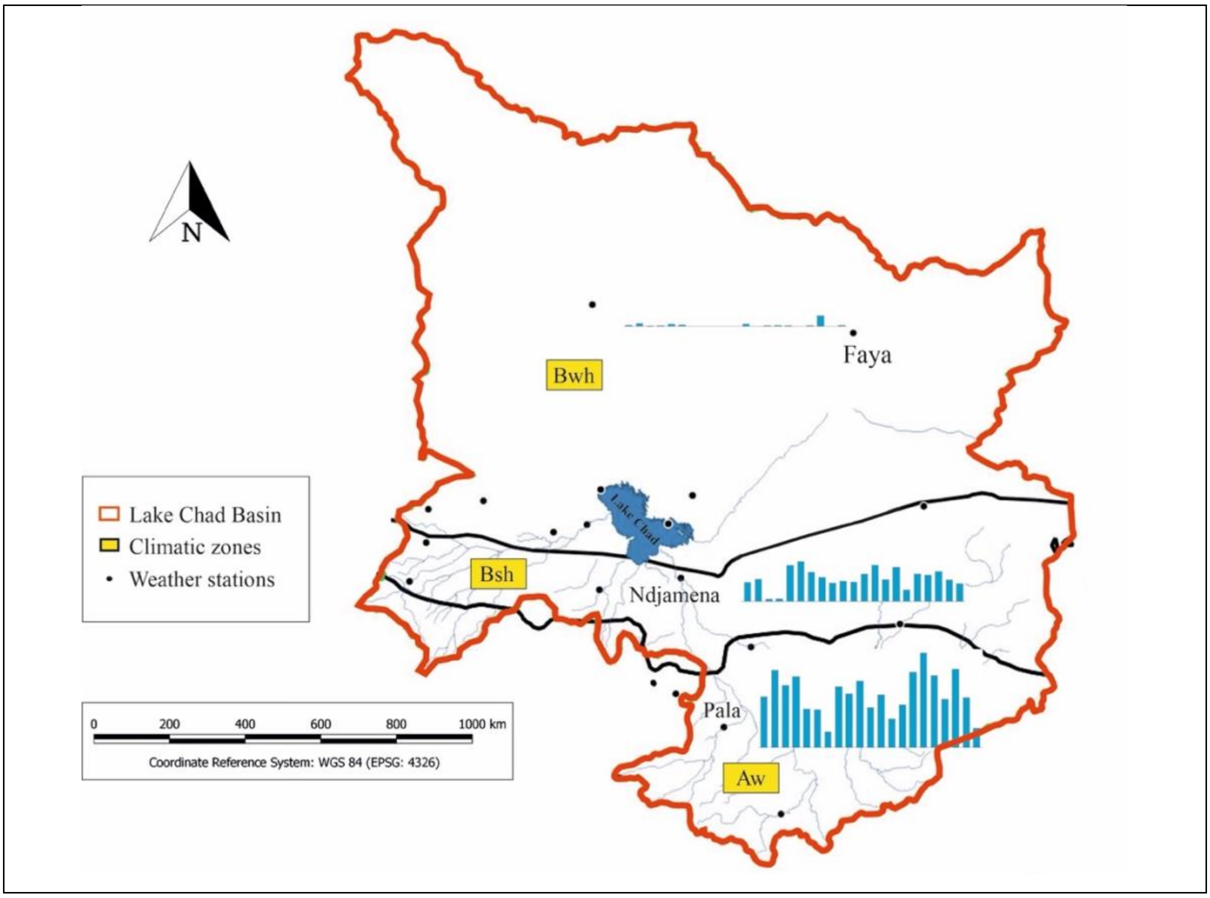


Figure 11. Climatic zones inside LCB. BWh: hot desert; BSh: hot semi-arid; Aw: wet and savanna (after Köppen-Geiger, 1961). Annual precipitation recorded in Faya, N'Djamena and Pala meteorological stations (1994-2014) and some meteorological field stations.

2.7. Geological setting

A Precambrian crystalline basement lies beneath the majority of the Lake Chad Basin's Late Cretaceous, Tertiary, and Quaternary sandy or sandstone formations, which have built up an elevation plain of an average 300 meters (Figure 12). The lowest point in the basin (120 m below the mean Lake Chad water level) is a lowland depression area southwest of Borkou, which is located north of the lake (Bodelé).

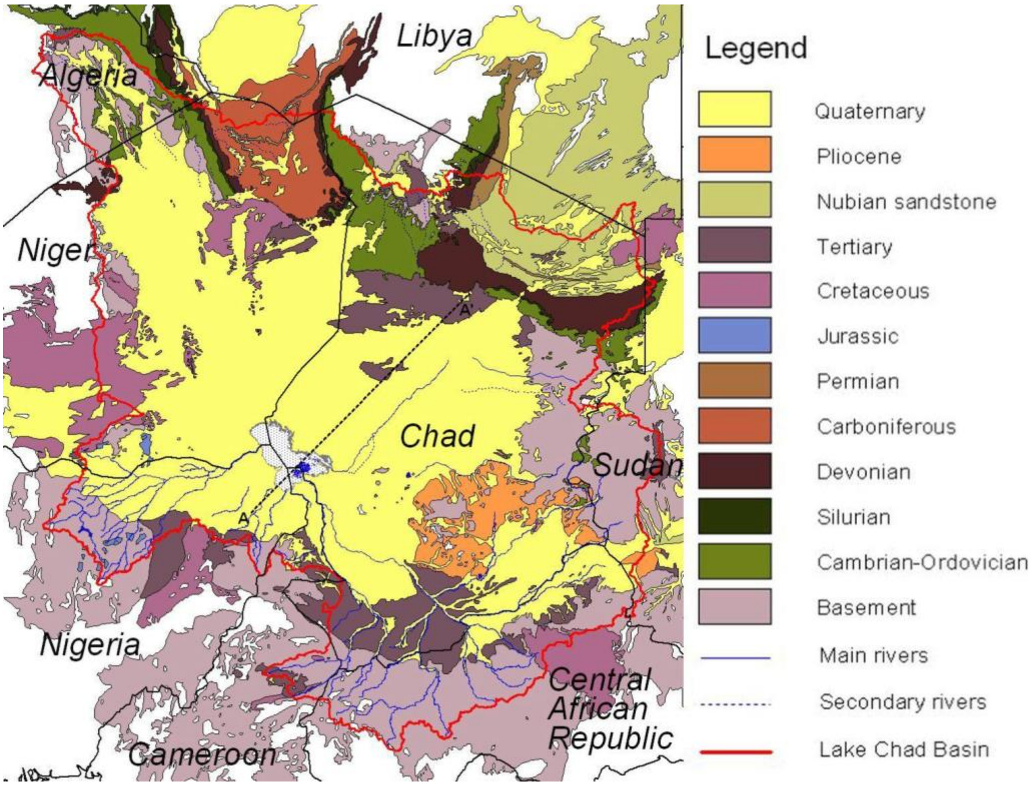


Figure 12. Geology of the basin area, geological formations, and age (modified from Schneider, 1989). The red line indicates the Lake Chad Hydrologic Basin limits. The black dotted line (A-A') denotes the Figure 13 cross-section location (Schneider, 1989).

From a geological perspective, the Precambrian/Paleozoic basement in the basin's southern and northern regions exhibits abrupt shifts (rises or falls) because of significant faults that have produced deep basins (Termit, Niger-Lake Chad, Bongor-Bousso, Doba-Salamat). They were filled with sand and sandstone formations from the Cretaceous and Paleogene eras and date back to that time (Vicat et al., 2002; Ganwa et al., 2009). In Termit, the greatest sediment thickness is 13,000 meters, and in the Bongor, Doba, and Salamat basins, it ranges from 6,000 to 7,000 meters. The Lake Chad Basin's central and northern portions underwent more significant sedimentation during the Neogene period than the southern portion of the basin did. As a result, the central and northern portions of the basin have higher Neogene and Quaternary sediment deposit. Sandstone and granite make up fractured Precambrian rocks (Gear and Schroeter, 1973). According to the results of exploratory drilling, the basement's depth varies from 60 meters to around 600 meters in the basin's center (Mbwou et al., 2012).

2.8. Sedimentary formations

Terrigenous clastics from the early Cretaceous, as well as shallow marine shales, sands, silts, and small carbonates from the late Cretaceous, make up the earliest deposits in the Lake Chad Basin (Genik, 1992). The northeast appears to have much thicker sediments. The following formations can be identified from bottom to top:

The Continental terminal (CT). In contrast to the rocks of the Cretaceous period, the Tertiary era is characterized by marine regression from the basin and the deposition of sandstone and clay series. Intense lateritization typically occurs in the top portions of this formation, especially along the border of the basin. The sedimentary formation that rests on top of the basement 46 complex is primarily composed of the CT. The study area's southern and northern edges are where it mostly outcrops. The CT is found at a depth greater than 100-300 m in the basin's center region (Schneider and Wolff, 1992).

The Pleistocene. The many sedimentary units that make up Pliocene formations range in thickness from 850 m to 4,000 m. The Lower Pliocene formation (LPli) is made up of river sands that range in thickness from 10 to 40 meters and lacustrine clays that are around 300 meters thick (the Upper Pliocene formation, Schneider and Wolff, 1992). The Tertiary epoch comes to an end with the clay deposits comprising diatomite layers. Due to lateral facies changes, the boundary between the Pliocene and Quaternary is not very sharp, and it's possible that changes in lake level have already had an impact on the top of the Pliocene.

The Quaternary. The top layer, the Quaternary, is composed of sands and clays with several subformations, as shown below (BGR-LCBC, 2012): • The Moji Sequence, a fluvio-lacustrine clayey series includes evaporites from the early Pleistocene (gypsum) • The "Ogolien" age aeolian sand dunes (overlying the Moji Series), which correspond to dunes built between 20,000 and 13,000 years ago (Swezey, 2001). These dunes are primarily made of quartz sands and may be found mostly north of Lake Chad.

The sodium-carbonate evaporite minerals, such as natron (Na_2CO_3, $10H_2O$), are frequently present in the interdunal valleys, up to 30 km from the shore of the former lake and are still exploited. To the south of the lake, Quaternary deposits are covered by alternating clayey or lacustrine layers that were formed during more humid times when the lake's size increased and the Logone and Chari riverbeds were wider. These clayey layers are an indication of past arid conditions because they are lacustrine or fluvial in nature. Quaternary deposits are also discovered covering CT layers in Central African Republic and along the basin's southern edge.

The strata near the end of the stratigraphic succession are primarily made of fluviodeltaic deposits and aeolian sand. It ranges in thickness from 15 to 100 meters (Lopez et al., 2016). The sedimentary layers in the Lake Chad Basin are connected to river and lake changes from the Quaternary era to the present.

2.9. Surface hydrology

The principal permanent rivers are Chari and Logone (more than 15,000 Mm^3/yr , in the basin's southern part, converge at N'Djamena), and Komadougou and Yobé in the western part (400-600 Mm^3/yr). Less important basins draining into Lake Chad (less than 15,000 km^2) include Yedseram, and Ngadda in Nigeria and El Beid (NE of Nigeria and north of Cameroon). The remaining hydrographic network is made up mainly of a number of intermittent watercourses (Figure 13).

The two main river basins Chari and Logone, occupy the area below the 15th southern parallel. The two river systems, with headwaters in the Central African Republic and the Cameroon, and an area covering 690,000 km^2 in southern Chad, are responsible for 95% of the inflow to Lake Chad.

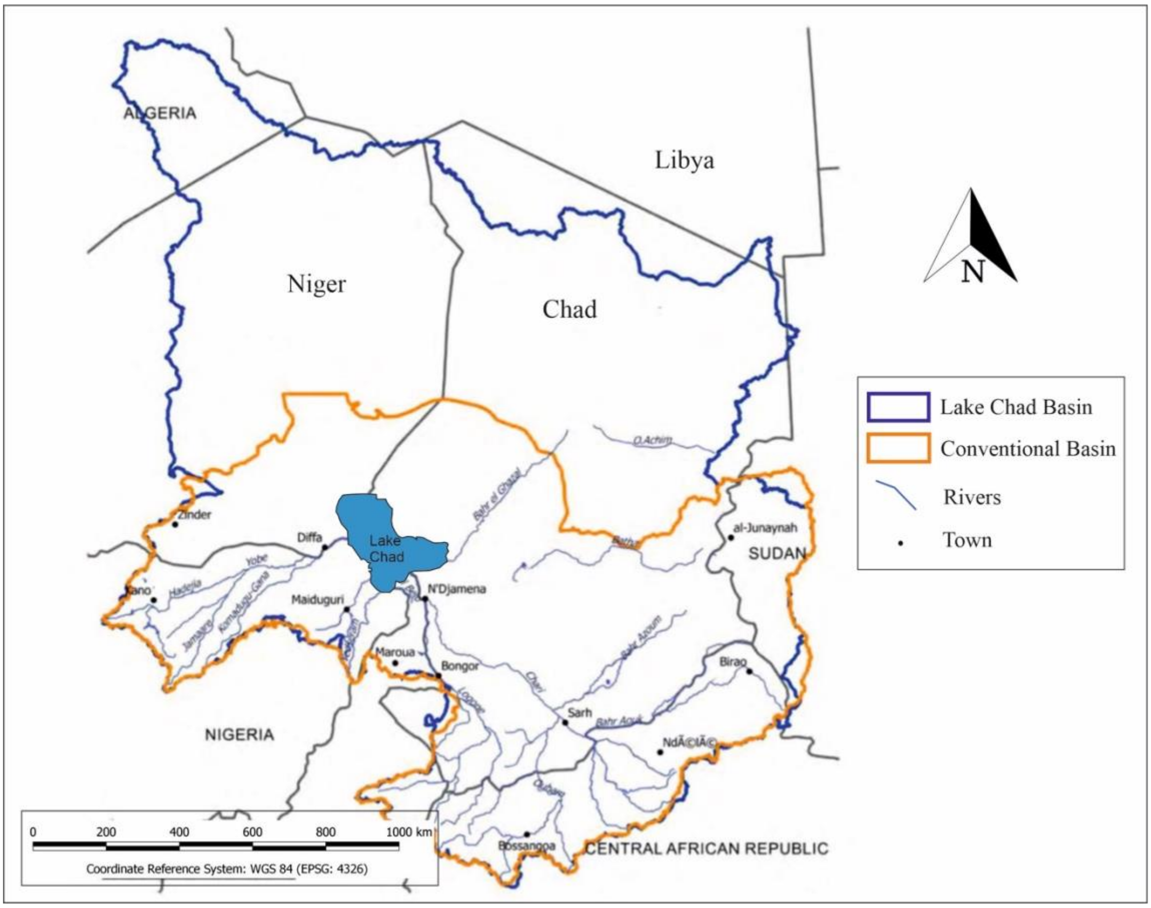


Figure 13. Main hydrographic network and Lake Chad location. The conventional basin refers to the geographical area drained by the Lake Chad and its tributaries.

The hydrological services of member countries maintain a network of hydrological stations (gauge stations) with streamflow information available at the LCBC (Table 4). Since the mid-1990s gathered information was stored on a daily basis, however, a number of gauge stations have not been operational due to lack of resources (LCBC-GIS, 2016).

Table 4. Gauge stations of the national networks of LCBC countries in 2012 (LCBC-GIS, 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

Lake Chad, in its current 'small Lake Chad' state (around 2000 km^2), is an endorheic system supplied mainly by the Chari-Logone River system (up to 95% of total inputs), other tributaries and from direct rainfall. Lakes Iro and Fitri (Figure 9) are hydrologically controlled by the rainy season from June to September. 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 exists and new dams are planned for further use in the Nigerian and Chadian areas.

2.10. Groundwater hydrology

Main aquifer units (water-bearing formation) in the basin are Quaternary (unconfined), Lower Pliocene and Continental Terminal (confined, unconfined), of different areal extension, spatial distribution of quantity and quality of groundwater and depths.

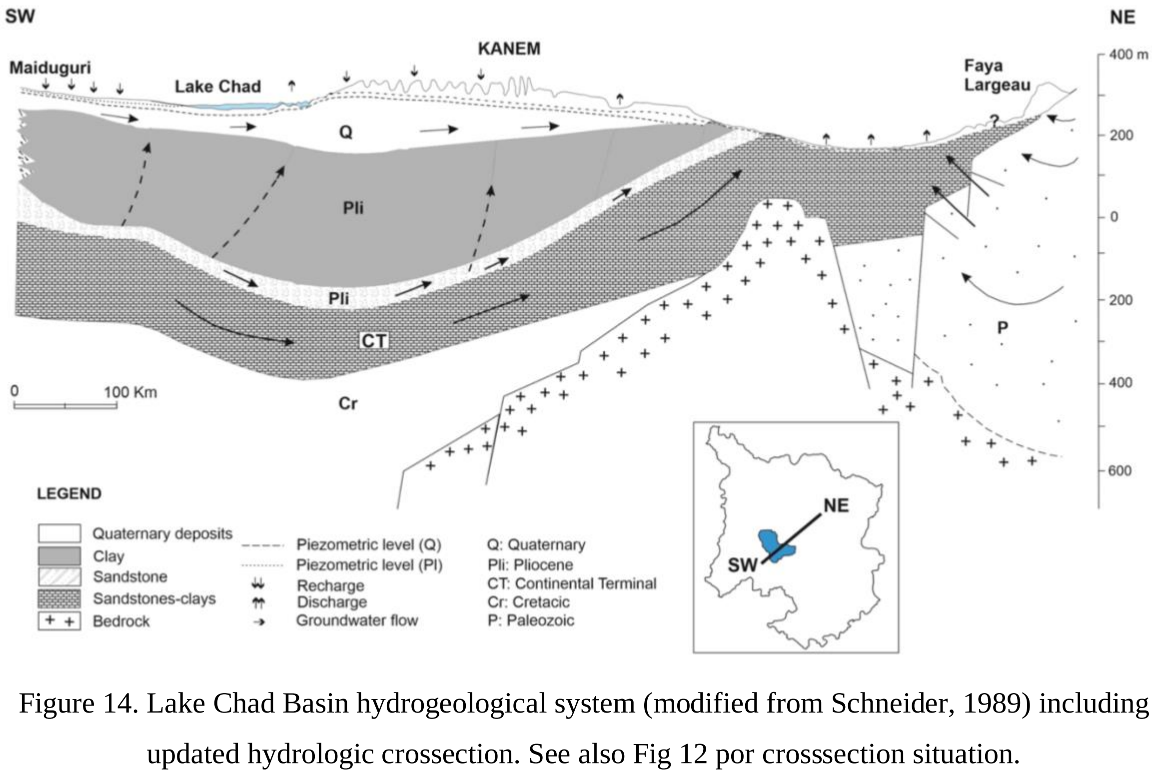


Figure 14. Lake Chad Basin hydrogeological system (modified from Schneider, 1989) including updated hydrologic crossection. See also Fig 12 por crosssection situation.

Precambrian crystalline rocks (schists, granite, etc.) compose the bedrock and outcrop on the southern edge of the basin. The depth to the bedrock increases toward the west, where a depth of more than 1,000 is found. Depth, however, presents abrupt changes rises or falls in the fault zones; a depth of more than 1,000 m bedrock is found at N'Djamena (Figure 14).

The sedimentary formations exploited belong the Chad Formation aquifer system are the research objective. Only hydrogeological aspects of interest are considered. The lithological variation of stratigraphic units controls aquifers' properties and their capacity to store and transmit groundwater, which will vary laterally and with depth. In some cases, a range of hydraulic properties can be attributed to a single aquifer.

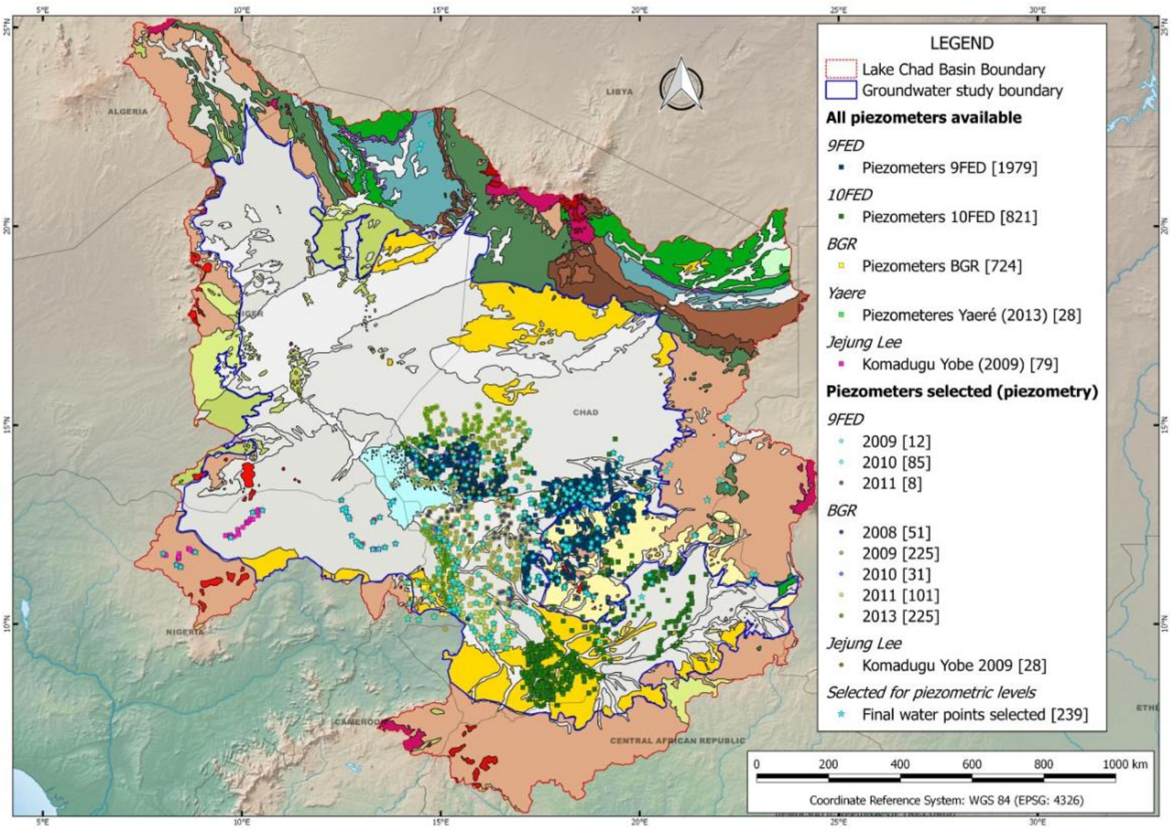


Figure 15. Spatial distribution of total water points (3,760) exploiting the aquifer system in the area. 9FED, data and year for the 9FED campaign (from RESOPIEZ and SUIVPIEZ databases).

The Chad Formation (CAF) (Quaternary- Miocene, FAO, 1973) has received most of the research interest. It is generally exploited in all the basin and is composed of the following hydrogeological units (Figs. 14 and 15) the upper phreatic aquifer, present throughout the basin and made up of Quaternary deposits; 2) the lower Pliocene materials comprise the intermediate confined aquifer; 3) a deep confined aquifer made up of the Continental Terminal-CT deposits (Oligocene-Miocene). According to the LCBC database inventory (boreholes, wells of different characteristics and associated information), aquifer system is exploited through 3,760 water points (Figure 15).

At the basin scale the regional piezometric map (Figure 16) obtained from the 1968 data (Eberschweiler, 1993) shows that the regional groundwater flow trend shifts the central part of the basin, where the Lake Chad outcrops. Water level depth varies between a few meters in the lowland area of the lake, to about 50 m below the surface in recharge zones. Several piezometric depressions are observed, which have also been reported by Leblanc et al., (2007), Boronina and Ramilien (2008) being the last update from BGR project (BGR-LCBC, 2010).

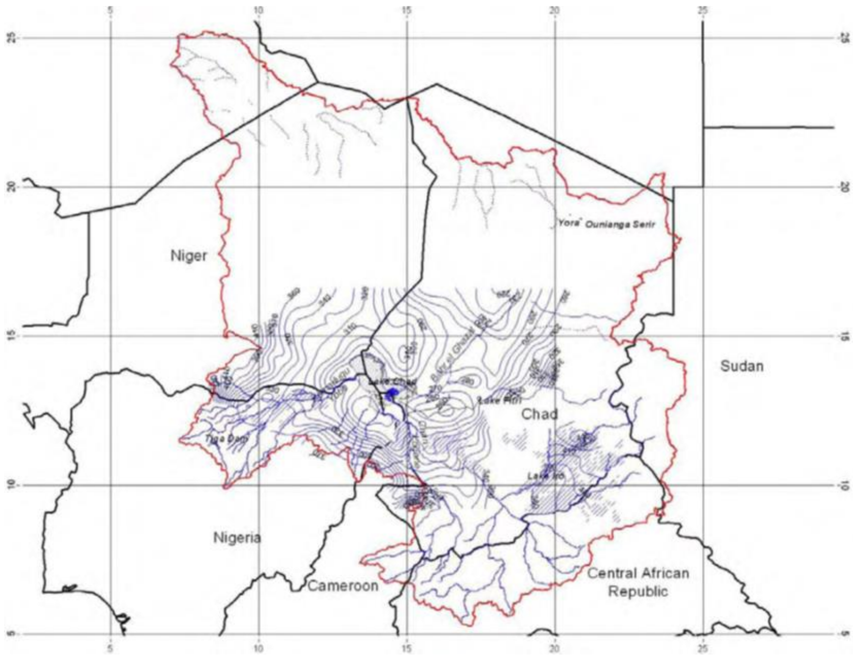


Figure 16. Piezometric level for the Quaternary aquifer (BGR-LCBC, 2010).

2.11. Hydrochemistry

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.

Chapter 3

Methodology

3.1. Introduction

The methodology of this PhD can be divided into two parts. The first part is data gathering and storage of new geo-hydrological information collected. Second part involves analysis and assessment of gathered data from collected information.

The data needed for this study are in two categories: bibliographic search of scientific publications, ground data and remote sensing data. An important bibliographic search has been carried out to obtain new publications and reports of the area from national and international institutions presently working in the Lake Chad Basin. Most '*in situ*' information has been provided by the: Project ResEau / UNITAR-UNOSAT, the LCBC (Lake Chad Basin Commission), IAEA, BGR, BRGM and University of Kansas Missouri (USA). Among the collected information, more than 10,000 digital files, including information from the 1960's mainly in French, were provided by the institutions.

The process was based in the data collection from individual organizations (Member State, International and National, papers and thesis) and analysis of information for the regional groundwater conceptual model update. An intensive data mining from existing reports, research publications and web search has been done. Search includes works of local interest, focusing on partial hydrogeological aspects, data sets of hydrologic interest or only focusing in some sectors. Practically, all information here presented and assessed has been provided by the CDIG (Centre de Documentation et d'Information Géographique), LCBC, Ministère de l'Eau et de l'Assainissement du Tchad and ResEau. Table 4 lists the main datasets (already collected information which comprise more than 10,000 files provided by the institutions).

Table 5. Summary of the datasets gathered for the development of the methodology

Name	**Types**
Land use and land cover,	DEM, cultivated crops; vegetation
Climatic data	Precipitation, temperature, wind
Geology	Geologic logs, maps, cross-sections
Hydrologic data	Runoff values, Dams, Lakes
Groundwater hydrology	Data base (wells, piezometers, springs); data series of groundwater level; use of wells (water abstraction and use of water); aquifer hydraulic; pumping tests; chemical and isotopic data

3.2. Climatic data

The most important climatic datasets storage platforms for Precipitation (*P*) and Temperature (*T*) are TAHMO (The Trans-African Hydro-Meteorological Observatory), SIEREM and ReSEau projects (Table 6). An alternative to gather meteorological data series is the use of remote sensing data sources merged with ground-based data. Several satellite products more or less available with information going back to 20-30 years exists (Sheffield et al., 2018).

Table 6. Availability of the most important raw data in the region. Ground-based platforms

Platform / Parameters	TAHMO	SIEREM	ReSeau
Number of field stations	32	310	52
Time range of data	1973 - 2018	1940-1990	1998-2012
Type of data	daily	daily	average
Continuous data series	yes	Lots of gaps	no
Precipitation (P)	yes	yes	yes
Temperature (T)	yes	no	no
P & T	yes	no	no
Wind	yes	no	no
Other parameters	yes	no	no

3.2.1. Ground-based platforms

TAMOH (The Trans-African Hydro-Meteorological Observatory). Selected data series

TAHMO http://tahmo.org/african-climate-data/; https://en.tutiempo.net/climate/africa.html aims to develop a vast network of weather stations across Africa. Inside the LCB, 45 weather stations are available for the 1957-2018 period: 32 of them (14 in Chad, 7 in Niger, 5 in Nigeria, 3 in Cameroon and 3 in CAR,) with daily data sets of precipitation and temperature, but with important gaps (Figure 18). Only 25 stations, present less than 20% observation gaps). As for ground-based weather stations, main spatial coverage is in the central part of the studied area. Few stations are in the inhabited areas North of Lake Chad.

The ground-based daily precipitation (P) and temperature (T) time series for 25 meteorological stations in the basin were compiled from the TAHMO Platform (Van de Giesen et al., 2014). Of the whole historic data record (1973–2018), the 2005–2014 period presents the narrowest data gaps (≤20%) in the time series (Figure 18).

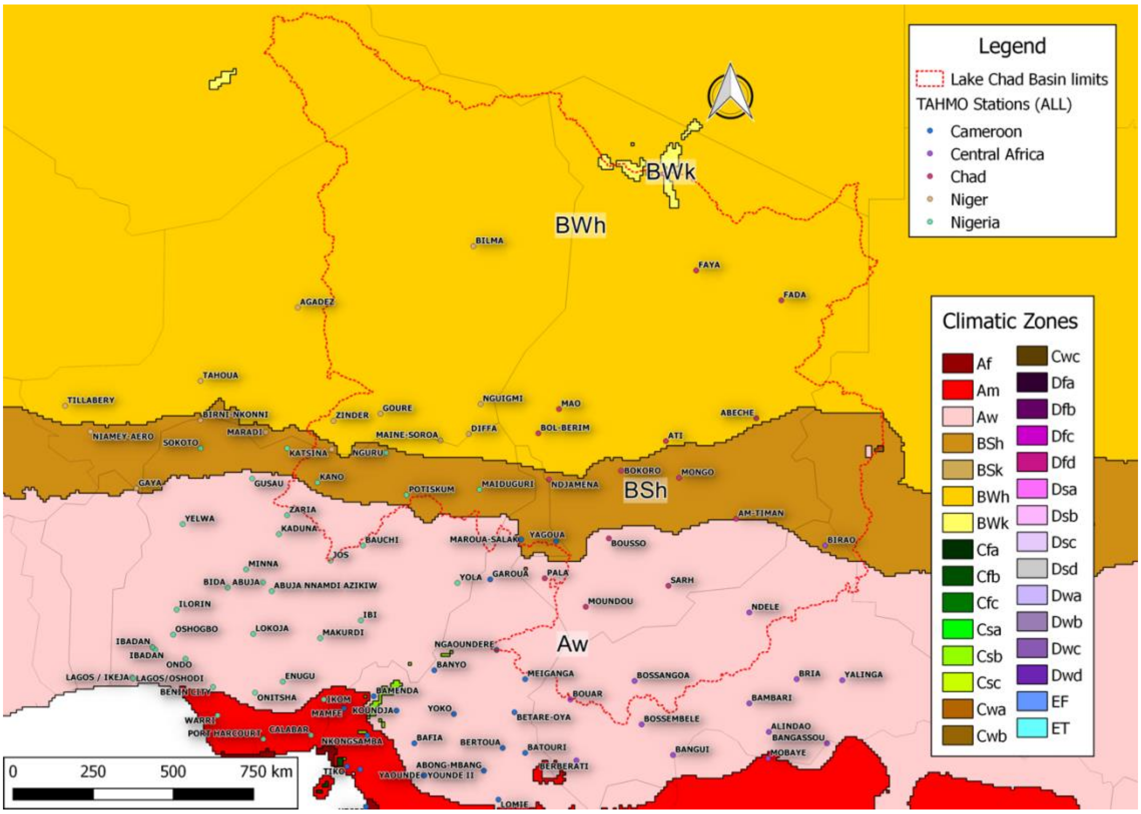


Figure 17. Location of TAHMO stations in the study area and climatic classification

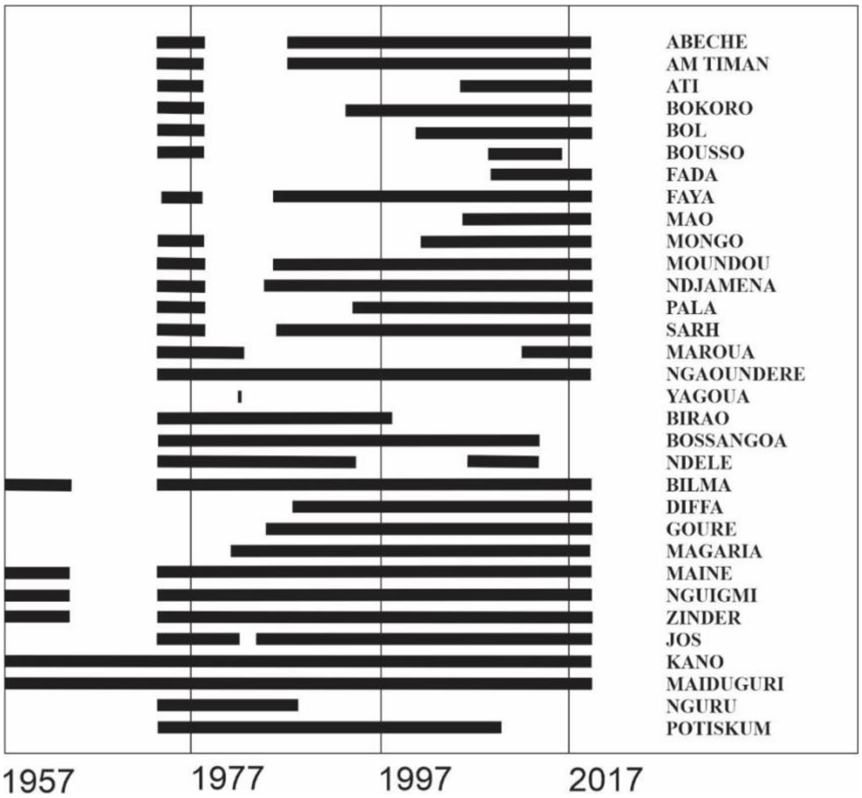


Figure 18. TAMOH. Ground-based stations and period length of data sets (LCBC). Daily records of P (mm) and T (ºC).

ReSeau- SIRE Tchad project

Information provided by the LCBC from the existing inventory includes 46 weather stations (daily rainfall and temperature data) located in Cameroon, CAR, Chad, Niger and Nigeria, and for a period extending since 1921 up to 2009 (Figure 19). The exploratory raw data analysis indicates that some ground stations also provide maximum-minimum temperature. Percentage of data gaps ranges between 9 and 55% (data-files provided by CDIG-ReSeau).

Hydrologic data are regularly collected at the Lake Chad Basin Observatory- LaCBO the regional database created in 2010. Meteorological information records include potential evapotranspiration, rainfall, temperature -average, maximum and minimum-, wind and solar insolation. In the ResEau project 44 weather stations are located in the area (http://geoportal.reseau-tchad.org/geonetwork/srv/eng/catalog.search), 25 in Chad, 8 in Cameroon, 5 in Niger, 5 in Nigeria and 1 in Sudan. They cover a variable data length ranging between 4 and 90 years and type of monitored parameters. Some climatic data have been assessed by remote sensing from the Rainfall Estimate RFE 2.0 (NOAA).

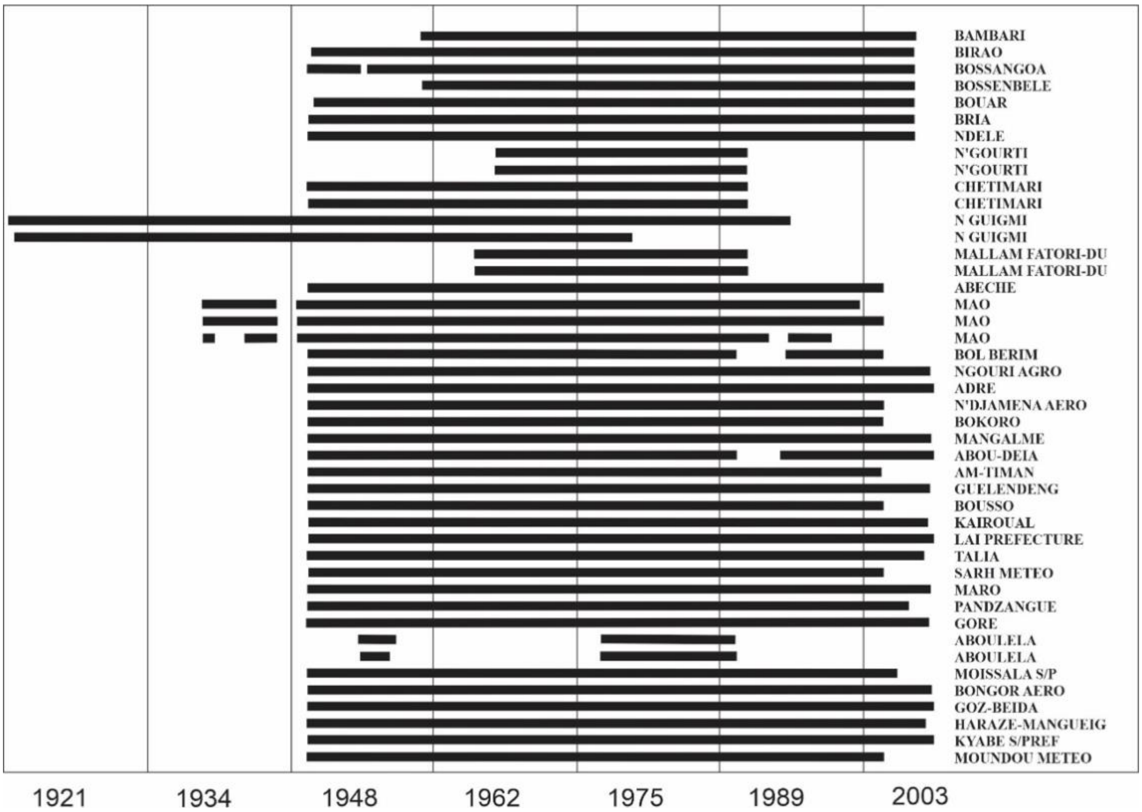


Figure 19. Ground-stations and period length (LCBC). Daily records of P (mm) and T (ºC).

SIEREM (système d'Informations Environnementales sur les Ressources en Eau et leur Modélisation)

SIEREM (Environmental Information System on Water Resources and their Modeling, http://www.hydrosciences.fr/sierem/, Boyer et al., 2006) . A total of 590 weather stations (332 in Chad, 80 in Cameroon, 74 in CAR, 70 in Niger, 25 in Nigeria, 10 in Sudan) are identified covering different, meteorological parameters, generally precipitation (mm) and temperature (ºC) (Figure 20). Daily temperature and rainfall (ground-based) is available. Information on ETP and humidity (monthly values) is scarce and only two weather stations were found. Data coverage extends from 1948 to 2002 with different data sets distribution along time; direct download from platform of quantitative information is not provided.

Ground-based climatic data, mainly precipitation and temperature, are recorded through a network of around 680 meteorological stations with a highly variable time span maintenance of regular observations and important gaps (Figure 20). Most complete and accurate daily dada set corresponds to TAHMO platform and it was finally selected for the natural recharge estimation.

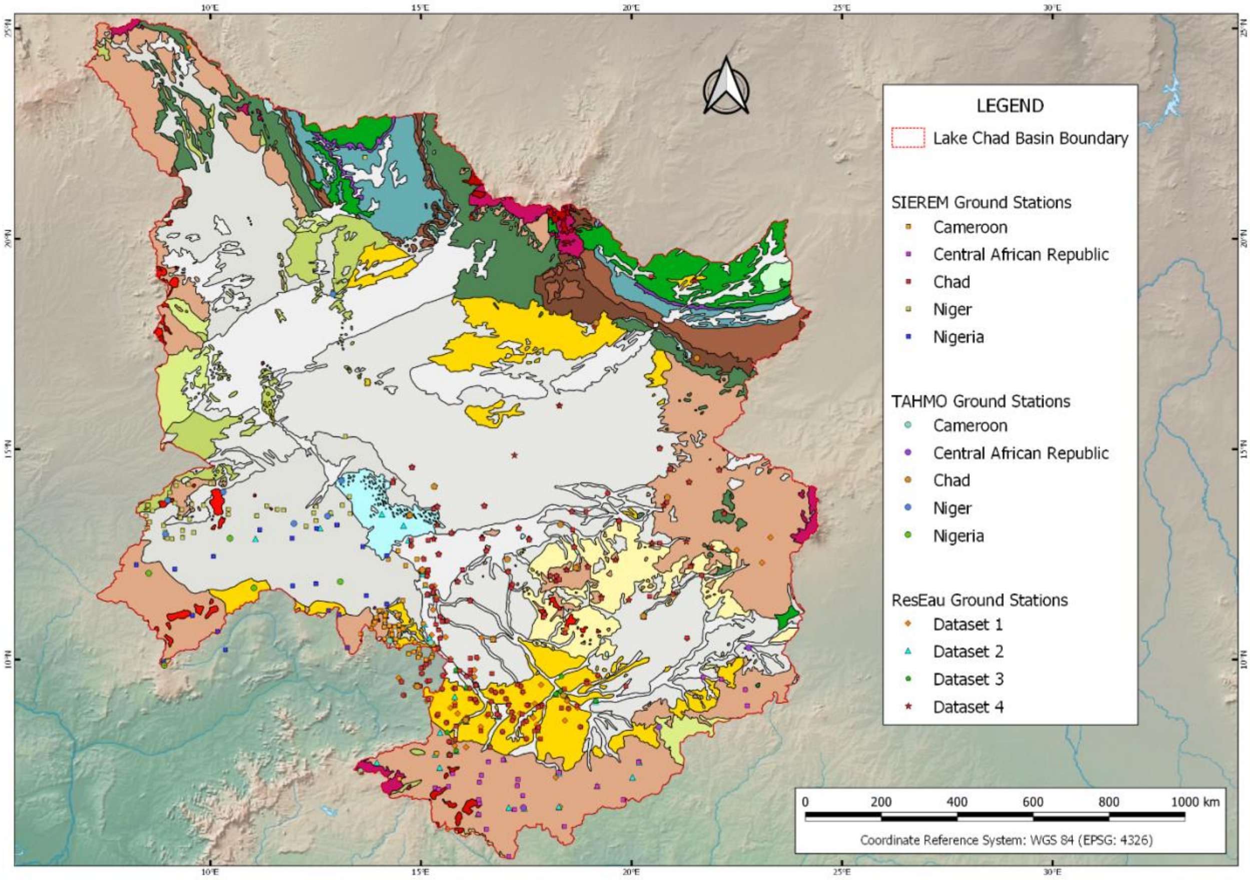


Figure 20. Ground-based meteorological stations within the LCB (various sources)

3.2.2. Remote Sensing Datasets

The primary identified platform to determine the precipitation and temperature in Lake Chad is the CHADFDM (Chad Flood and Drought Monitor, http://stream.princeton.edu/CHADFDM/WEBPAGE/interface.php?locale=en).

The remote sensing data merged with ground-based data (Sheffield et al., 2018). The CHADFDM was developed for hydrologic applications by Princeton University in collaboration with ICIWaRM (International Center for Water Resources Management) and UNESCO-IHP. The Multi-Source Weighted-Ensemble Precipitation (MSWEP) is a new fully global historic precipitation dataset. MSWEP takes advantage of the complementary strengths of gauge-, satellite-, and reanalysis-based data, providing reliable precipitation estimates (Beck et al., 2019a). The dataset has already implemented daily gauge corrections. Systematic terrestrial precipitation biases are corrected using river discharge observations. The provided gridded precipitation datasets have been validated using observations and by comparison with other satellite-based products (Beck et al., 2017, 2019b).

3.3. Geological information

The most of existing data are the works which have been done by Schneider (1989) and Eberschweiler (1993) and a great number of literatures exist as presented in previous chapters. Within this research, a geologic digital mapping of the basin area was made based on the information gathered from the BGS shapefiles (http://earthwise.bgs.ac.uk). Also, geological maps under digital support were available from the BGR-LCBC project (BGR-LCBC, 2009; 2012).

To geologically characterize the geometry of the basin and aquifer system delineation, data sets on well points (boreholes, wells, piezometers) in the different projects funded by several agencies since 1965 has been analyzed to determine the type and relevance of the provided data files and reports.

From a number of 9356 water points inventoried (Table 11), after data screening, 644 documented geologic logs were identified (Table 8). Provided records and observations are highly variable, ranging from deep oil-exploration boreholes (more than 3000 m deep) to shallow excavated wells. Generally, as generally geo-localization refers to the borehole village name and elevation is not reported, estimates of geographical coordinates was based on a map search for the place or village name. All logs are stored in a database with graphic output based in QGIS for further data exploitation

Subsurface geological information was obtained from 430 lithological well logs datasets (Figure 21). Selection was based on those records considered quite precise, with measured clearly geo-localized attributes, and with observations made whenever a change in stratigraphic sequence occurred and measurements were taken.

Subsurface mapping, basin's three-dimensional geological architecture, was undertaken using lithology logs and based in the RockWare software (Rock Works 17). Based on the geological logs' description, the top and bottom depths of hydrostratigraphical units were obtained (Figure 22). The model was also adjusted with existing cross-sections and geophysical information from the literature.

The base for the construction a 3D conceptual geologic model was the geologic logs analysis of stratigraphic sections from the only considered representative boreholes (430 out of 640) following screened data (Table 7). Selection was based on those records considered quite precise, with measured attributes, clearly geo-localized and observations whenever a change of stratigraphic sequence occurs, and measurements exist.

Table 7. Geologic logs selected from existing campaigns for subsurface geology mapping.

Name of 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 Pastoral	13	95.5	156
Nigeria	70	249.2	1044
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		

According to records, 131 logs present only information on the Quaternary aquifer; 128 contain geologic descriptions for the LPli and CT and in only 51 water-points the well was drilled through the three water bearing formations. Deep drilling, generally for oil research, occurs only in a few spots and not all oilrig logs existing in the area could be identified due to not provided information or data confidentiality.

Depth of top and bottom of the different hydroestratigraphic water bearing units (aquifers) or non-water bearing units was calculated for selected geologic logs based on lithologic descriptions and were subdivide into uniform intervals corresponding to hydroestratigraphic units. The five defined hydrostratigraphic units: Quaternary (Q), Pliocene (Pli), Lower Pliocene (LPli), Continental Terminal (CT), Cretaceous (Cr) and basement. Geologic logs were carefully analyzed from the stratigraphic point of view before DB storage; spatial distribution (XY coordinates) and elevation assessment (m.a.s.l) was based in the STRM 30m model DEM. (Figures 21 and 22).

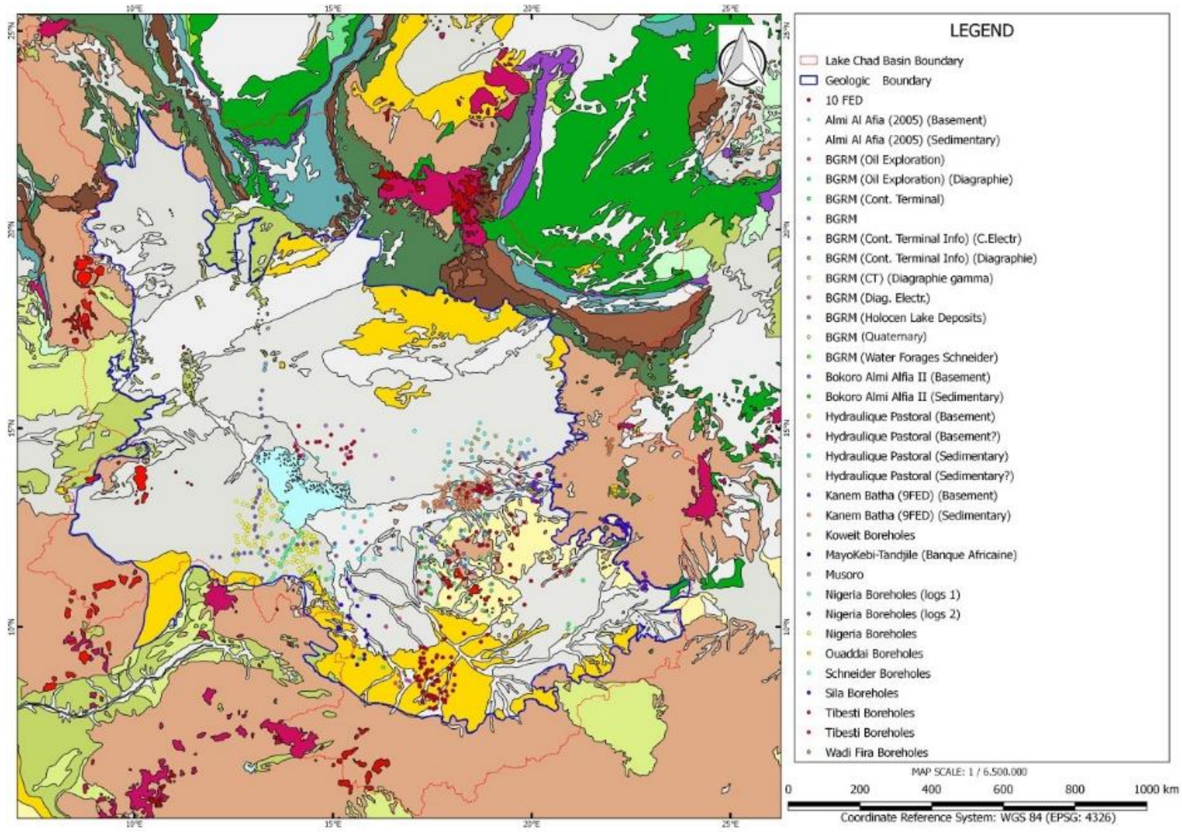
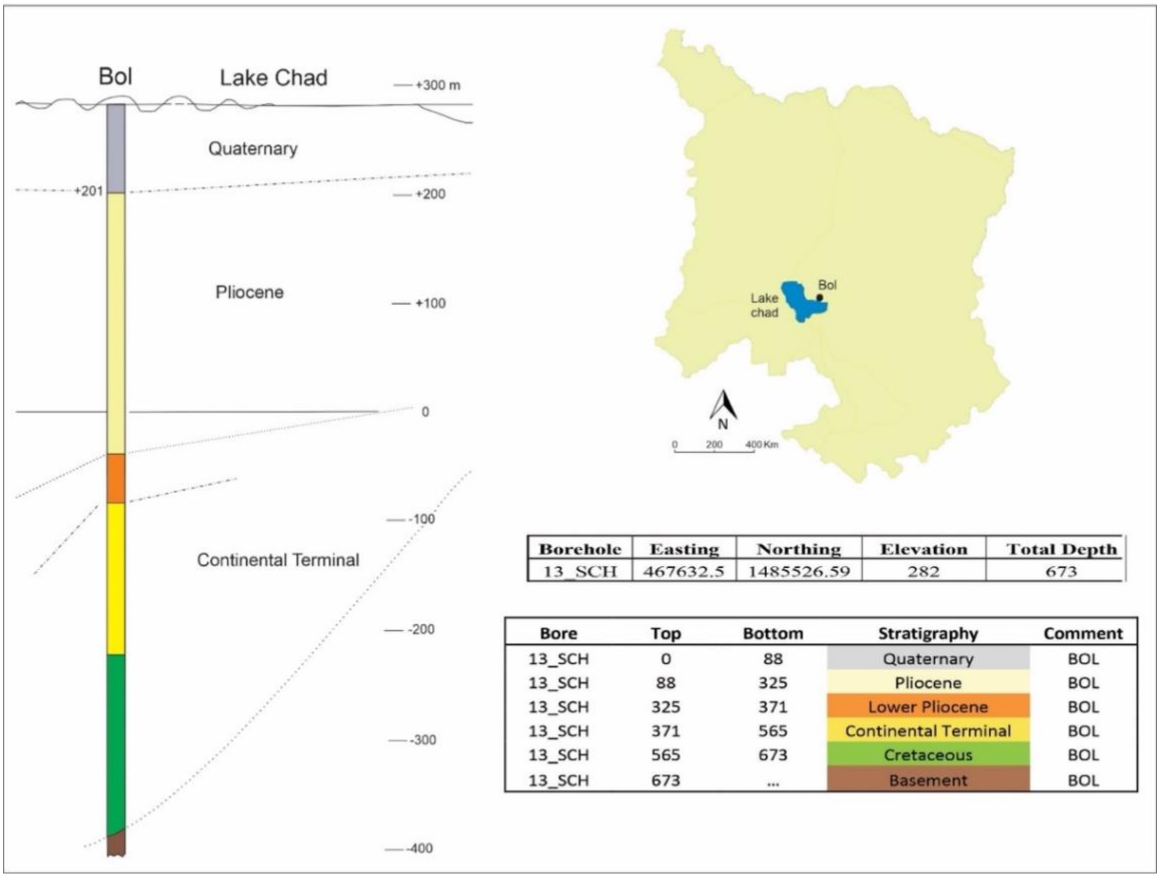


Figure 21. Spatial distribution of geologic logs (430) in the study area. The color dots indicate the different campaigns with available information

Most information gathered corresponds to the Quaternary aquifer, mostly covering Chad country, with limited information for the northern part. Data from neighboring countries are scarce, hard to collect and only a limited number of reports have been found.



Borehole	Easting	Northing	Elevation	Total Depth
13_SCH	467632.5	1485526.59	282	673

Bore	Top	Bottom	Stratigraphy	Comment
13_SCH	0	88	Quaternary	BOL
13_SCH	88	325	Pliocene	BOL
13_SCH	325	371	Lower Pliocene	BOL
13_SCH	371	565	Continental Terminal	BOL
13_SCH	565	673	Cretaceous	BOL
13_SCH	673	...	Basement	BOL

Figure 22. Record of successive stratigraphic layers, coordinates, and depth for borehole 13_SCH after being coded for storage.

3.4. Surface Water

The surface water data (streamflow and lake surface level) (Figure 23) include daily values of the streamflow at different gauge stations in the two main river basins. Estimates of the surface water elevations along the riverbed that borders the site were obtained from values reported from the MDT applied in the project. Existing gauge stations are presented in Tables 9 and 10.

Table 8. Total number of water points and geologic logs after screening the data sets from compiled information.

Number of water points **(Wells, piezometers, boreholes)**	**Number of geologic logs**
3767 (LCBC file)	50 (Schneider, 1989)
409 (2008-2011) + 226 (2013) BGR	22 (USGS-Nigeria, 1965); some in Schneider thesis
404 (RESOPIEZ) **SUIVIPIEZ**	129 (BRGM, 1992; from 60-70s). Compilation of many existing works. Several deep boreholes from oil exploration (>1000m 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 Yaere complet (19xx)	
Total 9356	Total 644

**Programme Regional Solaire (I and II); **CE, Agence Française de Developement (AFD) and Cooperation Alemande (KFW). xx: unknown*

Table 9. Gauging stations and data span (Chari-Logone, data from LCBC, file provided by ReSeau).

Name	Data				Hydrologic basin (km^2)
	DB	Period	Data (m^3/s)	Data (cm)	
N'Djamena	LCBC data	2000-2013	daily, complete		60,0000
	LCBC data	2015	daily, complete		
	LCBC data	1953-2003	monthly, 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, few gaps		60,320
	LCBC data	2011-2013	daily, few gaps		
	LCBC data	1948-2002	monthly, 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, 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 10. Gauging stations and data span (Komadugy Yobe, data from LCBC, file provided by ReSeau)

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

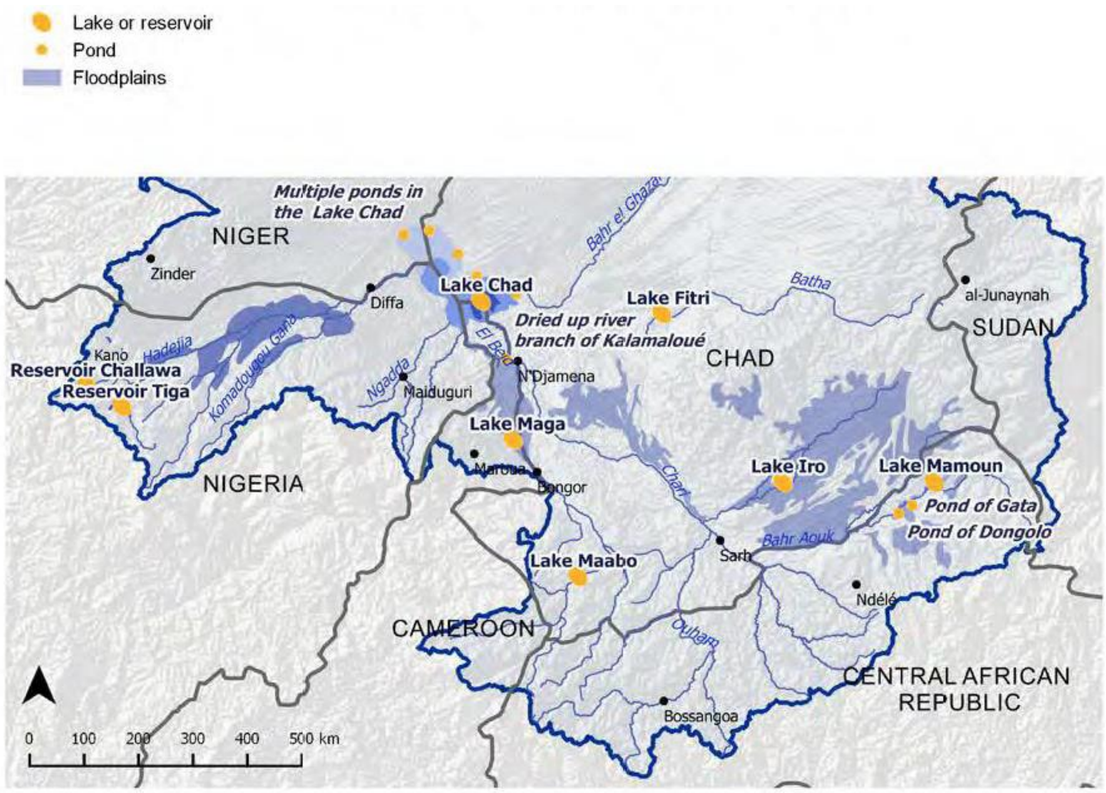


Figure 23. Surface hydrology in the Lake Chad Basin and delimitations and rivers (LCBC-GIZ, 2016)

Water level data were obtasined online from https://hydroweb.theia-land.fr/hydroweb/view/L_tchad?lang=en&basin=LAKE-CHAD which presented in Figure 24 for 1990 to current year.

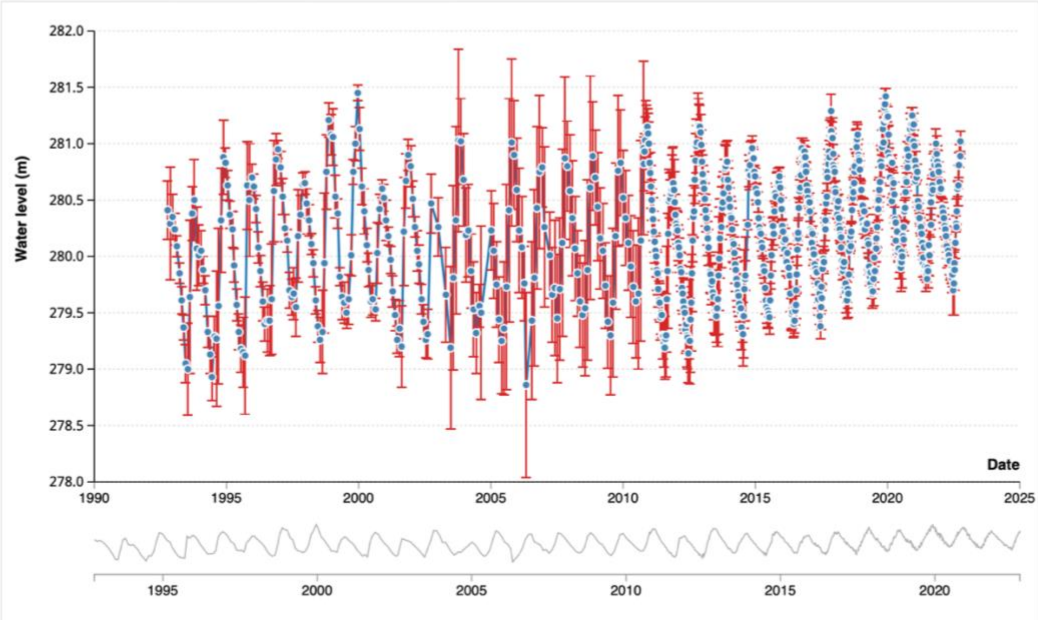


Figure 24. Water level in Lake Chad (1990 to 2022)

3.5. Groundwater data

Water level measurements in wells, piezometers or open wells were taken from public databases (LCBC) and reports (Table 11).

Water level measurements data span coverage from the different sources ranges from 2004 to 2017 (Figure 25) with important gaps. The 2008-2011 appears to be the most complete period based in data availability and spatial distribution. Shallow wells or with uncertain information were discarded and the final selection included a dataset of 239 (out of 9356) water points to infer a groundwater level map for the 2008–2011 period.

To construct the contour map of groundwater surface water levels collected during the 2008-2011 period from wells and piezometers, were converted from measured data in water points (steady-state field measurements of water levels,) to relative levels (m.a.s.l.). Graphic construction of groundwater contours and flow direction was created by trial and error by plotting the data set information in a topographic map at 1:1,200.000 scale.

Table 11. Water points in the study area

Programme/Inventory	Number of water points	Coverage	Owner
5-8 FED	5140	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	2918	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). Komadugu-Yobe (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
AEIA (RAF/7/011)	73	2010	LCBC
PHPTO	263	2004-2008	Project Almy-Bahaim LCBC; Direction de l'Hydraulique (Chad). (financed 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 AFD Agence Française de Développement)
PRODALKA_GTZ	230	2005-2007	Mayo-Kebi (Chad). LCBC

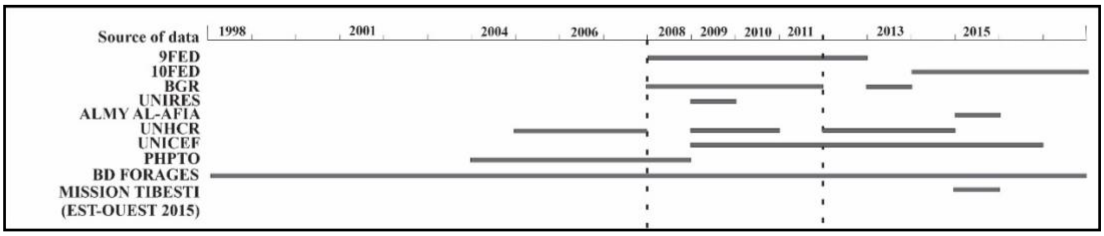


Figure 25. Water level measurements. Timespan of data coverage and source of information.

Values of the hydraulic parameters (K_h, T, S) of aquifer formations were based on the collected and reviewed information field observations deriving from 81 hydraulic tests. Most observations corresponded to the *Q* aquifer (54 tests) and were located mainly in the Komadougou-Yobe river basin (Chad), and the Chari-Baguirmi and Hadjer-Lamis regions of Chad (near Lake Chad).

3.5.1. Groundwater recharge

Quantification of the rate of natural groundwater recharge is a basic prerequisite for efficient groundwater resources management (Lerner et al., 1990). Groundwater recharge is a complex function of meteorological conditions, soil, vegetation, physiographic characteristics and properties of the geologic material within the paths of flow (Stephenson et al., 1981).

Groundwater natural recharge in the CAF for the 2005–2014 period was quantified with VisualBALAN 2.0 (Samper et al., 2005) (Figure 26). The meteorological stations with daily data from TAHMO were used for recharge estimation (Figure 17). The irrigation-derived recharge volume was obtained according to the irrigated surface area and water demand for cultivated crops. Processes in the saturated zone (aquifer) were not included by assuming that the infiltrated water through the vadose zone reached a depth beyond the action of roots and evaporation, which becomes direct infiltration to the aquifer. The lack of wells hydrographs (groundwater level time series for this period) did not allow model calibration.

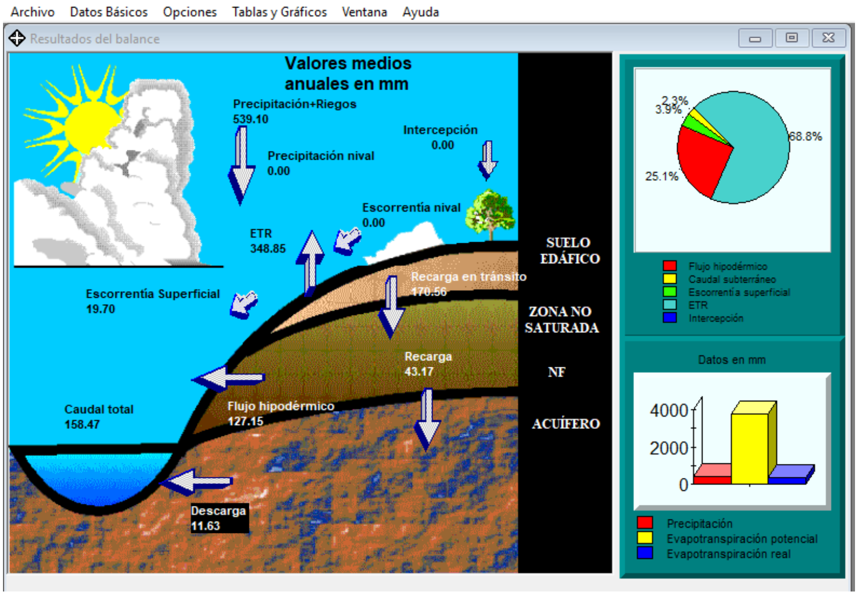


Figure 26. A schematic model of VISUAL-BALAN V2.0 (center part of the study area)

Soil-aquifer parameters were obtained from Leblanc (2002), Gaultier (2004), and Zairi (2008). Daily potential evapotranspiration (*ETp*) was computed by the Thornthwaite method (Thornthwaite & Holzman, 1939), suitable for data scarcity regions because of its very low data demanding character (Yang, Ma, Zheng & Duan, 2017). In areas of intense agricultural activity, volume of irrigation-derived recharge is obtained based in irrigated surface area and water demand by cultivated crops.

To estimate recharge, VISUAL-BALAN V2.0 has been applied which performs sequential daily water balances in the soil, the unsaturated zone and the aquifer. The main aspects of the balance are the input of precipitation and irrigation, the output by water interception, surface runoff, evapotranspiration, interflow and groundwater flow, soil water variation and water level in the aquifer. The program works with hydrological years. It evaluates each one of the balance aspects sequentially, beginning with precipitation and irrigation, which are known, interception (evaluated by Horton or Singh methods), surface runoff (by Horton's law or Curve Number method from US Soil Conservation Service) and actual evapotranspiration, and finishing with recharge (Samper and García Vera, 1992).

Six digital base maps were produced (climate, slope, land cover, cultivated crops, aquifers, soil attributes) and overlaid using GIS tools to create a final base map for recharge calculations by solving the water balance equation in a multicell pattern (Table 12 and Figure 27). Finally, 17 different layers have been defined for assign the zones of the recharge in the region (Figure 28).

Table 12. The layers used for estimation recharge in GIS database

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 irrigation areas from ground water • 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	• Köppen–Geiger climate classification system	Subdividing the area according to rainfall and temperature to three zones: • BWh: arid climate • BSh: semi-arid or steppe climate • Aw: tropical wet and dry climate

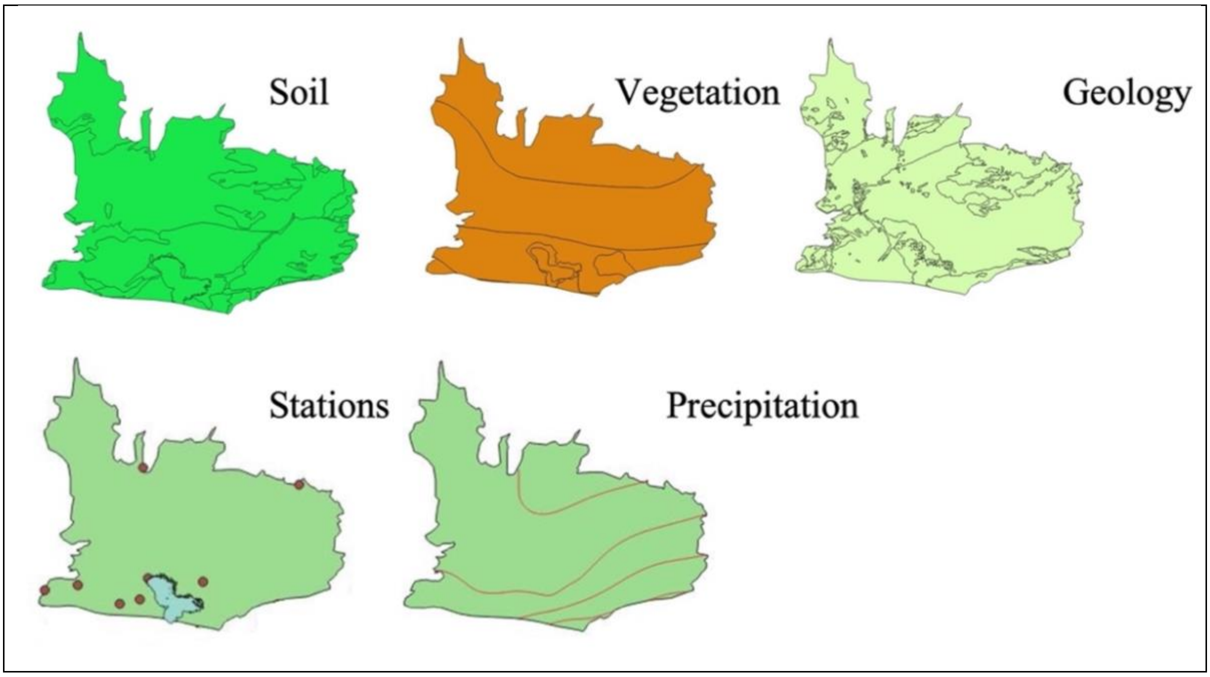


Figure 27. Layers used to categorize the study area

The 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 (Table 13 and Figure 28).

Table 13. The zones inside LCBC according to different layers for measuring the recharge. The area, gauge stations, latitude, related crops, agricultural area, average precipitation for all of these zones have been defined

Climatic zone	**No.**	**Area (Km^2)**	**Gauge stations**	**Lat.**	**Crops**	**Agri. Area (Km^2)**	**Ave. P (mm/yr)**
BWh	1	155,000	Bilma	18°40′48″	Palm tree	2	7
	2	80,854	bol, Nguigmi	13°25′48″	millet	27,277	250
	3	4,621	Nguigmi	14°15′0″	millet	485	156
	4	10,340	Diffa	13°24′36″	pepper, corn	3,000	240
	5	97,283	Mao	14°6′36″	millet	10,840	184
	6	189,000	Faya	18°0′0″	palm tree	60	30
	7	155,389	Goure, Zinder, Mao, Maine	13°58′48″	millet, pepper	21,295	267
	8	160,000	Bilma	18°40′48″	palm tree	370	7
BSh	9	34,541	Bokoro	12°28′48″	rice, wheat, millet, sorghum	2,000	716
	10	50,143	Ndjamena	12°7′48″	rice, wheat, millet, sorghum	5,000	743
	11	15,463	Magaria	12°58′48″	Rain fed		365
	12	106,058	Ati, Magaria, Maiduguri	13°12′26″	rice, wheat, millet, sorghum	10,000	591
	13	27,434	Am timan	11°1′48″	Rain fed		1,200
Aw	14	28,898	Am Timan	11°1′48″	Rain fed		1,200
	15	101,472	Pala, Mondou, Sarh, Bousso	9°21′36″	Rain fed		1,187
	16	11,814	Sarh	9°9′0″	Rain fed		1,187
	17	96,723	Ndele	8°24′0″	Rain fed		1,433

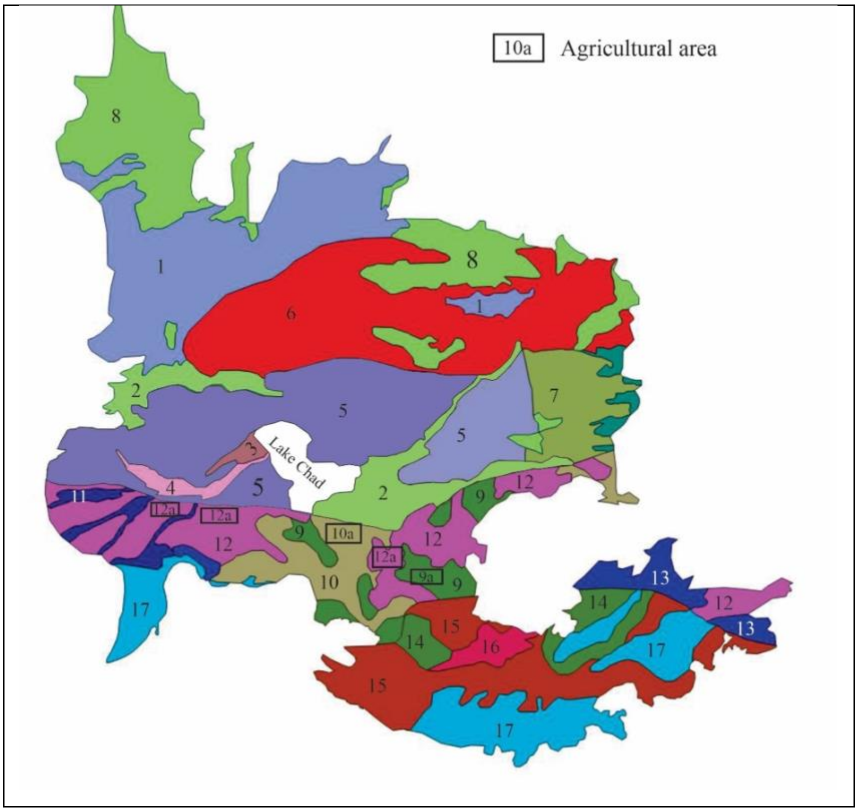


Figure 28. Zonation of recharge areas for the surface aquifer. Numbers in squares indicate areas that have undergone agricultural development in the zone.

3.6. Tools

3.6.1. Digital mapping

Soil surface elevation (2010 data, m.a.s.l.) was obtained with SRTM30 DEM (https://earthexplorer.usgs.gov/) of 30 arc-seconds.

Land use and Land cover, 20 m resolution, created from Copernicus Sentinel-2A images, the European Space Agency-ESA (CCI Land cover-S2 prototype map of Africa 2016; https://www.esa.int/ESA_Multimedia/Images/2017/10/ African_land_cover).

Soil maps were from the European Soil Data Centre (https://esdac.jrc.ec.europa.eu/content/soil-map-soil-atlas-africa#tabs-0-description=0), resolution of about 1 km).

Geological maps with a digital support have been dowloaded from various platforms at different working scales from the BGS platform (http://earthwise.bgs.ac.uk/index.php?title=File:Cameroon_Geology2.png&filetimestamp=20150908085241), IRD (http://sphaera.cartographie.ird.fr/pays.php), the Nigerian Geological Survey Agency (https://www.ngsa.gov.ng/. and the BGR-LCBC project.

3.6.2. Applied tools and methods

The code VisualBALAN v.2.0 (Samper et al., 2005), a suitable spatially distributed computer code for long-term simulations of the daily water balance in soil, the vadose zone, and the aquifer was applied for natural recharge estimation.

The basin's three-dimensional geological architecture was generated with the RockWare code (Rock Works 17). All gathered information was stored in free open source database with graphic output for further data use (QGIS). This code allows for for exploitation and visualization in 2D-3D (including cross-sections, borehole locations, etc.).

HYDRUS, to simulate hydrologic processes taking part in the unsaturated zone (Simunek et al., 2013).

For missing precipitation data, a number of methods exist with minor or greater complexity. To complete the missing rainfall data, Inverse Distance Weighting was applied, based on four rain-gauge stations in the vicinity of the analyzed station (Lam, 1983). In this method, weights for each sample are inversely proportionate to its distance from the point being estimated (Lam, 1983). To execute this way, the area around gauge of interest divide into four quadrants and then by using records at nearest station in each quadrant as the following:

$$P_X = \frac{\sum_{i=1}^{N} \frac{1}{d^2} p_i}{\sum_{i=1}^{N} \frac{1}{d^2}}$$

Where, P_X = estimate of rainfall for the station with gap, p_i = rainfall values of near rain gauges used for estimation, d_i = distance from each location the point being estimated and N = N_o of surrounding stations. To calculate each missing data for a given station, a cluster of four rain-gauging stations in vicinity of station were selected. These stations analyzed according to similarity in elevation and climatic classification, lowest distance, and highest correlation.

Thiessen Polygon was used to estimate the average rainfall over the area and simple descriptive statistics (mean, median, mode, standard deviation) with the EXCEL Analysis Toolpack 2013 (Microsoft®). applied. Out-of-sample testing (for selected time periods) was conducted to assess if the statistical analysis results could be generalized to an independent dataset.

A double-mass curve (Figure 29) was used to check the consistency of a rain gauge record to assess: i) compute cumulative rainfall amounts for suspect gauge and check gauge, ii) plot cumulative rainfall amounts against each other (divergence from a straight line indicates error), iii) multiplying erroneous data after change by a correction factor *k* where:

$$k = \frac{gradient\ of\ line\ before\ change}{gradient\ of\ line\ after\ change}$$

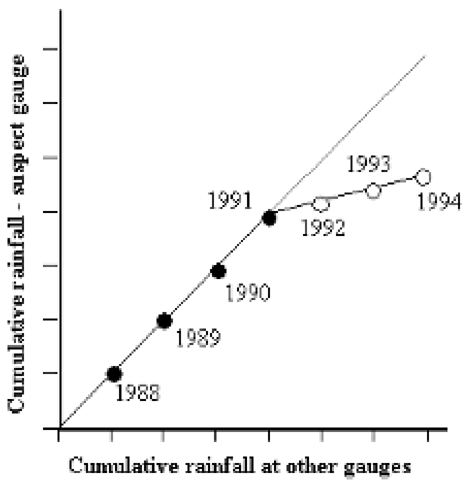


Figure 29. A double-mass curve

3.7. Modelling the unsaturated zone. Numerical model

The code Hydrus-1D (Simunek et al., 2013) was applied for the 2005 to 2014 time-period (3651 days). Simulation for both sites (Bokoro and Amdedoua, Figure 30) include running numerical model for bare soil conditions and with *Acacia Tortilis* land cover, to assess changes in water balance components driven by plants. To estimate hydrologic processes along soil profile, several monitoring points distributed along depth of both geologic logs were set up following the code capabilities.

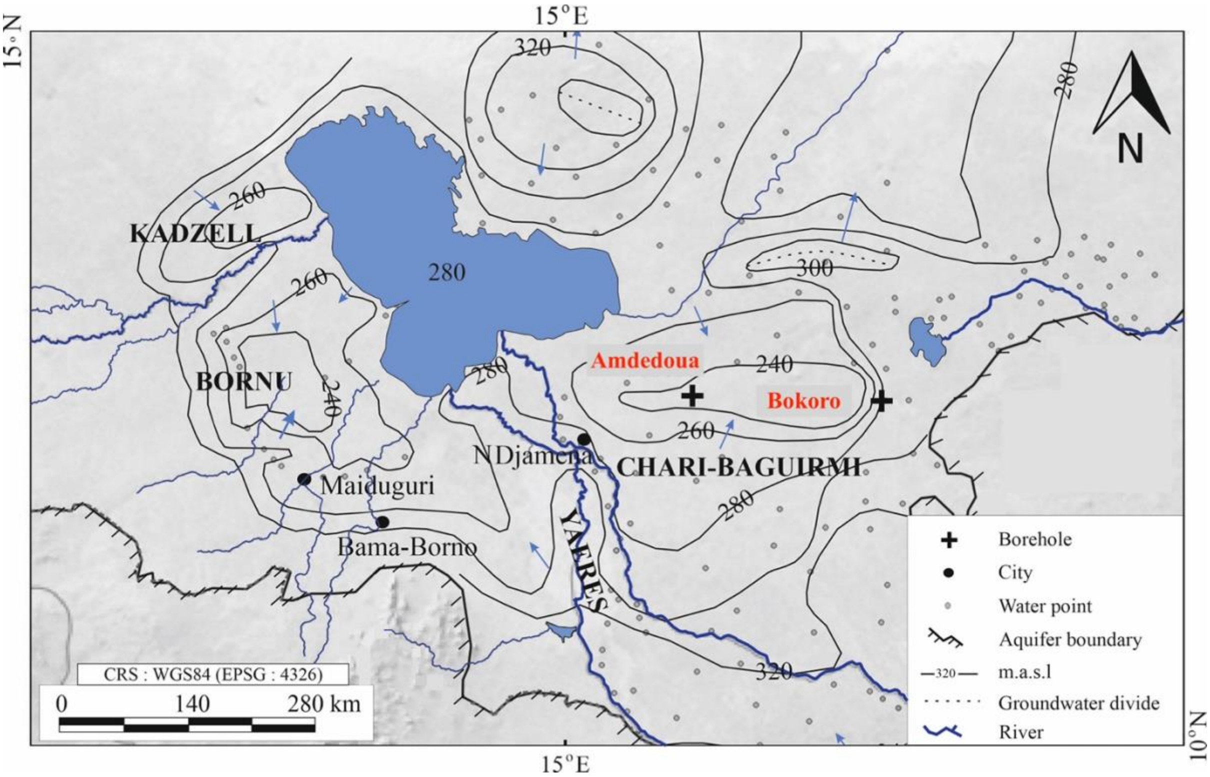


Figure 30. Chad Formation piezometric map from 2008 to 2011 displaying the Chari-Baguirmi depression and other existing depressions (after Vaquero et al., 2021).

The code is a numerical model for simulating the one-dimensional flow of water, heat, and solute in variably saturated media (Simunek et al., 2009b). It solves the Richard's equation (Richards, 1931) for variably saturated water flow and the heat and solute transport advection dispersion equations numerically. The modeling procedures are detailed in Simunek et al., (2008).

In the current code, water flow, vapor flow, heat transport and root water absorption are simulated under saturated and unsaturated conditions in a water, soil, and plant system. It also allows to specify a number of observation nodes along depth for which the values of the pressure head, water content, temperature, and carbon dioxide are saved at every time level.

The input parameters for Hydrus include geometric data, climatic data (precipitation, potential evapotranspiration), soil hydraulic properties, geological profile, and vegetation parameters.

The efficiency of the unsaturated region is deep penetration and drainage. Outputs are evapotranspiration from soil and plant.

3.7.1. Governing equations

Darcy-Richards equation is the governing equation for water movement in soil, which is implemented in transient conditions. Richards equation (Richards, 1931) in one-dimensional mode is shown as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)(\frac{\partial h}{\partial x} + cos\,\alpha)\right] - S$$

Where θ (dimensionless) is volumetric soil water content, h (L) soil matrix pressure head, S *(*dimensioneless*)* water intake by root, K (θ) (LT^{-1}) variable saturated hydraulic conductivity, α angle between flow direction and vertical axis, *x* distance and *t* time. Saturated and unsaturated hydraulic conductivity are related by:

$K(h,z) = K_S\,(z) \cdot K_r\,(h,z)$

Where K_r is the relative hydraulic conductivity (dimensionless) and K_S is the saturated hydraulic conductivity (LT^{-1}). HYDRUS solves the equation using linear finite elements pattern.

To obtain a predictive equation for the unsaturated hydraulic conductivity, in terms of soil water retention parameters, soil-hydraulic functions of van Genuchten (1980) with the statistical pore-size distribution model of Mualem (1976) were selected:

$$\theta(h) = \begin{Bmatrix} \theta_r + \dfrac{\theta_s - \theta_r}{[l + |\alpha h|^n]^m} & h < \\ \theta_s & h \geq \end{Bmatrix}$$

$$K(h) = K_s S_e^1 \left[1 - (1 - S_e^{1/m})^m\right]^2$$

where

$$m = 1 - \frac{1}{n}$$

and

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

Where α (L^{-1}) is inverse of the air-entry value (or bubbling pressure), n (dimensionless) is pore-size distribution index, and l (dimensionless) is pore-connectivity parameter, S_e (dimensionless) is effective saturation, and θ_r and θ_s are residual and saturated water contents respectively (dimensionless). The parameters α n and l are empirical coefficients affecting the shape of the hydraulic functions.

Chapter 4

Results

4.1. Introduction

Following are the key findings presented in this chapter: climatic data analysis, recharge estimation, water budget estimates for both the Quaternary and Lower-Pliocene and Continental Terminal aquifers, establishing the new conceptual model and modelling results to asses water balance processes the Chari-Baguirmi depression. Constructing a conceptual model for the aquifers is done based in hydro-stratigraphic units, water budget and defining the flow system following the obtained information.

4.2. Climatic data from Ground-measured stations[1]

The rain gauges without gaps in time series are scarce in LCB and records from gauges in the region are typically old and discontinued or new with only several years of quality data. The period of 2005 to 2014 (Figure 31) was the best period with the highest percentage of available data and lowest gaps (less than 20%) in time series. Daily rainfall data from 2005 to 2014 were obtained for TAHMO twenty-five rainfall stations within the area (Figure 32).

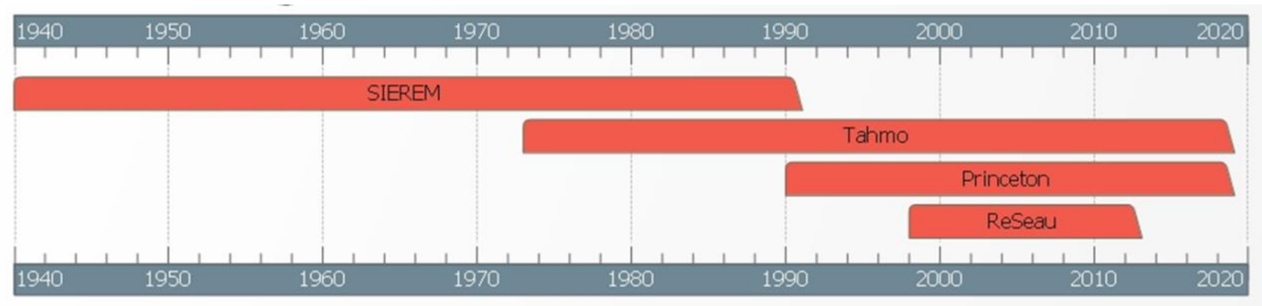


Figure 31. Time span coverage at daily step of meteorological data. Princeton: CHADFDM, Chad Flood and Drought Monitor satellite platform.

[1] Salehi Siavashani et al. (2021). Assessment of CHADFDM satellite-based input dataset for the groundwater recharge estimation in arid and data scarce regions. Hydrological Processes. 2021;35:e14250.

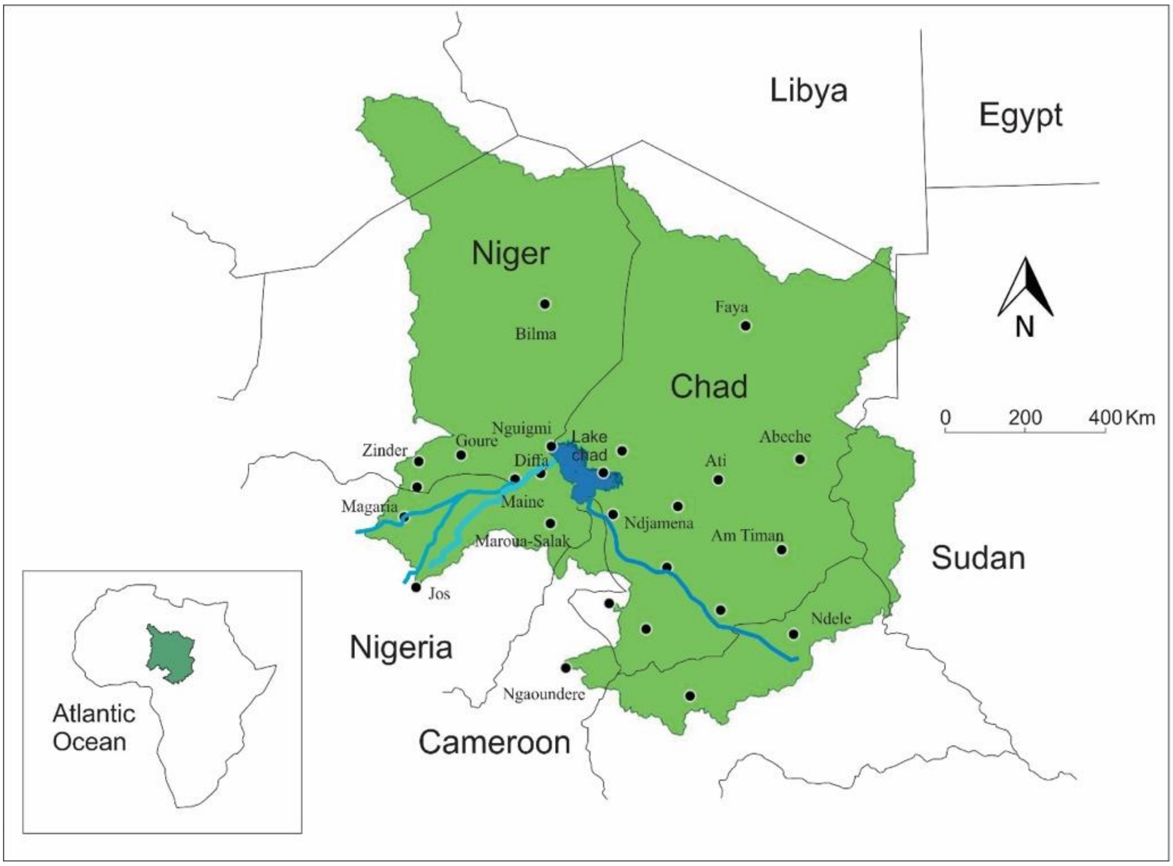


Figure 32. Lake Chad Basin showing available TAHMO meteorological stations

Only fourteen of the stations (Abeche, Am-Timan, Ati, Faya, Ndjamena, Sarh, Ngaoundere, Bilma, Diffa, Goure, Magaria, Maine-Soroa, Nguigmi, Zinder, Kano), were not missing any daily rainfall totals (100%) and had complete daily records of air temperature and precipitation over the 2005–2014 time period and they were used for recharge estimation. For the other stations, some months and some years have gaps in their time series (Table 14).

In order to obtain more and spatially distributed meteorological data, a comparison between TAHMO and CHADFDM platform data sets was assessed for the 2005 to 2014 period (Salehi Siavashani et al., 2021). Only stations have been selected that are available in both of rain gauges and satellite platforms. The 10-yr length of the dataset enables it to capture a robust amount of the variability of daily rainfall in the region.

Table 14. Name of stations inside LCBC for TAHMO

Name of stations	**Country**	**Lat.**	**Long.**	**Altitude (m)**	**Available time range**	**% Of data availability**
Abeche	Chad	13.9	20.9	545	1973-1979, 1987-2018	100
Am-Timan	Chad	11	20.3	433	1973-1979, 1988-2018	100
Ati	Chad	13.2	18.3	334	1973-1979, 2003-2018	80
Bokoro	Chad	12.4	17.1	300	1973-1979, 1990-1999, 2007- 2018	83.07
Bol-Berim	Chad	13.4	14.7	291	1973-1979, 2000-2018	81.53
Bousso	Chad	10.5	16.7	336	1973-1979, 2007-2016	34.61
Fada	Chad	17.2	21.6	540	2008 - 2017	38.46
Faya	Chad	18	19.2	235	1973-1978, 1987-2018	100
Mao	Chad	14.1	15.3	355	2007-2017	34.61
Mongo	Chad	12.2	18.7	430	1973 1979, 2003 - 2017	50
Moundou	Chad	8.56	16.1	428	1973-1979, 1987 - 2018	80
Ndjamena	Chad	12.1	15	295	1973-1979, 1985- 2018	100
Pala	Chad	9.36	14.9	467	1973-1979, 1993 - 2018	88.46
Sarh	Chad	9.15	18.4	365	1973-1979, 1987- 2018	100
Maroua-Salak	Cameroon	10.4	14.3	423	1973-2001, 2012-2017	81.53
Ngaoundere	Cameroon	7.35	13.6	1114	1973-2018	100
Yagoua	Cameroon	10.4	15.2	322	1981	0
Birao	Central Africa	10.3	22.8	463	1973-1999	38.46
Bossangoa	Central Africa	6.48	17.4	464	1973-2002, 2005-2013	84.61
Ndele	Central Africa	8.4	20.6	510	1973-1995, 2002, 2005, 2009-2012	87.69
Bilma	Niger	18.7	12.9	355	1957-1967, 1973-2018	100
Diffa	Niger	13.4	12.8	303	1985-2018	100
Goure	Niger	14	10.3	464	1983-2018	100
Magaria	Niger	13	8.93	403	1980-2018	100
Maine-Soroa	Niger	13.2	12	338	1957-1967, 1973-2018	100
Nguigmi	Niger	14.3	13.1	286	1957-1967, 1973-2018	100
Zinder	Niger	13.8	8.98	452	1957-1967, 1973-2018	100
Jos	Nigeria	9.86	8.9	1295	1973-1984, 1988-2006, 2008, 2010-2017	83.07
Kano	Nigeria	12.1	8.53	476	1943-2018	100
Maiduguri	Nigeria	11.9	13.1	354	1943-1945, 1973-1994, 2004-2017	80
Nguru	Nigeria	12.9	10.5	344	1973-1981, 1988-1989	0
Potiskum	Nigeria	11.7	11	414	1973-1982, 2006, 2010	7.69

Figure 33 shows the total precipitation through TAHMO and CHADFDM for the selected stations. The time-series plots of the region exhibit high-frequency fluctuations. Comparison of the data with the overall mean indicates that wet and dry conditions during the periods of 2005-2014, have different trends for these two scenarios.

It seems that there are discrepancies between CHADFDM and TAHMO. For some stations CHADFDM overestimation the amounts. This phenomenon has been reported by many of authors (Mccollum et al., 1999; Caparoci Nogueira et al., 2018; Young et al., 2014). The reasonable reasons for this should be cloud microphysical, rain processes, and the moisture distribution of the environment (Mccollum et al., 1999). In the addition, gaps in the rain gauges data can limit the comparison.

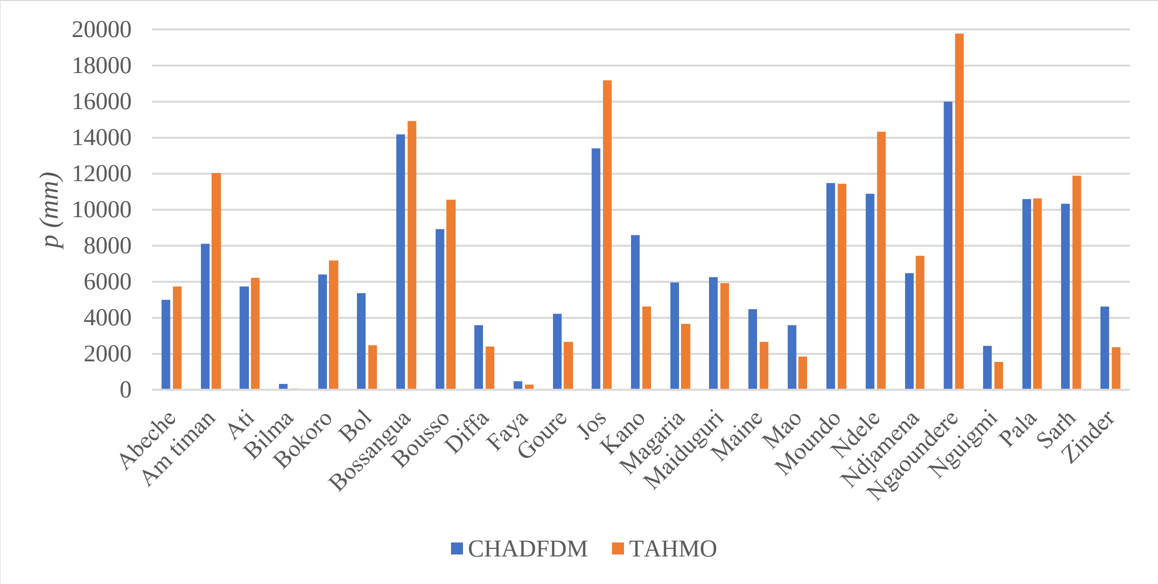


Figure 33. Ten years (2005-2014) precipitation for all the Stations from TAHMO and CHADFDM platforms.

4.3. Surface hydrology

Time distribution of streamflow measurements (daily gage heights, cm) and the corresponding rating curves at specific gauge stations (hydrometric) obtained from the information provided by the LCBC (files from CDIG-ResEau) allowed for annual streamflow estimation. 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.

Streamflow in the Komadougou-Yobé (Figure 34) ranges from 498 Mm^3 (2009-2010; 2011-2012) to a maximum of 894 Mm^3 (2012-2013). The runoff events begin at the end of June and may conclude as early as March. The hydrograph peaks in November, and the decreasing slope of recession (segment of the hydrograph) begins at the end of December. Hydrographs from 2008 to 2012 show runoff duration periods (streamflow from precipitation) ranging from 184 to 222 days.

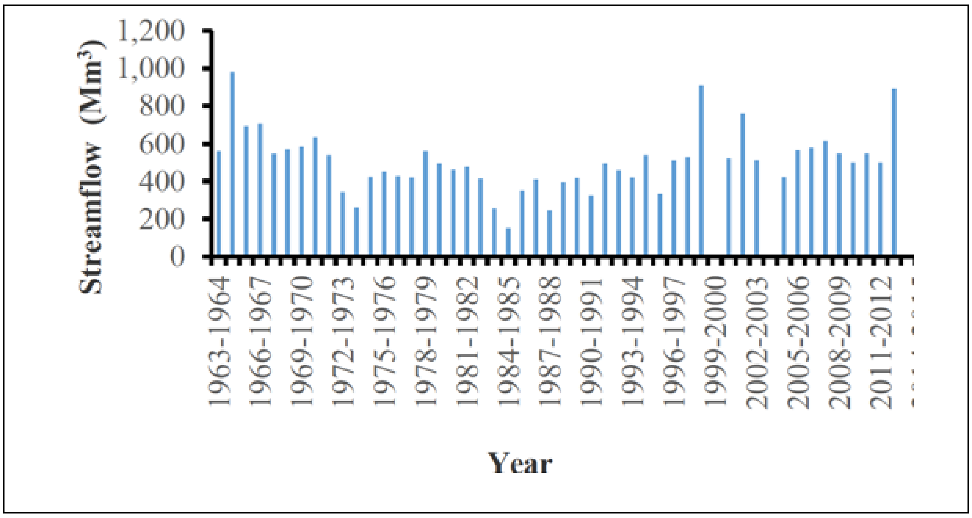


Figure 34. The Komadougou-Yobé annual streamflow (Mm3) at the Bagara-Diffa gauge station (LCBC data)

Streamflow in the Chari and Logone (Figure 35) ranges from 15,000 Mm^3 (2001-2002; 2010-2012) to a maximum of 28,000 Mm^3 (2000-2001). With an average annual flow of 27.14 km^3 (2001 to 2011), the Chari River flows into the southern pool of Lake Chad near N'Djamena, where it drains all of its water to Lake Chad (Lemoalle et al., 2012). The Chari River contributes more than 90% of the lake's total inflow, with the remainder coming from the Komadugu, Ngadda, Yobe, Yedseram, El-Beid, and Gubio Rivers (Gao et al., 2011; Lemoalle and Magrin, 2014; Komble et al., 2016). The annual discharge of the Chari and Logone rivers following their confluence at N'Djamena depicts in Figure 35. High streamflow volumes occur from September to November, resulting in floods.

The existing reservoirs at LCBC and storage capacity are presented in Table 15.

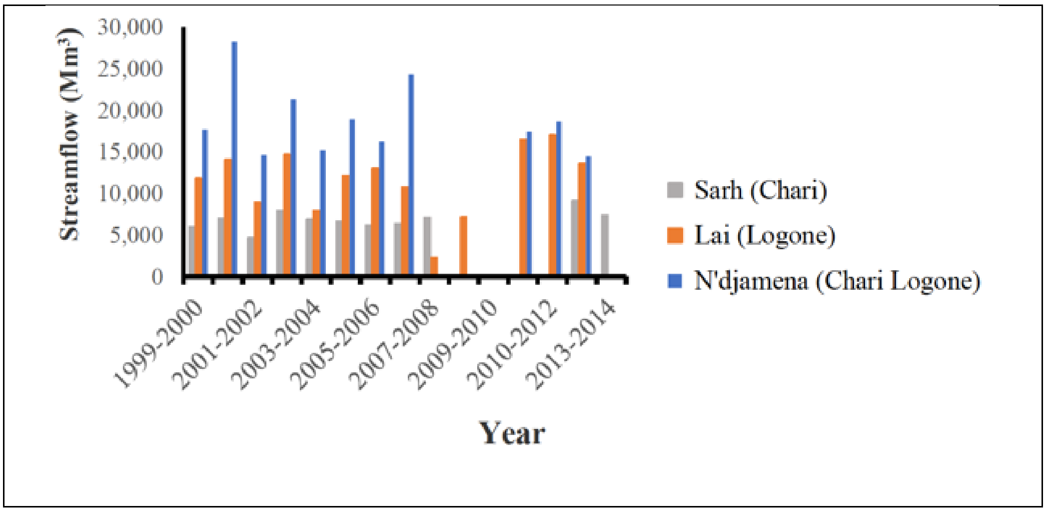


Figure 35. The Chari-Logone annual streamflow (Mm^3) at gauge stations N'Djamena, Lai and Sarh (LCBC data)

Table 15. 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	1968
Tomas	Nigeria	15	60.3
Tudun Wada	Nigeria	3.5	20.8
Warwade	Nigeria	5.3	12.3
Watari	Nigeria	19.6	104.5

4.4. Groundwater conceptual model[2]

4.4.1. The Chad Aquifer Formation system-CAF

4.4.1.1.Aquifers

The entire region is composed by Quaternary, Pliocene and Continental Terminal deposits and three aquifer systems extend over the area: the Quaternary aquifer, the Lower Pliocene and the Continental Terminal aquifer. However, at local and intermediate scales, units may contain a mix of sands and clays with varying hydraulic conductivities. For hydrogeological purpose, and working scale constraints deep aquifer will be referred as the system Lower-Pliocene/Continental Terminal.

The Quaternary aquifer

With very diverse facies, which range from sands without fine grain content to impermeable clays, a different hydraulic connection is presented between them. For some areas, it is difficult to establish where the aquifer system consists of Quaternary or Tertiary (CT) deposits.

According to the new information assessment (Vaquero et al., 2021) and based in the Geological boundaries and geologic logs, the Quaternary phreatic aquifer, the upper aquifer, outcrops over an estimated surface of 1,014,000 km^2 (Figure 36) and consists of alternating sand and clay layers of a continental origin with varying thicknesses from 30 to above 100 m to the North of the basin (190 m at Kosaki, Chad). Two types of sands are described (Schneider, 1989): a fluvial origin (Lower Pleistocene), associated with riverbeds; an Aeolian origin (Upper Pleistocene) that makes up the phreatic aquifer in the Kanem (Chad) and Manga (Nigeria). The alluvial deposits that accompany the surface water streams in the south are also associated with the Quaternary.

[2] Vaquero et al., 2021. The Lake Chad transboundary aquifer. Estimation of groundwater fluxes through international borders from regional numerical modeling, Journal of Hydrology: Regional Studies. https://doi.org/10.1016/j.ejrh.2021.100935

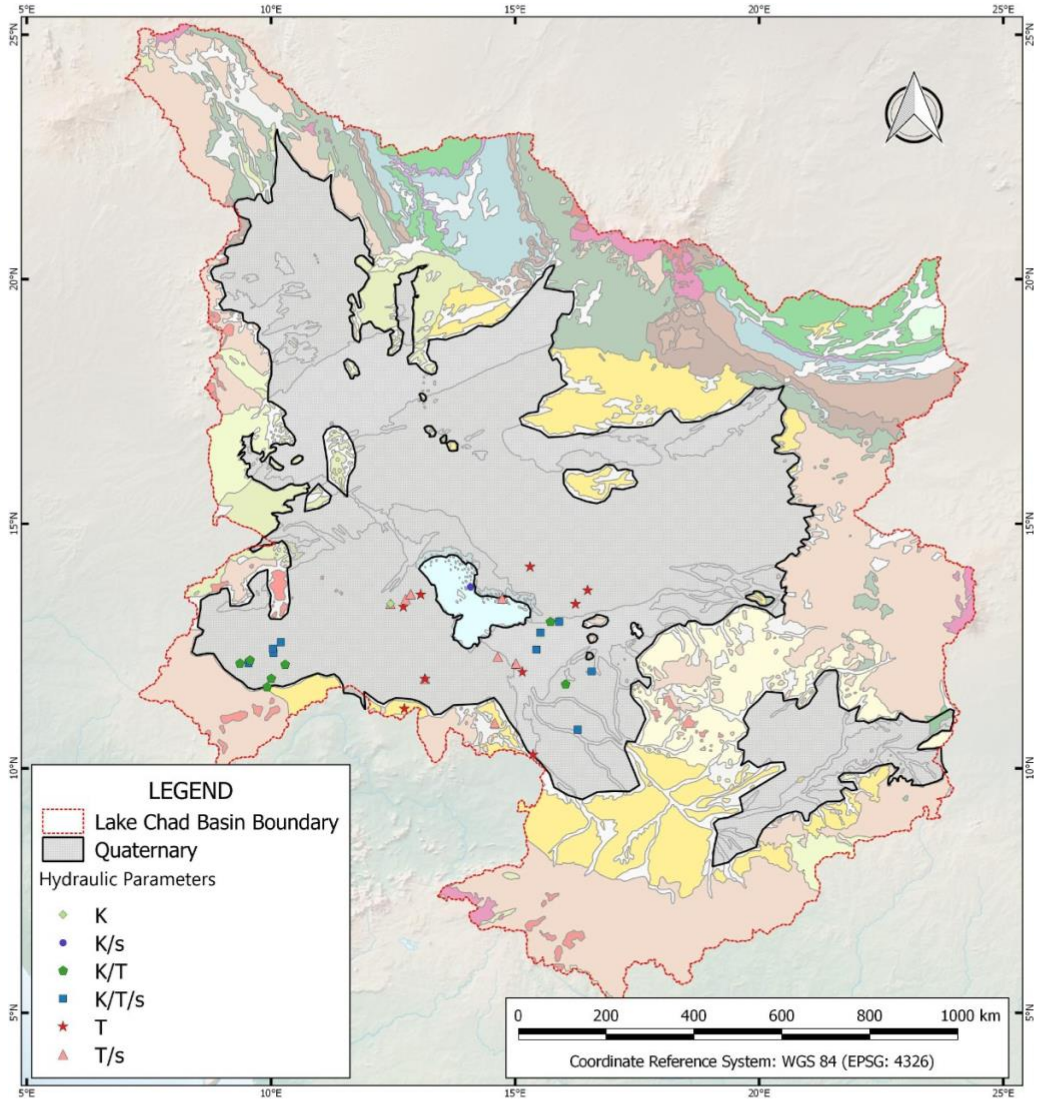


Figure 36. Boundaries and outcropping extension of the Quaternary hydroestratigraphic unit and hydraulic parameters data spatial location.

In hydraulic terms, it behaves as a multilayer aquifer with considerable variability, both vertically and horizontally. A hydraulic connection with the Continental Terminal exists in the Bongor area (Chari-Logone, southern part of basin), where the CT outcrops and also makes up the upper aquifer (Figure 37). In the Kanem region (Chad), sands are directly deposited on CT materials, and behave as a single aquifer of a thickness of more than 275 m (Eberschweiler, 1993). The aquifer thickness is estimated to be at least 60 m.

Results from the 54 hydraulic testing developed in the aquifer and spatial distribution (figure 36), the range of 10^{-6} to 1×10^{-2} m/s for k; 8.7×10^{-7} to 1.6×10^{-1} m^2/s for T and 16 to 32% for porosity. According to the data provided in the BRGM/LCBC simulation model (BGR-LCBC, 2010), the transmissivity values for the quaternary aquifer fall within the range of 10^{-2}-10^{-4} m^2/s. The storage coefficient range lies between 10^{-3}-10^{-5}.

Aquifer recharge (natural infiltration) is primarily controlled by precipitation, even in the arid northern part of the aquifer, and river-groundwater interactions from seasonal or perennial surface water, where aquifer outcrops. Aquifer output is through pumping wells for agriculture or water supply and discharge to surface water (rivers and lakes).

The Lower Pliocene

The Lower Pliocene aquifer (semi-confined aquifer) consists of layers of lacustrine clay with some alternating layers of alluvial sand (red sand, Lower Pliocene) at the base of the formation, detected only through deep boreholes (more than 100 m). The Lower Pliocene acts as a confined aquifer over the study area, overlaid by a thick silty-clay impervious material from Upper-Medium Pliocene age (Figure 37).

The aquifer is exploited by deep boreholes (more than 200 m) located north of the city of N'Djamena. From data review, it appears to be a totally confined aquifer, and recharge/discharge characteristics and the conceptual aquifer behavior model are still unknown (Figure 37). The artesian Pliocene Aquifer is deeper as is found between a 250m depth and a 400m one with a more mineralized water. This water is mainly used in Nigeria and the Cameroon extreme North regions. The artesian pressure is currently lowering possibly due to over pumping and as this aquifer is only recharged in limited areas and there is no hydraulic connection with the lake (Global Water Partnership-GWP (2013).

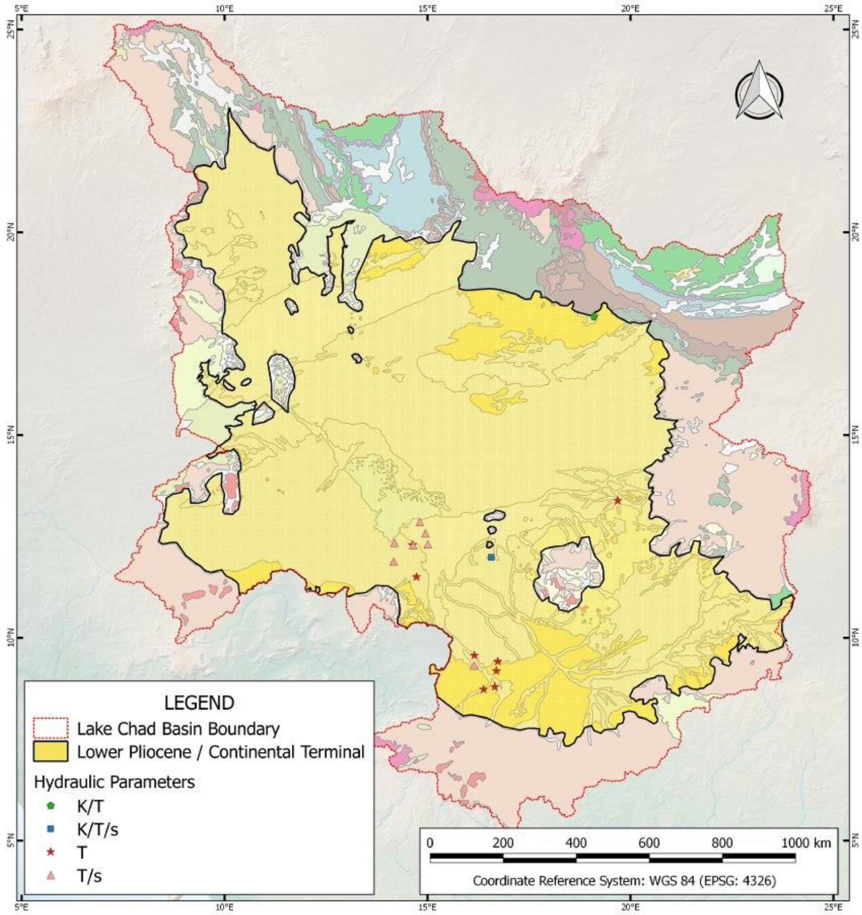


Figure 37. Boundary and extension of the lower Pliocene and Continental Terminal and hydraulic parameters data distribution.

The continental Terminal

The aquifer (confined/unconfined and deep aquifer) may extend for around 1,363,000 km^2 and is composed of sandy-clay deposits, with the presence of a hardpan, is around 100 m thick, which may reach up to 600 m in existing tectonic grabens. It appears to overlay the Lower Pliocene deposits and is encountered at more than 450 m from the soil surface in the surroundings of Lake Chad. Most of the aquifer is confined (although there are no data in the Northern part to confirm) It outcrops in the southern part of the area (Chari-Logone), where it is currently exploited and in the northern part of the area (Figure 37).

In the northern part, the impervious layers of the Upper-medium Pliocene confine the aquifer, according to the data about existing deep boreholes. In the Bongor area (Southern Chad), it 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.

The hydraulic relationships with the Lower Pliocene and the Quaternary aquifer are barely known in most of the area.

Spatial distribution of pumping tests developed in this aquifer show that average hydraulic properties derived from test pumping data are: K, porosity, T and m. In many cases, there is no indication about the test procedure and methodology applied. For the Lower Pliocene-Continental Terminal aquifer, the transmissivity values lie between 10^{-2}-10^{-5} m^2/s and the storage coefficient is 10^{-2}-10^{-5} (BRGM/LCBC, 2010).

In Figure 38, a schematic 3D conceptual model diagram with the dominant input-output processes occurring in the basin is presented.

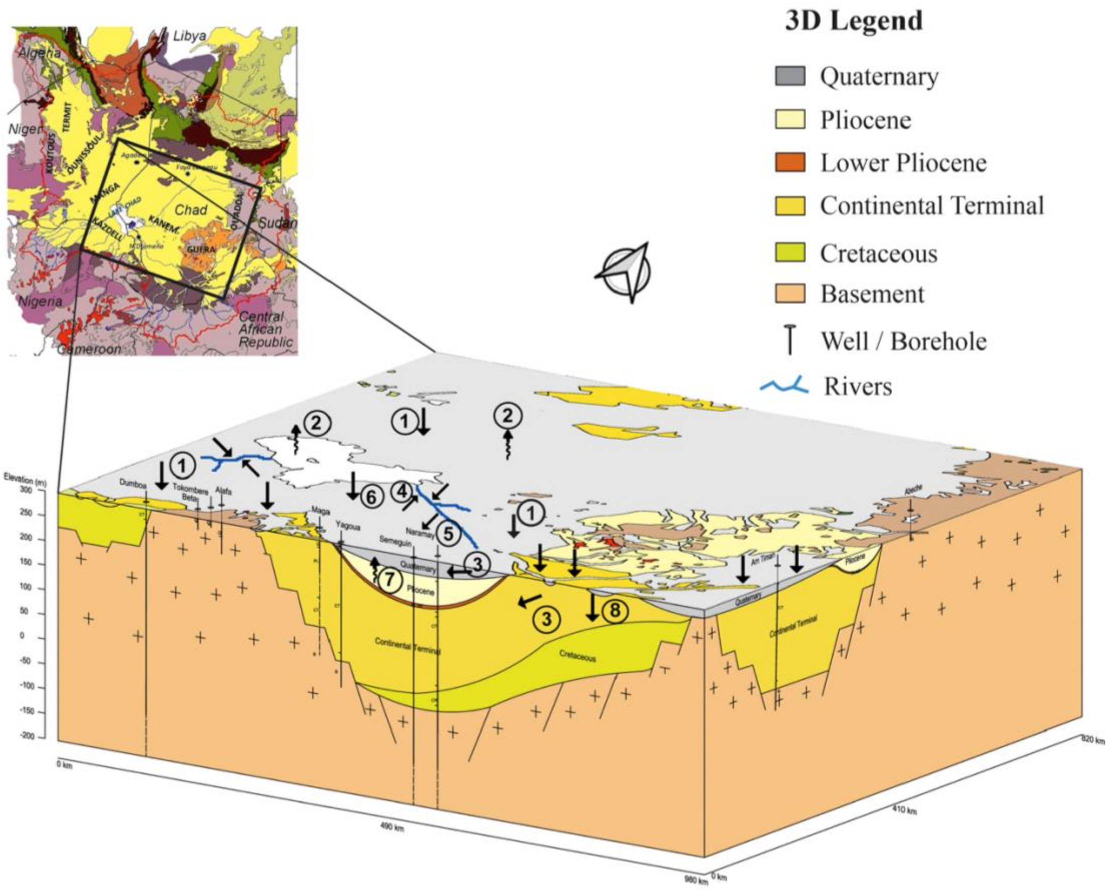


Figure 38. A schematic 3D conceptual model diagram with the input-output processes in the basin. (1) Natural recharge, (2) evapotranspiration, (3) groundwater inflow, (4) recharge from river, (5) discharge from river, (6) recharge from Lake, (7) up flow from deep aquifer, (8) vertical recharge from shallower aquifer to deep aquifer

The main water source, rainfall, is recharged primarily through infiltration directly to outcropping aquifers (unconfined, upper), and occurs primarily on the southern margins (including a narrow zone for the CT), where high precipitation occurs, and in the dune systems (Kanem and Harr areas, Q) to the north. Groundwater inflow into the upper aquifer occurs as a result of river-groundwater interactions in the eastern and southern parts (Chari-Logone and Komadougou-Yob'e river systems). South of Manga, vertical leakage (or cross-formational flow upwardly) from the aquitard occurs through the overlying Q. Inflow from weathered crystalline bedrock on the southern and western boundaries is also possible. Input from the Nubian Sandstone aquifer and Tibesti may exist to the saline Yoa lake (NE of Faya Largeau) and Bodelé depression in the northern part but difficult to quantify (Eggermont et al., 2008; Grenier et al., 2009; and Kropelin et al., 2008).

The aquifer system discharge takes place via groundwater abstraction through agricultural and drinking pumping wells, primarily from the Q aquifer, and mainly via surface water systems' (gain flows) from Q and CT (in the southern basin section). At the Bodelé topographic depression, the basin's lowest topographic point, groundwater discharge may occur to the northern Lowlands region (approx. 165 m.a.s.l.).

4.4.1.2. Groundwater flow system

After data examination the 2008-2011 appears to be the most complete period (data availability and spatial distribution) due to frequent gaps. For piezometric map, data selection was based on available database information from: *i*) different sources with unknown accuracy or data collection method *ii)* some water level measurements could not be definitively attributed to a specific aquifer unit, *iii*) no new data exist for the Tibesti, Borkou and Ennedi areas (northern basin).

The mapped groundwater level contours were derived from a limited dataset of 239 points belonging to both aquifers and several different years (2008-2011) were assessed simultaneously. Estimates of the surface water elevations along the riverbed that borders the site were estimated from values reported from the MDT.

The map displays the water table aquifer (Quaternary and Continental Terminal) and the semi-confined aquifer (Lower Pliocene and Continental Terminal) and is presented in Figure 39; Hydrogeological cross-sections are also shown.

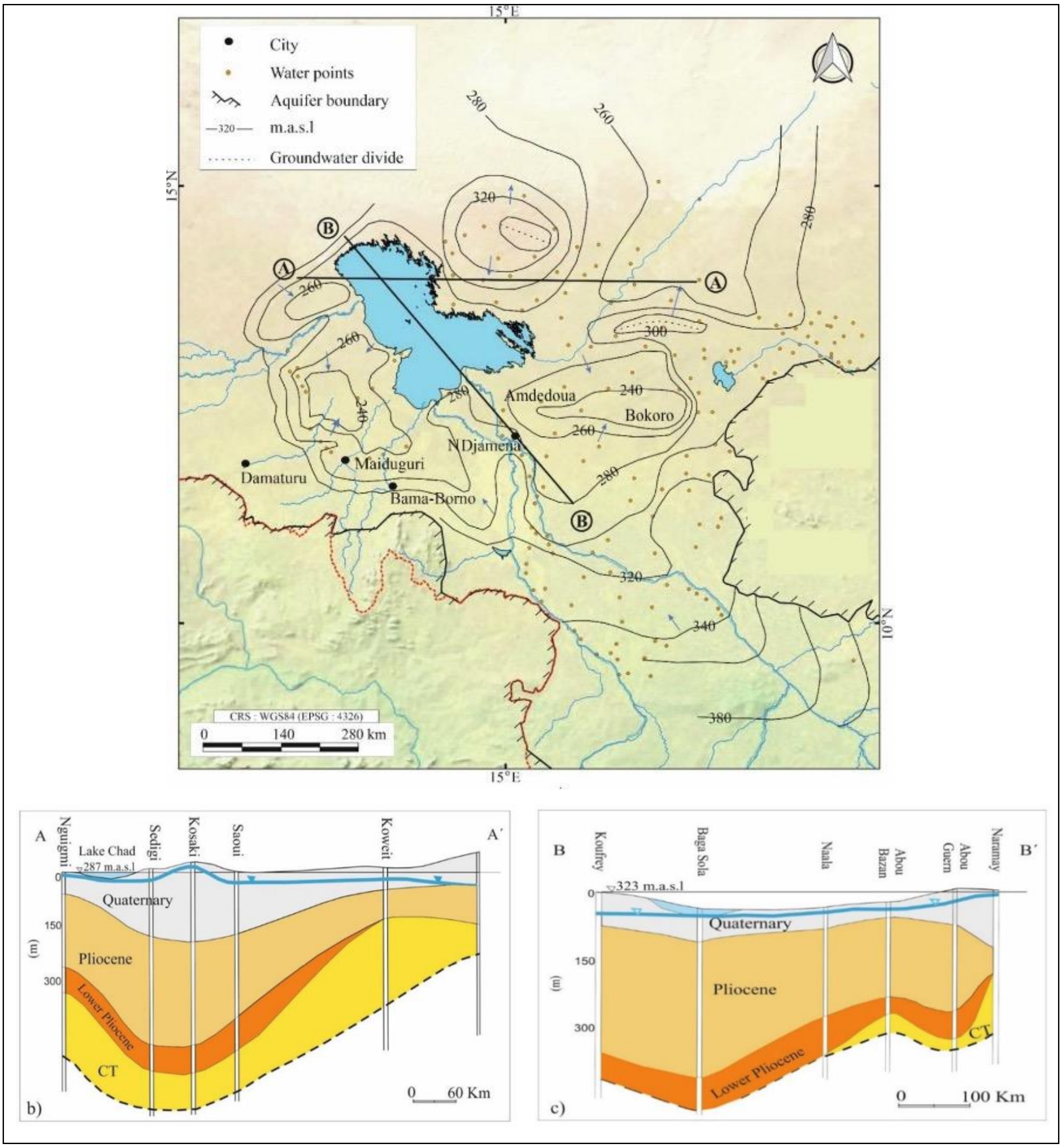


Figure 39. A) Piezometric level for the CT+Lower Pliocene (dashed line) and the Quaternary aquifer for the 2008-2011 period (20m contour lines). B) and C) Hydrogeological cross-sections are indicated.

Groundwater regional gradient is broadly to the northern part of the basin with low hydraulic gradients (Lowland area, Bodelé); from the Kanem and Harr groundwater divide, the gradient is to the north (Lowlands). Time series of groundwater level for the project study period have been only found for the 'FIRS' piezometer located in Nigeria, plotted in Figure 40 (provided by Maidiguri University, Nigeria). For 2008-2011 groundwater level decrease in the area is around 2m. At basin-scale, recharge in the upper aquifer occurs mainly along the southern margins of the study area were high precipitation occurs. This is observed in the enclosed piezometric map. At the working scale, local pumping from residential supply wells does not appear to have an appreciable impact on local groundwater flows.

Piezometric domes present (i.e. Kanem, Harr) are associated with dune-fields recharge areas. Piezometric depressions of Bornu (Nigeria), Yaere and Chari-Baguirmi (Chad), Kadzell (Niger) and inter-fluvial zone of the Komadugu also exist.

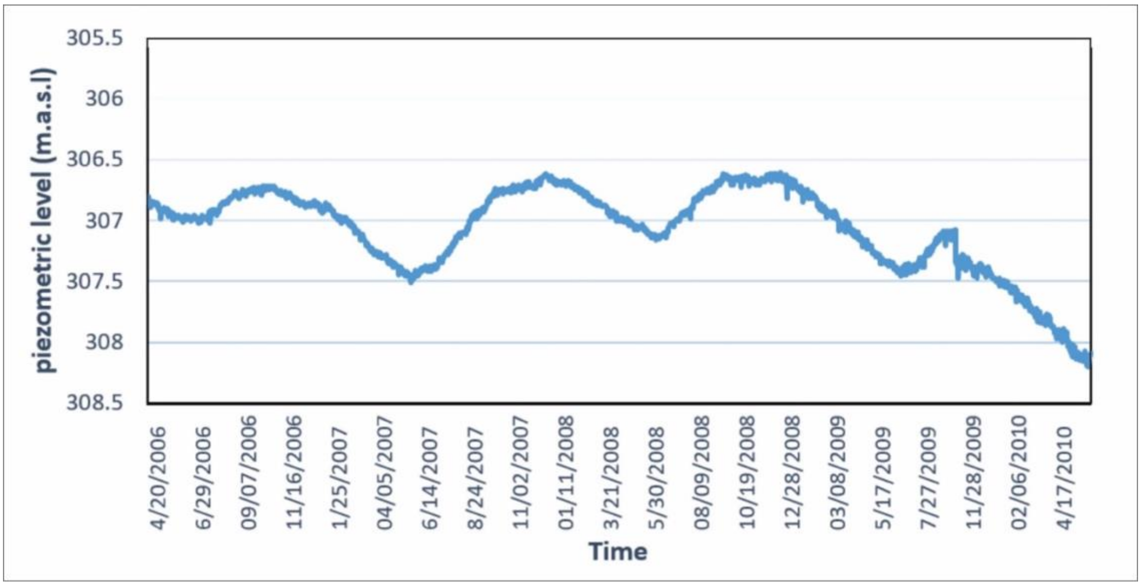


Figure 40. Piezometric level recorded at FIRS observation borehole (Nigerian Hydrological Service)

Hydraulic connectivity between the two aquifers (Q-LPli/CT) clearly exist in the southern part of aquifer area (Chari-Logone) where the Continental Terminal outcrops. Groundwater may also flow upwards from lower aquifers or the aquitard into upper aquifer. Determining the connectivity between aquifers is important to accurately assess exchanges among hydroestratigraphic units. However, there is currently little to no information available to assist this assessment.

Flow between surface and groundwater (Lake and rivers) occurs from areas of high hydraulic head to areas of low hydraulic head. Hydraulic head is greater along and adjacent to river channels (Komadugu-Yobe and Chari-Logone, mainly Chari) in the eastern and southern parts of the basin, where the topographic gradient is relatively flat, suggesting that groundwater recharge/discharge via surface water inflow is a significant mechanism in these areas. According to other authors (Naah, 1989), there is no hydraulic connection in the flooded areas of Yaere and Quaternary aquifer.

It is important to mention that piezometric map is an indication of a complex regional flow pattern in a dynamic system during the considered period (2008-2011), but variable with time. In the map, contours of both aquifers have been plotted. However, as there are insufficient data available to produce a map for the deeper aquifer (confined in the Guera area) only the southern part groundwater surface is displayed. Obtained results are consistent with previous results (Scheneider, 1989; Leblanc, 2002 and BGR, 2010).

4.4.1.3. The Chari-Baguirmi groundwater depression. Modeling with HYDRUS[3]

A previously mentioned, to explain the existence of these anomalies a number of theories have been set, being the exfiltration theory the most accepted up to date. For the 2005-2014 period, two sites with existing lithological logs (Figure 41) were considered for the vadose zone hydrologic simulation with HYDRUS: one located in the central part of the depression (Amdedoua) and another one in the E boundary of the aquifer and depression (Bokoro) (Figure 30).

[3] Salehi Siavahani et al., Modeling vadose zone hydrological processes in naturally-occurring piezometric depressions. The Chari-Baguirmi region, southeastern of the Lake Chad Basin, Republic of Chad, Environmental Earth Science, Under review.

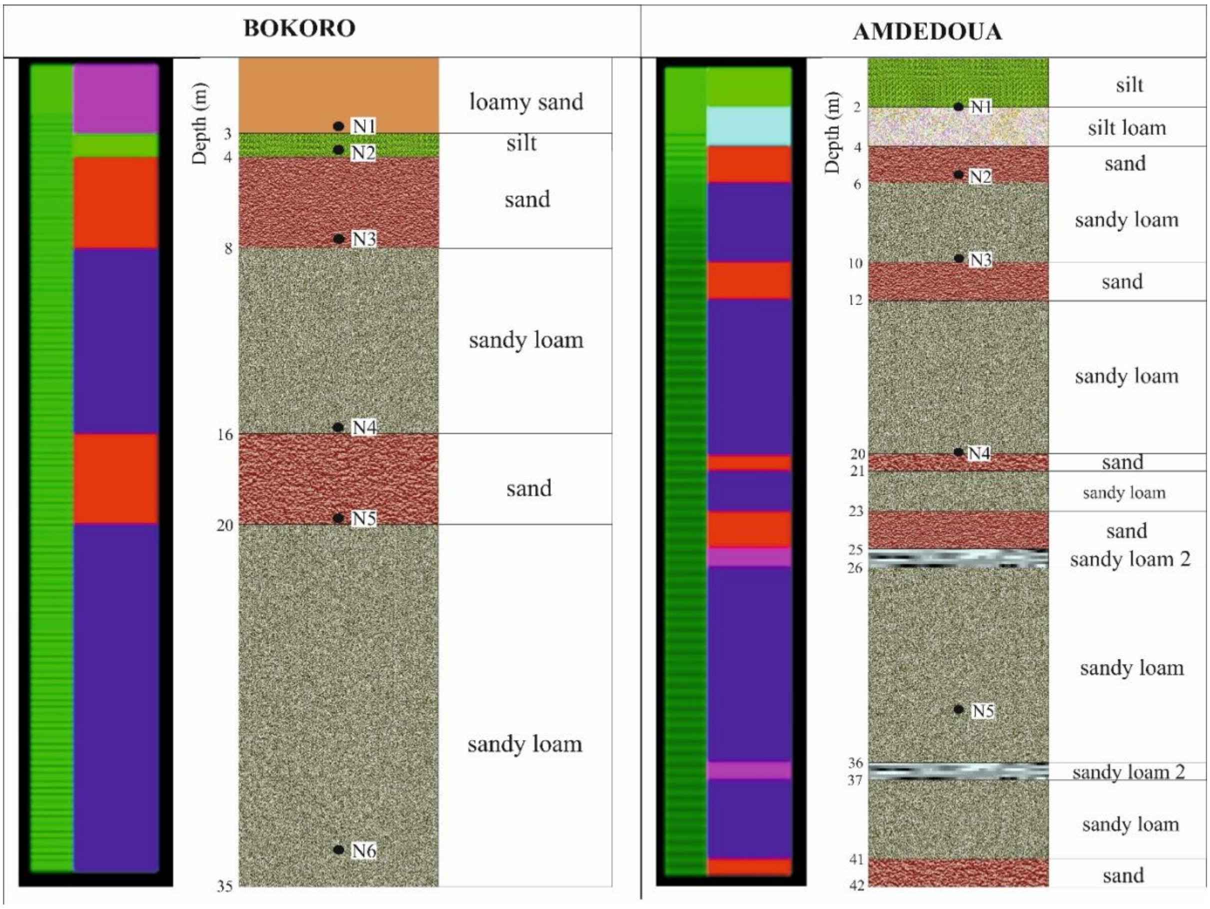


Figure 41. a) HYDRUS input. b) The Bokoro and Amdedoua distribution of geologic materials and control points along depth (N1-N5 or N6). The adopted discretization of the geological logs and materials (red, blue, purple, green and turquoise) for HYDRUS input is jointly shown on the left side of the Bokoro and Amdedoua geological logs description.Green column shows the number of defined nodes used in HYDRUS to discretize soil profile

For Bokoro and Amdedoua, respectively, Figures 42 and 43 show HYDRUS simulations of water content and water flux over time in bare and vegetated soil at the control locations spread along the soil depth profile (left bare, right acacias). Both sites exhibit a similar pattern of flux and water content throughout depth, however the recharge values are often higher for vegetated soil.

The three shallowest layers of the soil profile at Bokoro receive the majority of their recharge from precipitation during intense rainfall intervals (Figure 42, N1 to N3). For the deepest layers, from 15 m deep to the lower boundary, the effect of main recharge events is hardly noticeable because high downward water fluxes are absorbed by intermediate layers. For Amdedoua (Figure 43), changes in soil water content and the recharge flux mostly take place at a depth of 2 m below the soil surface.

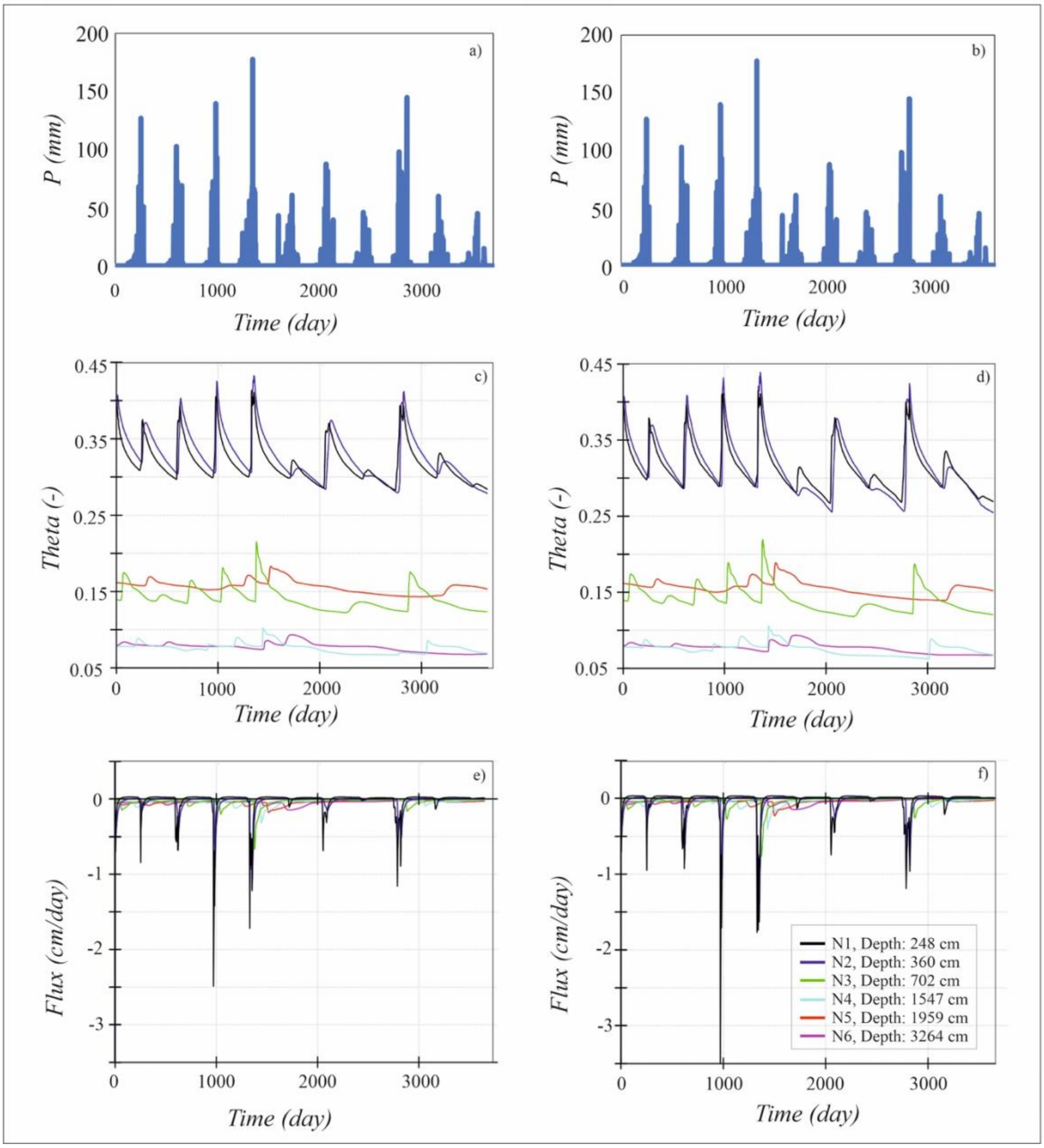


Figure 42. (a,b) Precipitation P. Results of water content (c and d) and recharge (e and f) for the control points at Bokoro (left bare, right acacias); HYDRUS outputs.

When there is a significant amount of precipitation, changes take place at the N2 monitoring point (Figure 43, 5.59 m). However, for both simulations and Figure 43, 19.5 m, there is no recharge impact from N4. The greatest water recharge value for the lowest layers (N3, N4) can be less than 0.1 cm/day and is only seen after prolonged periods of heavy rain. It's crucial to remember that these results could still fall within acceptable error ranges. The primary explanation for this occurrence is the existence of intermediary layers between those observation places with low to moderate hydraulic conductivity levels.

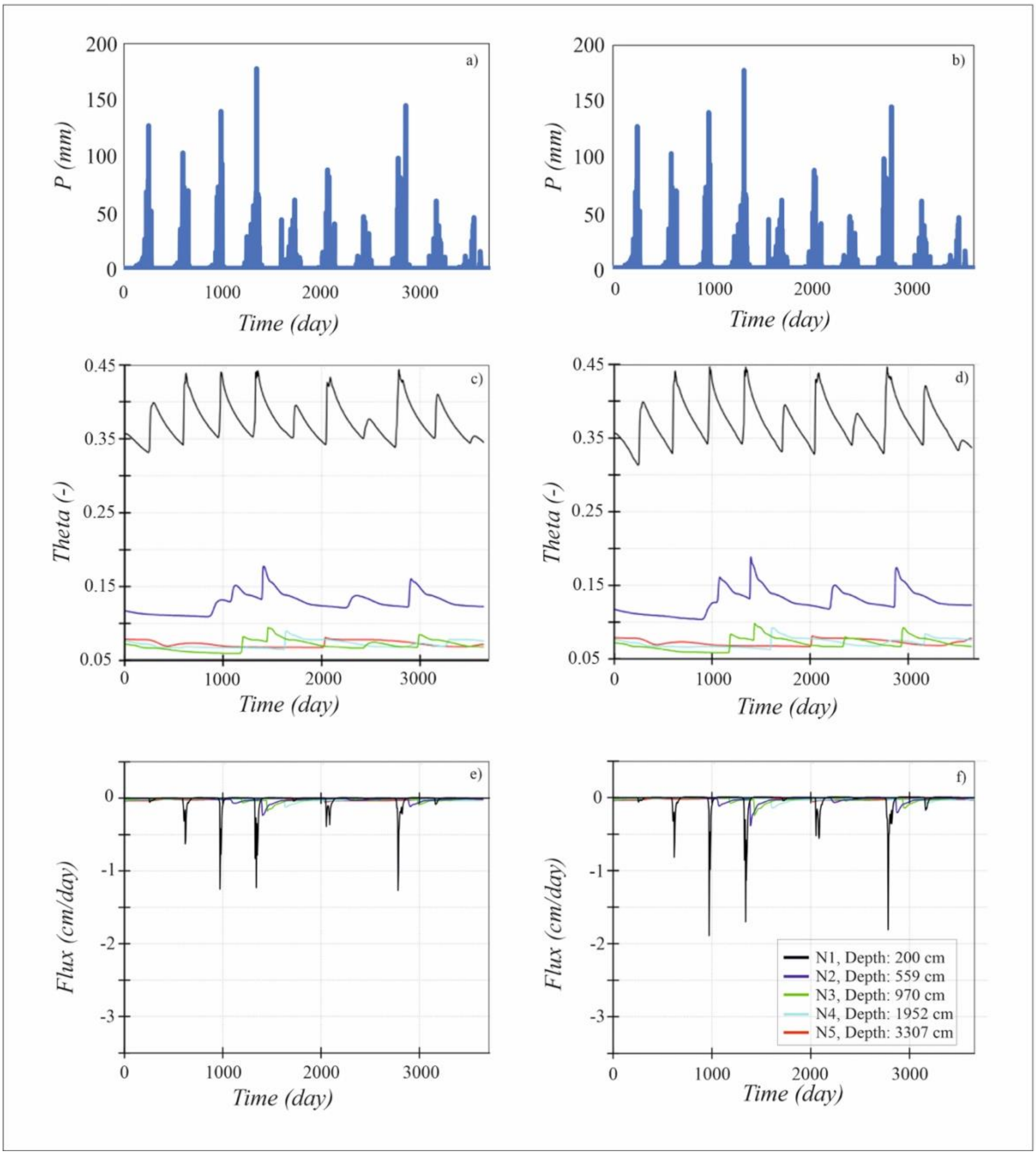


Figure 43. (a,b) Precipitation P. Results of water content (c and d) and recharge (e and f) for the control points at Amdedoua (left bare, right acacias); HYDRUS output.

At Bokoro and Amdedoua, the regional groundwater level is more than 50 m below the root zone. The data for the water that reaches deep strata indicate that recharge to aquifers from rainfall appears to be severely constrained. The models show that the predicted recharge rates are very low and that, given the existing climatic circumstances, it would take a very long time to reverse the current piezometric depression.

Simulation results indicate that shallow top soil layers are most affected by the response to precipitation. Additional simulations of these sites' past climatic conditions from the pluvial Pleistocene to the dry Holocene (changes from mesic to xeric vegetation) show the significance of the upper water flux reduction to create a drying front (and an upward water flux) that propagates more deeply into the profile and reaches the water table after several kyr of drying.

4.5. Regional water Balance Estimation

The regional water balance in a simplified steady-state condition has been undertaken with the attempt to characterize the hydrogeological system behaviour. This section summarizes the key elements of water budget estimates for both the Quaternary and Lower-Pli and continental Terminal aquifers.

The water balance quantitatively assesses the amount of water (inflow) into the system and amount of water out of the system (outflow) and the change in water storage (ΔS):

$$Inflows - Outflows = \Delta S$$

In Figure 38, a schematic 3D conceptual model diagram with the dominant input-output processes occurring in the basin is presented. For the water balance analysis, the 2008-2011 time span is considered for the calculations required.

4.5.1. Natural recharge estimation for the Quaternary aquifer

There are likely to be five major recharge mechanisms in the basin: direct recharge as rainfall infiltration; irrigation return flow in the intensely irrigated areas; recharge via surface water systems specially during flooding periods and vertical leakage through aquifers.
Surface water systems present gaining and loosing streams conditions with regard to the surficial aquifer when hydraulically connected. No current data are available for an estimation of surface water discharges (rivers).

There is currently no known estimate or information about groundwater exploitation (water supply or irrigation). Current extraction amount from wells and wells location is lacking has been estimated according to population needs and irrigation demand of crops. For rural use water supply 20 l/person/day is assumed and 40 l/animal/day for husbandry. A pumped volume from the refugee settlement is difficult to obtain as water points location changes on time.

An effort has been made to independently estimate recharge from precipitation and infiltration from agricultural fields based in Visual-Balan code, as presented in chapter 3. The recharge has been calculated for each of these zones as an average of one hydrologic year and for the period of 2005 to 2014 (Figure 28).

According to climatic data, the estimated mean annual recharge from precipitation was 0 mm/yr for northern parts to 194 mm/yr for the southern zones as an average (Table 16). For extremely dry and wet years, such as 2006 and 2008, showed $\pm 10\%$ differences that were noticeable. According to achieved rasults, the highest recharge happen in the southern part, i.e. the areas with high precipitation and lowest temperature The computed mean annual aquifer recharge in the irrigated areas (precipitation and irrigation) has a range of 102 mm/yr to 646 mm/yr (Table 16).

Table 16. Annual (mm/yr) and total recharge (R, mm) estimates for the study period (2005–2014) in the irrigated and non-irrigated areas. P denotes precipitation

No.	**Ave. P (mm/yr)**	**Average R Non- irrigated (mm/yr)**	**Total R Non-irrigated (mm)**	**Average R Irrigated (mm/yr)**	**Total R (2005-2014) Irrigated (mm)**
1	7	0.01	0.03	---	---
2	250	30.4	91.2	102	302
3	156	27.66	82.98	---	---
4	240	70.355	211.065	---	---
5	184	35.417	106.251	117	350
6	30	3.186	9.558	---	---
7	267	25.23	75.69	---	---
8	7	1.794	5.382	---	---
9	716	77.43	232.29	258	854
10	743	88.708	266.124	298	986
11	365	38.697	116.091	---	---
12	591	80.15	240.45	268	887
13	1,200	153.745	461.235	512	1695

14	1,200	140.662	421.986	469	1552
15	1,187	123.89	371.67	412	1363
16	1,187	161.642	484.926	539	1784
17	1,433	193.956	581.868	646	2138

The recharge estimate for the area for the whole period (2005 to 2014) was also computed in order to more accurately quantify the recharging process (Table 16). Recharge primarily occurs between June and October, during the wet season, in both irrigated and non-irrigated lands. The recharge response to rainfall events was most variable and somewhat independent of rainfall amount and changes over time, but it was strongly conditioned by antecedent soil moisture condition and highly dependent on precipitation distribution over both time and space. Generally, recharge occurred only after one significant rainfall episode (more than 100 mm over two days, with a peak after three days of continuous rainfall. Groundwater recharge varies spatially due to climatic and physical factors such as precipitation pattern, soil type, vadose zone porosity, depth to groundwater, and hydrogeology. Groundwater recharge appears to occur during intense precipitation events in arid and semiarid environments, as opposed to other environments described as having a mix of constant-rate and episodic behaviors and frequently conditioned by preferential flow (De Vries & Simmers, 2002).

It seems that in the areas with low precipitation and high temperature, irrigation is a major source of recharge to aquifers, whether they use groundwater or surface water. Previous compilations in the study of recharge in irrigated zones in a semi-arid environment at the global scale show that irrigation causes an increase in recharge of between 1% and 25%, with the average being ~15% (Scanlon et al., 2006).

4.5.2. Water budget

Inflow and outflow from the Lake Chad and other aquifers for the aquifer of concern was derived from groundwater flow analysis of piezometric map (based in water level elevations) and performing Darcy's Law.

Quantitative analysis of inflows and outflows into the system and values are shown in Tables 17 and 18 and the discrepancy between the input and output value estimates highlights the large data gaps in the assessment. The inflow and outflow to Lake Chad and the aquifer systems under consideration (to and from Q, CT/LPli and lateral inputs from weathered bedrock) are found in the following locations: the lake boundaries of Kazdell (Lake input to Q), Bol and Chari-Baguirmi (Q input to Lake), the Chari Logone river head, and the Koros region (CT to Q). Vertical leakage upward flow from deep aquifers and down-flow volumes to deeper aquifers are unknown.

The share of recharge from rainfall in sector is about fifty percent more than PL and CT sectors. This is despite the fact that the irrigation return from agriculture and water supply in the Quaternary sector is sixty percent less and two hundred percent higher than PL and CT, respectively.

An accurate estimate of surface water inflow is unavailable for the basin. Although stream-flow data is available and rivers scarce information was obtained. Data provided in the balance correspond to estimations provided from modelling in the works of Massuel (2001) for the Chari-Logone and Gaultier (2004) for the Komadugu-Yobe.

The method for calculation of water supply for domestic abstractions is based on a primary assessment of the population in rural or urban areas. It is important to notice that 'The water and sanitation program for the refugees' of the Darfur conflict covers five refugee camps in Chad. In some camps, such as those in Djabal and Goz Beida, over 300,000 liters of water are supplied daily (Water for the refugee camps in eastern Chad, Oxfam). For husbandry, the withdrawals for breeding are given by applying a rate for each category of animal. The estimation of the abstractions with the number of works tapping the aquifer does not seem to be a reliable method as it is difficult to assess the number of traditional open wells. About 50% of it comes from groundwater origin according to 1990 data (Project 507/RAF/45). Only 28% of water supply comes from CT.

The water balance assessment also relied on key assumptions, including the: aquifer extension is continuous over the area; rivers are constantly flowing; deeper formations outcrop.

Table 17. Water-budget Parameters for Quaternary Aquifer based in estimated and referenced data (average for the 2008-2011 period).

INPUT	Mm^3/yr	OUTPUT	Mm^3/yr
Recharge from precipitation	7×10^4	**Pumping for irrigation**	63
Irrigation returns	22	**To Lake Chad**	4.6×10^2
From Lower-Pli/CT	20	**To river (Chari-Logone)***	1.5
From Lake Chad	6	**Water supply**	1.7×10^2
River (Komadugu Yobe)*	Range from 1.2 to 16	**To Lower-Pli/CT**	2.8
River (Chari-Logone)*	1.6		
TOTAL INPUT	?	**TOTAL OUTPUT**	?

*from literature review

Table 18. Water-budget Parameters for LCB for Pl and CT.

INPUT	Mm^3/yr	OUTPUT	Mm^3/yr
Recharge from precipitation	1.3×10^3	**Pumping for irrigation**	2.7×10^2
Irrigation returns	3.7×10^1	**To Lake Chad**	-
From Lower-Pli/CT	2.8	**To river (Chari-Logone)**	-
		Water supply	0.8×10^2
		To Lower-Pli/CT	8.3
TOTAL INPUT	?	**TOTAL OUTPUT**	?

Chapter 5

Conclusions and recommendations

Conclusions

Based on the findings of this study, the conclusions can be categorized into three distinct aspects: *i) Data analysis and sources of information, ii) Chad Formation Aquifer and 3D conceptual model and iii) Groundwater flow and recharge:*

Data analysis

- This part of the study provided a detailed overview of the data availability, collection, analysis, and final selection process. The information presented included the number of geologic logs identified, groundwater data availability, time span coverage, meteorological stations, and the discrepancies between TAHMO and CHADFDM datasets. This comprehensive overview serves as a foundation for the remainder of the study, to ensure if the data used is accurate, reliable, and relevant to the research questions at hand.

- The Chad formation (Quaternary-Miocene) has received most of the research interest. Research have focused on the Quaternary aquifer and central Lake Chad Basin part; scarce information exists from parallel 14 N, north of the Lake. Most information gathered corresponds to the Quaternary aquifer in Chad, with limited information available for the northern part and neighboring countries.

- Data availability through data collection, analysis and final selection indicate: geologic logs mainly concentrated in the central part of the Chad Basin. A number of 644 documented geologic logs were identified and stored in a database for further analysis., however deep information from oil rigs only provided for few local points.

- Groundwater data available mainly for the Quaternary aquifer (Q) in the central and southern part of the area; aquifer-testing data to define key parameters (Q and LPli-CT) only available at few points; lack of time series of groundwater level along time.

- Groundwater level measurements data span coverage from the different sources ranges from 2004 to 2017 with important gaps. The 2008-2011 period appears to be the most complete one in terms of data availability, reliability and spatial distribution

- Almost non-existing streamflow data from river gauges and estimates are available at a few points impairing an accurate analysis of surface water inflow in the basin.

- Overall, there is a network of around 680 meteorological stations with variable time span maintenance and important gaps. For the period of 2005 to 2014, there were 25 rainfall stations within the area with the highest percentage of available data and lowest gaps in the time series. Only 14 of these stations had complete daily records.

- The TAHMO storage platform for climatic data (mainly ground-based precipitation and temperature) provide the most complete and accurate daily data set. Remote sensing data from CHADFDM merged with ground-based data is also available to determine precipitation and temperature.

- Comparision between TAHMO and CHADFDM data sets showed discrepancies, with CHADFDM sometimes overestimating the amounts. The reasons for these discrepancies were suggested to be due to cloud microphysics, rain processes, and environmental moisture distribution, as well as gaps in the rain gauge data.

The Chad formation aquifer and conceptual model

- A 3D conceptual geologic model, covering the whole basin, was constructed based on the analysis of stratigraphic sections from 430 representative geologic logs. Limited stratigraphic, geological and geophysical information exists for some areas and most lithological log records are located in the central part of the basin.

- The three-dimensional architecture of the basin has been generated through the identification and definition of hydro-stratigraphic units, water-bearing formations with more or less hydraulic connections, and the establishment of geologic correlations among them

- Five hydrostatigraphic units, were defined: Quaternary, Pliocene (clays, aquitard), Lower Pliocene, Continental Terminal and basement are established. The top and bottom depths of units were calculated based on lithologic descriptions and geologic mapping.

- The Chad Aquifer Formation system (CAF) in the region consists of three aquifer systems: the Quaternary aquifer, the Lower Pliocene, and the Continental Terminal aquifer. Due to the extension, thickness and data availability of the Lower Pliocene, the LPli and CT hydrostratigraphic units have been considered as an aquifer system for simplicity.

- Hydraulic parameters of aquifer formations were based on 81 hydraulic tests, with most observations corresponding to the Q (54) and LPli/CT (25) aquifer units mainly located in the Komadougou-Yobe river basin and nearby regions in Chad. Most tests have been used to test specific yields of wells, but not to characterize aquifers and do not allow storage coefficients estimation, neither to help quantify parameters. Few hydraulic tests could not be clearly identified in the area and most of them correspond to a short test duration.

Groundwater flow and recharge

- Groundwater level contours and flow direction were constructed from 239 water points. Several years of measurements (2008 to 2011) were assessed simultaneously to draw the groundwater level map. The map is an indication of a complex regional flow pattern in a dynamic system during the considered period, but variable with time.

- Groundwater regional flow with low hydraulic gradients is broadly shown in the central part of the basin. The flow is directed towards the North (to the Lowlands, in Bodelé with the lowest topographic elevation). The interactions between Lake Chad and the

Quaternary aquifer are mostly insignificant, and they are only noticeable within a short radius from the lake's shoreline.

- Two piezometric domes are present in the north of Lake Chad and are associated to recharge areas located in dune-fields sectors. Large natural piezometric depressions with relation to the regional groundwater level depressions exist in Nigeria (Bornu), Chad (Yaere, Chari-Baguirmi and inter-fluvial zone of the Komadugu) and Niger (Kadzell) and also exist.

- According to the vadose zone simulation with HYDRUS, no upward water flux (positive outputs or 'exfiltration') is shown for the current climatic setup. The topsoil layers are most affected by precipitation, with the majority of recharge taking place during intense rainfall events. However, the recharge rate was found to be very low, indicating that it would take a long time to reverse the current groundwater depression. The simulations also showed that the response of the soil to precipitation was greater in vegetated soil than in bare soil.

- Simulations of past climatic conditions elsewhere, showed that the upper water flux reduction can lead to a drying front that propagates deeper into the soil profile and reaches the water table after several thousand years of drying. This fact emphasises the existence of earlier climatic conditions when the depressing process should have manifested leading to present conditions.

- Recharge to the Quaternary aquifer is primarily controlled by precipitation and river-groundwater interactions. The Lower Pliocene part, recharge/discharge characteristics and conceptual aquifer behavior model are still unknown. The Continental Terminal aquifer is mainly exploited in the southern part of the area (Chari-Logone).

- Estimation of the regional water balance for the 2008-2011 time span indicates that the main source of water is rainfall that infiltrates into the Quaternary, Lower-Pli and Continental Terminal aquifers. Surface water systems (rivers) present gaining and loosing flow conditions following streamflow conditions with regard to the surficial aquifer when hydraulically connected. Not any accurate quantitative estimate of surface water inflow-outflow into the groundwater system is available for the basin. Groundwater may also flow upwards from lower aquifers (or from aquitard located deeper) into the upper aquifer. Exchanges between Lake Chad and the aquifer are not very important) and are mainly taking place within 50 km from the lake shore.

- Recharge estimates from precipitation and irrigation, calculated with Visual-Balan, for the period of 2005 to 2014, were found to be highest in southern areas with high precipitation and lowest temperature. The recharge is primarily between June and October, during the wet season and varies spatially due to climatic and physical factors such as precipitation pattern, soil type, and depth to groundwater. The recharge response to rainfall is dependent on the antecedent soil moisture and the distribution of precipitation over time and space.

- The discharge from the aquifer system is through groundwater abstraction and surface water systems to the north while regional flow is to the Lowlands (Bodelé). At the working scale, local withdrawal from water-wells does not appear to have a major impact on local groundwater flow. High Evapotranspiration (ET) losses would be expected mainly in wetlands and surface water.

Recommendations and suggestions for future studies

- Significant data and knowledge gaps may influence the uncertainty on the hydrogeological conceptualization. Particularly, the lack of previous regional-scale hydrogeological assessments covering all basin area. There is also spatially limited stratigraphic and geophysical data available in the northern and western part of the basin to improve definition of key groundwater parameters and processes. As new data may become available in the future, the conceptual model for the basin could be updated appropriately.

- The most important gaps in current data are: a widespread (spatial distribution) and detailed information on the layer-thickness continuity and hydraulic parameters of the aquifers; updated and continuous stream gauging data to support base flow analyses for surface-groundwater interaction; continuous groundwater level measurements, piezometers at different depth (nested boreholes) to understand inter-aquifers connectivity, magnitude and groundwater flow in the hydroestratigraphic units, geophysical surveys and hydrogeological testing to determine estimates of vertical gradients, and water volume estimates for water balance assessments. Any enhancement of this information might further our understanding of the hydrogeology of the Lake Chad basin.

- Hydrographs describing high rainfall events and groundwater levels are not available for the groundwater system and a full study was not possible. A review of the spatial distribution of observation bores (and their temporal trends) is an important next step in further progressing the understanding of the groundwater system and data gap.

- Geologic data from newly drilled wells for subsurface exploration as well as data from oil and gas would be needed for the mapping of aquifer unit thickness. In order to determine hydraulic characteristics (hydraulic conductivity, porosity), hydrogeological research in the Upper aquifer of the basin should be addressed.

- Additional information is needed for the basin's water balance evaluation in order to manage groundwater use properly. The details that are very necessary include: Data on the extraction of groundwater and surface water based on accurate demand projections for the entire basin and installing water level monitoring wells at correctly constructed hydrogeological sites in river basins to gauge the connectivity between surface and groundwater and to comprehend and quantify recharge/discharge processes, the quantity of water delivered for irrigation from dams and other water storage facilities, as well as the precise locations where transfers occur, placing gauges at particular river basin monitoring locations to provide streamflow data.

- Moreover for further studies more hydrochemical and isotopic data are needed.

- Groundwater monitoring is critical to decisions concerning water management, especially in the southern part of the region. 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.

- It is highly recommended to implement a long-term monitoring program to regularly measure and observe a particular resource or system. This is essential for evaluating changes over time, identifying trends, detecting patterns, and assessing the effectiveness of management actions, thus promoting environmental stewardship and sustainability.

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Appendix: Published or under-review articles

Type of publications	Remarks
Journals	• **Salehi Siavashani, N.**, Jiménez-Martínez, J., Vaquero, G., Elorza, F.J., Sheffield, J., Candela, L., Serrat-Capdevila, A., (2021). Assessment of CHADFDM satellite-based input dataset for the groundwater recharge estimation in arid and data scarce regions. Hydrological Processes. 35(6) e14250. DOI: 10.1002/hyp.14250. • Vaquero, G., **Salehi-Siavashani, N.**, García-Martínez, D., Elorza, F.J., Bila, M., Candela, L., Serrat-Capdevila, A., (2021). The Lake Chad transboundary aquifer. Estimation of groundwater fluxes through international borders from regional numerical modeling, In: Journal of Hydrology: Regional Studies, 38, 100935, DOI: 10.1016/j.ejrh.2021.1009. • **Salehi Siavahani, N**., Valdés-Abellánb, J., Do, F., Jiménez-Martínez, J., Elorzae, F.J., Candela, L., Serrat-Capdevilah, A., (2023). Modeling vadose zone hydrological processes in naturally-occurring piezometric depressions. The Chari-Baguirmi region, southeastern of the Lake Chad Basin, Republic of Chad, Submitted to Environmental Earth Science, Under review.
Conferences	• **Salehi Siavashani, N.**, Vaquero, G., Elorza, F.J., Candela, L., Serrat-Capdevila, A., Remote sensing application for investigating groundwater recharge at Lake Chad Basin, 20th EGU General Assembly, EGU2018, Vienna, Austria, p.17433. • **Salehi Siavashani, N**., Vaquero, G., Elorza, F.J., Candela, L., Sheffield, J., Serrat- Capdevila, A., Assessment of groundwater natural recharge in difficult environments: A case study at the Lake Chad Basin, 46th IAH congress, Malaga, Spain, 2019. • **Salehi Siavashani, N**., Vaquero, G., Elorza, F.J., Candela, L., Lee, J., Serrat-Capdevila, A., 3-D groundwater modelling of lake chad basin: challenges and success of regional scale modelling for a data poor region in sub-Saharan, AGU Chapman conference, Valencia, Spain, 2019. • **Salehi Siavashani, N**., Vaquero, G., Elorza, F.J., Candela, L., Serrat-Capdevila, A., toward an updated understanding of the groundwater dynamics at Lake Chad Basin, 47th IAH conference, Brazil, 2021. • **Salehi Siavashani, N**., Vaquero, G., Elorza, F.J., Gomez, M., Candela, L., Serrat-Capdevila, A., Data integration transboundary Chad aquifer formation for groundwater flow understanding. 49th IAH Online Congress, Wuhan, China, 19-23 Sep 2022. • **Salehi Siavashani, N.**, Elorza, F.J., Vaquero, G., Candela, L., Gomez, M., Serrat-Capdevila, A., The Lake Chad transboundary aquifer arid north zone. groundwater fluxes estimation, Sustainable Groundwater Management Conference, Valencia, Spain, 2022.

Report	• WB., (2020). Groundwater model for the Lake Chad Basin: Integrating data and understanding of water resources at the Basin Scale: A cooperation for international Waters in Africa (CIWA). Technical Report (English). Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/ 271881583228188294/A. Cooperation-for-International-Waters-in-Africa-CIWA-Technical-Report. 184pp.

Paper 1. **Assessment of CHADFDM satellite-based input dataset for the groundwater recharge estimation in arid and data scarce regions**

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RESEARCH ARTICLE

WILEY

Assessment of CHADFDM satellite-based input dataset for the groundwater recharge estimation in arid and data scarce regions

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Abstract

Aquifer natural recharge estimations are a prerequisite for understanding hydrologic systems and sustainable water resources management. As meteorological data series collection is difficult in arid and semiarid areas, satellite products have recently become an alternative for water resources studies. A daily groundwater recharge estimation in the NW part of the Lake Chad Basin, using a soil–plant–atmosphere model (VisualBALAN), from ground- and satellite-based meteorological input dataset for non-irrigated and irrigated land and for the 2005–2014 period is presented. Average annual values were 284 mm and 30°C for precipitation and temperature in ground-based gauge stations. For the satellite-model-based Lake Chad Basin Flood and Drought Monitor System platform (CHADFDM), average annual precipitation and temperature were 417 mm and 29°C, respectively. Uncertainties derived from satellite data measurement could account for the rainfall difference. The estimated mean annual aquifer recharge was always higher from satellite- than ground-based data, with differences up to 46% for dryland and 23% in irrigated areas. Recharge response to rainfall events was very variable and results were very sensitive to: wilting point, field capacity and curve number for runoff estimation. Obtained results provide plausible recharge values beyond the uncertainty related to data input and modelling approach. This work prevents on the important deviations in recharge estimation from weighted-ensemble satellite-based data, informing in decision making to both stakeholders and policy makers.

KEYWORDS
CHADFDM data set, ground-satellite meteorological data, groundwater recharge modelling, Lake Chad Basin

1 | INTRODUCTION

Scarce precipitation, interannual dry periods, marked seasonal and spatial variability and extreme rainfall events are the main features of arid and semiarid zones that condition groundwater recharge (Lerner et al., 1990). Therefore, reliable rainfall and temperature data in these areas are extremely important for accurately assessing both soil water balance and aquifer recharge (Wu et al., 1996). Beyond inherent uncertainties to available in situ data, that is, from ground-based weather stations, one of the main difficulties is field data scarcity (Bhowmik & Costa, 2014; Dumolard et al., 2007). Meteorological stations are generally scarce, unevenly distributed, and may operate during short periods or imply major gaps. This can, in turn, lead to problems if long-term values are required when only short dataset periods are available (Lerner et al., 1990). Data and information are also often scattered among different agencies with limited access, which makes it difficult to obtain complete records. This generally results in information that is not very suitable for practical needs. To overcome this challenge, researchers have traditionally increased data availability using different statistical methods (Wagner et al., 2012), especially by bridging gaps in time series, interpolating between data points, introducing uncertainties given rainfall intermittency and large distances between observation points.

An alternative and complementary source of information comes from satellite products (e.g., TRMM, CMORPH, TMPA, PERSIANN), which can provide meteorological data series over large areas, and are useful for making multiple applications in hydrology (Beck, van Dijk, et al., 2017; Beck, Vergopolan, et al., 2017; Habib et al., 2008; Mzirai et al., 2005; Sheffield et al., 2018; Velpuri & Senay, 2013). For example, these sources of information have been used to develop large-scale drought monitoring systems with also the goal of stakeholders use in mind, which monitor in near real-time the terrestrial water cycle based on remote sensing data and land surface hydrological modelling (Sheffield et al., 2014).

Given the general ground data scarcity in arid and semiarid zones, satellite remote sensing products are a potentially useful direct or indirect data source of most hydrological cycle components. Nevertheless, satellite products use is influenced/limited by uncertainties resulting from its wide space–time coverage and spatial resolution, which is especially relevant in these regions due to the high spatial and temporal variability of surface meteorology and elevation-dependent biases (Bitew & Gebremichael, 2010). In some cases, satellite sensors may overestimate precipitation given its ability to identify events not recorded by gauge data (Milewski et al., 2009). Besides, satellite-based physical sensor limitations (Knoche et al., 2014; Prigent, 2010) or changes in sensors that lead to temporal non-homogeneity are also challenges as to their use. To understand/verify the utility of such products for hydrological studies, it is necessary to compare satellite data with ground-based data in order to indicate the hydrologic system response to these inputs and a range of predictions. Much work has been done especially on precipitation, (e.g., Beck, van Dijk, et al., 2017; Beck, Vergopolan, et al., 2017; Haile et al., 2015; Jiang, Yu, et al., 2016; Jiang, Zhou, et al., 2016; Lu, Sun, et al., 2016; Lu, Wang, et al., 2016; Nogueira et al., 2018). For groundwater recharge quantifications based on the water balance equation, the use of field and satellite products has been assessed in similar climate areas, ranging between less than 100 km^2 and 10^4 km^2, as summarized by Coelho et al. (2017). Most approaches generally use rainfall and evapotranspiration inputs for studies conducted in the Guarani aquifer (Lucas et al., 2015), Pakistan (Usman et al., 2015) and in the West Bank (Khalaf & Donoghue, 2012); the lately also incorporates irrigation data parameters and surface water input. For arid Northern Brazil, the work of Coelho et al. (2017) considers spatially varying runoff and soil moisture in the water balance equation, along with ancillary land use/land cover data. Wu et al. (2019) determined the aquifer annual and long-term recharge trend at regional scale with GRACE and GLDAS in the semiarid region of the Ordos Basin, China. There was no obvious long-term trend observed, and the annual recharge can be explained by the variability in precipitation. For modelling purposes, several physically based distributed numerical codes, found in different water balance approaches such as SAHYSMOD (ILRI, 2005), VisualBALAN (Samper et al., 2005), TOPOG (CSIRO, 2008) or SWB2 (Westenbroek et al., 2018), among others, are currently applied. The generally available requested input data, estimated reasonably accurately, and the facility to modify or substitute different input datasets, make VisualBALAN an excellent candidate for recharge calculations. VisualBALAN v2.0 offers an intermediate level of difficulty. This model code estimates a sequential water balance for the soil, the unsaturated zone and the aquifer, and has proven successful in calculating groundwater recharge in various hydrogeological conditions (Samper et al., 1999; Espinha-Marques et al., 2011; Touhami et al., 2013).

The quantification of natural groundwater recharge is a basic requirement for efficient water resources management. The diffuse recharge is a complex function that results from the coupling of several factors: precipitation (volume, intensity, duration), air temperature, topography, vegetation (cropping pattern, rooting depth) and evapotranspiration, soil and subsoil types, flow mechanisms in the unsaturated zone, bedrock geology and available groundwater storage (Scanlon et al., 2002). Of these, precipitation and evapotranspiration are the system's driven forces. Depending on relief, not concentrated recharge from runoff and ponding may be also dominant mechanisms in arid environments. Several reviews on aquifer recharge quantification based on different methods have been conducted in the past, and have focused primarily on arid and semiarid regions (de Vries & Simmers, 2002; Moeck et al., 2020; Scanlon et al., 2002; Scanlon et al., 2006). Although the spatio-temporal distribution of precipitation is the most critical factor (Wu et al., 1996), the chosen method can make estimations highly variable (Leduc et al., 2000). For regional scale studies, the soil water balance method is widely used due to its versatility to estimate spatially and temporally distributed aquifer recharge. This analysis calculates the temporal (e.g., daily) response over a wide area based on a physically robust recharge estimate process, taking into account the conditions of the land cover and the rainfall and irrigation contributions. With regard other methods, it presents more complexity as it also takes into account further information from different sources on climatic, soil data, vadose zone/ aquifer parameters and vegetated areas.

This work focuses on the Lake Chad Basin, an arid region in which surface water is not enough to fulfil urban and rural population needs, and groundwater is the main water supply. Natural recharge (diffuse) for the region, which is widely variable on spatial and temporal scales, still remains uncertain. In the last 40 years, much attention has been paid to improve recharge estimations in this area, generally by local research. Methods for recharge estimation mainly included isotopic studies (Djoret & Travi, 2001; Edmunds et al., 1998; Gaultier, 2004; Goni, 2006; Leduc et al., 2000; Ngounou Ngatcha, Mudry, Aranyossy, et al., 2007; Njitchoua & Ngounou Ngatcha, 1997; Tewolde et al., 2019) and mathematical modelling for different hydrologic objectives (Babama'aji, 2013; Leblanc, 2002). Main findings indicate maximum values in the southern part of the Lake Chad Basin (South of 14th parallel) and in northern boundary part of the Lake, while it is almost inexistent in the northern part of the Basin. Different research studies have applied remote sensing data (e.g., Meteosat thermal data), combined with hydrogeological data, for groundwater research purposes. Leblanc (2002) and Leblanc et al. (2007) worked at the basin level to identify surface indicators of recharge and discharge areas for groundwater modelling. Buma et al. (2016) inferred the effect of rainfall on water storage on the basin by applying remote sensing datasets from the Gravity Recovery and Climate Experiment (GRACE) and Global Land Data Assimilation System (GLDAS) for water storage and soil moisture, respectively. Subsurface water variations were compared with groundwater outputs from a global hydrological model that showed a similar pattern.

The main objective of this work was to explore changes in groundwater diffuse recharge; that is, performance evaluation of climate data inputs in a generated daily water budget from a soil–plant–atmosphere model based on the water balance by considering two meteorological data sources and existent agricultural irrigation: (i) available ground-based meteorological data from local stations stored in the Trans-African Hydro-Meteorological Observatory, TAHMO (Van de Giesen et al., 2014); (ii) satellite-based rainfall from the Multi-Source Weighted-Ensemble Precipitation (MSWEP, Beck, van Dijk, et al., 2017; Beck, Vergopolan, et al., 2017; Beck et al., 2018; Beck et al., 2019) and air temperature data from the Princeton Global Forcing (PGF, Sheffield et al., 2006) provided by the Lake Chad Basin Flood and Drought Monitor System platform (CHADFDM; Amani et al., 2021; Sheffield et al., 2014). The CHADFDM was developed for hydrologic applications by Princeton University in collaboration with ICIWaRM (International Center for Water Resources Management) and UNESCO-IHP.

The ultimate goal is to assess the suitability of satellite products (based in a user-friendly platform CHADFDM) to develop spatially and temporally estimates of groundwater recharge for regional management studies with the goal of stakeholder use in mind. This analysis essentially provides 'a controlled experiment' to assess the effects of changes driven only by running the model varying data input from the two sources. The recharge estimations were carried out for the 2005–2014 period. he reliability and uncertainty of the estimated recharge values in the non-irrigated area from the two data sources as regards climate and soil parameters were evaluated by a sensitivity analysis of the model parameters.

2 | STUDY AREA

The study area is located in the north-western part of the Lake Chad basin system, which covers an area of about 155 000 km^2 of the basin in Chad, Niger and Nigeria (Figure 1). The Lake Chad size is highly variable across seasons and years 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. At regional level, aquifer exchanges with surface water and diffuse recharge constitute the main control mechanism of groundwater level. This region is categorized as arid to semiarid, with a main rainfall season between April and September. Average annual precipitation ranges from 20 to 600 mm, daily temperatures between 8 and 45°C, and mean annual potential evaporation exceeds 2000 mm (LCBC-GIZ, 2016; Mahmood & Jia, 2018). A succession of dry periods in the last 100 years has led to a severe depletion of the lake area from 22 000 km^2 to 8 000 km^2 today, which has drastically reduced the extension of seasonally inundated river plains. The associated impact on infiltration and groundwater recharge remains unknown, but is likely important.

The region is relatively flat with gentle slopes (10%) from the highlands in the NW towards the SE. Land cover is grassland (65%), bare land (20%), sparse vegetation (5% e.g., acacias) and croplands (rain fed and irrigated, 10%) (LCBC-GIZ, 2016). Non-irrigated crops are millet, sorghum, corn and rice. In the studied area, crop irrigation (5000 mm/yr, mainly peppers; LCBC-IRD, 2016) is done by combining groundwater and surface water from Yobe river and covers approximately 21 295 km^2.

On the regional scale, the geology of the study area consists of materials from the Precambrian, Mesozoic (Cretaceous), and Plio-Quaternary (BRGM, 1994; Burke, 1976; Schneider, 1989; Schneider & Wolff, 1992). The Cretaceous is predominantly continental and, along with Miocene formations, it is known as the Continental Terminal. Plio-Quaternary deposits comprise fluvio-lacustrine, fluvio-deltaic and aeolian material. Outcrops of igneous rocks complete the geology in the region. From a hydrogeological point of view, three aquifers are distinguished in the area (Schneider & Wolff, 1992), Quaternary, Lower Pliocene and Continental Terminal, and are mainly confined. Only the groundwater recharge to the Quaternary upper unconfined aquifer is the objective of this research work (Figure 1).

3 | METHODOLOGY

A soil water balance modelling approach was applied to estimate the groundwater diffuse recharge to the Quaternary unconfined aquifer for the 2005–2014 period. For modelling purposes, the model was set up and the values of the plant–soil-hydrologic parameters remained

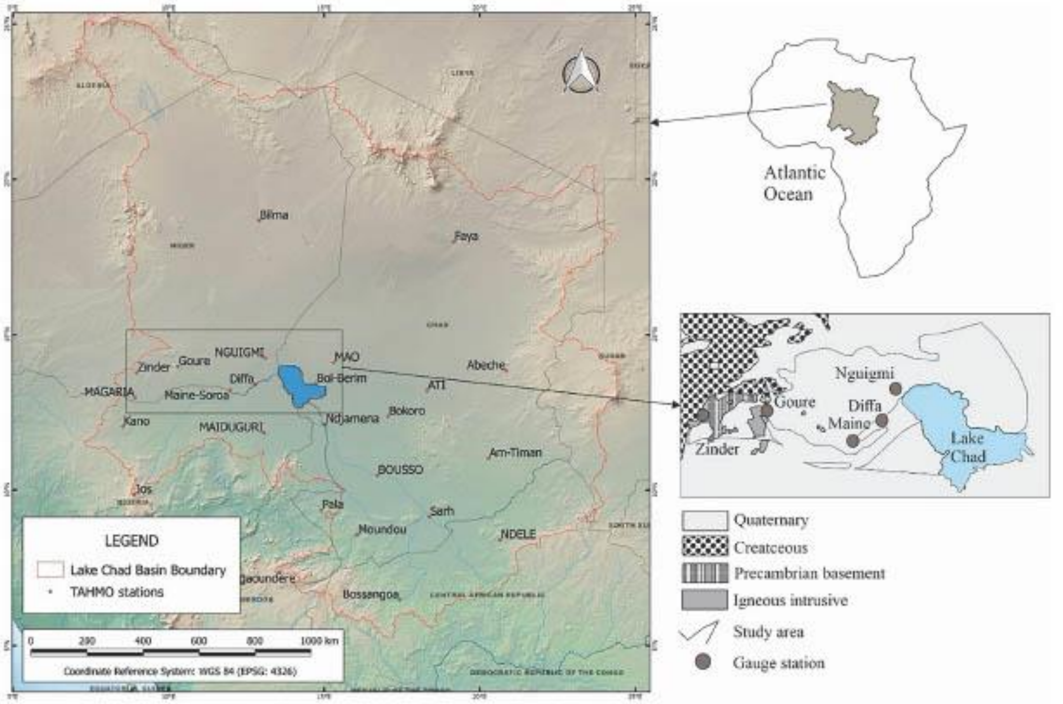

FIGURE 1 The Lake Chad Basin and location of the study area. Existing ground-based meteorological stations are indicated on the map

invariant as only the climatological data inputs were modified. Two sources of precipitation (*P*) and air temperature (*T*) data were used: (i) ground-based data from the selected local meteorological stations; (ii) satellite-based rainfall and air temperature data downloaded from the CHADFDM (Amani et al., 2021; Sheffield et al., 2014) for the same time period and geographical location (coordinates) of the field stations. The *P* and *T* data downloaded from the CHADFDM platform are always referred to as satellite data throughout the text.

The exploratory inspection for the 9-year series of meteorological daily data of each data source involved an analysis with simple descriptive statistics (mean, median, mode, standard deviation). Out-of-sample testing was conducted to assess if the statistical analysis results could be generalized to an independent dataset. The *P* and *T* data deriving from the CHADFDM were checked against the ground data to evaluate temporal hydrological patterns, to validate assumptions and to compare the results. A dependence assessment (correlation) between the two datasets was made with a regression analysis and goodness-of-fit was assessed by the coefficient of determination (R^2) to identify the possible presence of trends. Annual precipitation as cumulative deviation from the mean was calculated. Finally, a statistical data analysis was carried out with the EXCEL Analysis Toolpack 2013 (Microsoft®). A sensitivity analysis was also carried out on the aquifer recharge estimations for the non-irrigated area.

3.1 | Soil water balance model description

Aquifer recharge was calculated using VisualBALAN v.2.0 (Samper et al., 2005), a numerical model to simulate water balance in soil, vadose zone and aquifer with a user-friendly modular design. It requires specific information on climate, land use, land cover and topography to simulate recharge process. This numerical tool has been successfully applied in different areas (e.g., Candela et al., 2016; Jiménez-Martínez et al., 2010, among many others).

The model is divided into three sub models (Figure 2), which considers the processes in: (i) the upper part of soil (root zone) to solve the critical interactions of the soil–plant–atmosphere continuum; (ii) the vadose or unsaturated zone (below the root zone); (iii) the saturated zone (aquifer). The water balance (in water depth) for a vegetated soil is represented by:

$$P + Ir - In - Es - ETa - R = \Delta\theta.$$

where *P* (mm) represents precipitation, *Ir* (mm) irrigation, *In* (mm) canopy interception, *Es* (mm) runoff, *ETa* (mm) actual evapotranspiration, *R* (mm) potential recharge to the vadose zone and $\Delta\theta$ variation in soil water storage (mm).

Precipitation (*P*) and irrigation (*Ir*) are distributed between surface runoff and infiltration. The *In* volume is a fraction of the precipitation intercepted by vegetation (leaves, branches, trunks) to deal with water

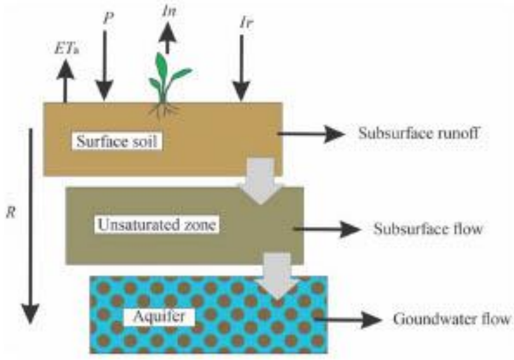

FIGURE 2 VisualBALAN conceptual model (adapted after Samper et al., 2005), where the nomenclature denotes: *P* precipitation, *Ir* irrigation, *In* interception, *ETa* actual evapotranspiration, *R* aquifer recharge

loss by evaporation. The residual water after evapotranspiration, infiltration term *I* (mm), was included in the water balance equations as:

$$I - (ETa - R) = \Delta\theta$$
$$P + Ir - In - Es = I$$

Part of infiltration comes back to the atmosphere by evapotranspiration (*ETa*), another part increases the water content in soil and the rest contributes to potential recharge, the water input in the unsaturated zone. In this zone, flow direction can present a horizontal component as interflow, or can vertically percolate to the aquifer (*R*) (Figure 2).

The code allows the water balance to be solved in a multicell pattern by considering the defined zones, assumed homogeneous in relation to soil parameters land use, aquifer and meteorological data. The model simulates the temporal differences (between initial, t_i, and final time, t_f, $\Delta t = t_f - t_i$) of the actual evapotranspiration and groundwater recharge. The model outputs are the water balance components (runoff, interflow, vegetal interception, *ETa*, groundwater recharge) expressed as daily rates. The recharge is estimated according to the assumption of homogeneity and isotropy of soil. In the aquifer, the groundwater level is estimated for each Δt by considering the entry of water by vertical flow. It also allows parameter calibration by comparing between the measured (observations) and estimated groundwater levels. A comprehensive explanation of the conceptual model and its corresponding parameters can be found in Jiménez-Martínez et al. (2010).

3.1.1 | Model setup

The current model requires some input parameters which include: geographical coordinates, daily precipitation and air temperature, vegetation types and spatial distribution, crops and irrigation provisions (i.e., time and volume), maximum root-depth (m), evapotranspiration (mm), physical soil characteristics like thickness (m), porosity (%), saturation (m^3/m^3), field capacity (m^3/m^3), wilting point (m^3/m^3), and vertical hydraulic conductivity (m/day) and Curve Number (*CN*, non-dimensional). The state variable is water volume, expressed as volume per surface unit (e.g., L/m^2 or m^3/m^3) or equivalent height of water (e.g., mm). For instance, the water volume in soil is the product of saturation and soil thickness.

Surface components daily irrigation (*I*) and precipitation (*P*) rates are the main input variables. The water needs of each crop were extracted from Allen et al. (1998). Runoff, *Es*, is estimated from the Curve Number method (Soil Conservation Service, 1975) based on loss and precipitation ratios; the *CN* values, directly selected from the VisualBALAN data base on *CN*s for most general land-cover and hydrologic soil group, and from existing spatial information of topography and vegetation cover in the study area. Interception, *In*, derived from the method of Horton. Daily potential evapotranspiration (*ETp*) was computed by the Thornthwaite method (Thornthwaite & Holzman, 1939), suitable for data scarcity regions because of its very low data demanding character (Yang et al., 2017). Note that potential evapotranspiration estimated with the Thorthwaite formula tend to be short in vegetated arid environments (Tukimat et al., 2012).

Model parameterization uses datasets on topography, land cover and soil type. Soil-aquifer parameters (porosity, hydraulic conductivity, storage coefficient, field capacity, wilting point, soil depth) and plant parameters (height, interception coefficient) complete the system as main inputs. Processes in the saturated zone (aquifer) were not included by assuming that the infiltrated water through the vadose zone reached a depth beyond the action of roots and evaporation, which becomes direct infiltration to the aquifer.

For the model setup, the land surface topography (elevation and slope) was obtained from a 30 × 30 m Digital Elevation Model-DEM (ASTER GDEM 2.0) from NASA Earthdata (GDEM2). The digital elevation model (DEM) is used for slope and elevation. Land use and land physical coverage were supplied by The European Space Centre (ESA, CCI land cover – S2 prototype land cover 20 M map of Africa, 2016). Soil-related information (e.g., clay and silt content, hydrological soil group) was acquired from the European Soil Data Centre (ESDAC), European Commission – Joint Research Centre (Jones et al., 2013) and the literature. Homogeneous loamy sand was considered the main soil type, according to the United Sates Department of Agriculture-USDA Soil Textural Classification (Gaultier, 2004; LCBC-IRD, 2016). Soil-aquifer parameters were obtained from the works of Leblanc (2002), Gaultier (2004) and Zaïri (2008).

Finally, six digital base maps were produced (climate, slope, land cover, cultivated crops, aquifers, soil attributes) and overlaid using GIS tools to create a final base map for recharge calculations by solving the water balance equation in a multicell pattern.

3.2 | Climate datasets

The meteorological data inputs for the period 2005–2014 for the model were the daily air temperature (°C) and precipitation (mm) time series reported from five ground stations in the study region (Diffa, Goure, Maine, Nguigmi, Zinder) and CHADFDM data (satellite-based) for the same locations and period.

3.2.1 | Ground data

Ground-based time series from local meteorological stations were directly compiled from the TAHMO platform (Figure 1). For the historic data record (1973–2018), the study period (2005–2014) was chosen as that presenting the fewest gaps (≤ 20%) in the precipitation and air temperature time series. The 9-year length of the dataset enabled the variability in daily precipitation and air temperature in the region to be captured.

The representativeness of the available dataset included: assessment of missing values, accuracy of measurements (inaccuracy of the amount of precipitation), stationarity and homogeneity (changes to stations, relocation of stations, among others). To complete the missing rainfall data, Inverse Distance Weighting was applied, based on four rain-gauge stations in the vicinity of the analysed station (Lam, 1983). Thiessen Polygon was used to estimate the average rainfall over the area.

3.2.2 | Satellite-based rainfall and air temperature data from the CHADFDM

The Multi-Source Weighted-Ensemble Precipitation (MSWEP v2.1; Beck et al., 2018), a fully global historic precipitation dataset developed by Princeton University, was selected as the source for the satellite-based data, based on the data availability for the region of interest. MSWEP is produced as 3-hourly and monthly data, 0.1-degree, by merging a set of about 12 satellite and reanalysis datasets; 0.1-degree is the highest resolution that is presently supportable from these datasets and is typical of other similar satellite-based datasets that range from about 0.05-degree (e.g., CHIRPS, PERSIANN-CCS) to 0.25-degree (e.g., TMPA). MSWEP provides reliable rainfall estimates by taking advantage of the complementary strengths of gauge, satellite, and reanalysis-based data (Beck et al., 2019). The dataset includes daily gauge corrections, and systematic biases (e.g., from the orographical enhancement of precipitation) are corrected using readily available gauge data observations (about 25 gauges in the Lake Chad Basin) with enough quality (long record, filtered for spurious values, adjusted for reporting times, and no step changes) and by comparing to other satellite-based products (Beck et al., 2018; Beck, van Dijk, et al., 2017; Beck, Vergopolan, et al., 2017). Air temperature data is taken from the Princeton Global Forcing dataset (PGF, Sheffield et al., 2006), which merges satellite, reanalysis and gridded gauge data to produce a 0.25-degree, 3-hourly, global product. Both datasets were downloaded from the CHADFDM.

3.3 | Sensitivity analysis

Knowledge of the model parameters, and their statistical variability and correlation structure, is a key aspect to quantify the effect of uncertainties on recharge estimates according to the used data source to define the boundary condition, that is, ground- or satellite-based. The importance of the parameter uncertainties on recharge can be evaluated as the objective function by a sensitivity analysis (Jiménez-Martínez et al., 2010). To this end, several simulations were run on individual model parameters modified by a given amount of perturbation (±25% of the original value), and by estimating the groundwater recharge for both sources of precipitation and air temperature used to define the boundary condition.

4 | RESULTS

4.1 | Ground- versus satellite-based datasets

For the selected 2005–2014 time period, three of the five ground-based stations (Figure 1; Nguigmi, Zinder and Maine) had complete daily air temperature and precipitation records, while Goure and Diffa presented 3.3% and 2.5% missing precipitation values, respectively. Occasionally, one station can have higher precipitation values than nearby stations for one particular year when most annual amounts fall during one rainfall event or two.

On a daily scale, the rainfall measured at the five meteorological ground stations presented less variability in the recorded amount than the satellite-based data at the same locations (Earth coordinates) (Figure 3). The maximum rainfall occurs during the June–October period, with the values recorded at gauges being the highest. For the 2005–2014 period (Table 1), the satellite-based mean annual precipitation (417 mm) was 46% higher than the ground observations (284 mm). However, the air temperature values for both time series (TAHMO and satellite) well agreed, and ranged between 15°C and 40°C (average 29°C).

At the monthly scale, the satellite data generally overestimated the amount of ground-based precipitation (Figure 4), except for the two heavy (extreme) rain events recorded at the Diffa (August 2008: 440 mm) and Zinder (August 2011: 411 mm) weather stations. A similar effect, but with generally higher values for satellite records compared to the ground data, have been reported by some authors (McCollum et al., 1999; Mehran & AghaKouchak, 2013; Nogueira et al., 2018; Young et al., 2014).

Between the ground- (gauged) and satellite-based data sources, annual rainfall varies according to location, and wet and dry condition distribution appears to be different (Figure 5(a),(b)). The wettest and driest years of the period took place in 2008 (600 mm) and 2006 (10 mm) for the ground data, and in 2006 (920 mm) and 2011 (200 mm) for the satellite data, respectively. An inspection of the cumulative deviation of precipitation from the mean (Figure 5(c),(d)) revealed no significant trend on the annual scale.

For the months with continuous rainfall (July to September), the ground-based rainfall versus satellite-based, average daily data and average monthly data, are plotted in Figure 6. On a daily basis, the ground and satellite rainfall data relation analysis (Figure 6(a)) did not present any correlation ($R^2 = 0.06$) between datasets; a poor regression fit may arise from high scatter in data by considering all the recorded values throughout the hydrologic year. By arranging datasets

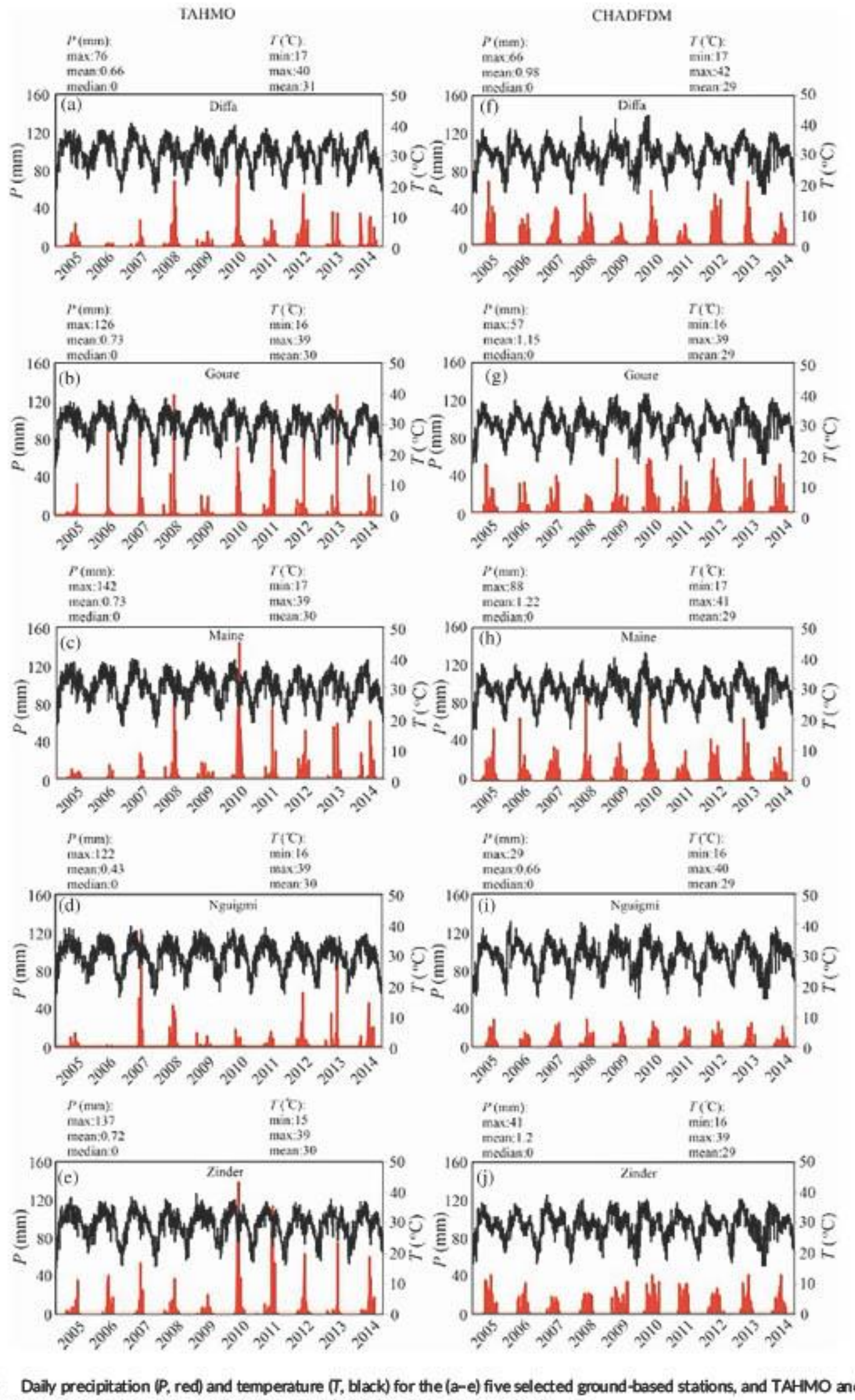

FIGURE 3 Daily precipitation (*P*, red) and temperature (*T*, black) for the (a–e) five selected ground-based stations, and TAHMO and (f–j) CHADFMD outputs at the same earth coordinate locations (rainfall and temperature data)

TABLE 1 Annual (mm/yr) and total recharge (*R*, mm) estimates for the study period (2005–2014) from the ground-based stations (TAHMO) and CHADFDM (satellite-based data) in the irrigated and non-irrigated areas. *P* denotes precipitation and *ET*a evapotranspiration

Data source	Total *P* (mm)	Average *P* (mm/yr)	Total *ET*a (mm)	Average *ET*a (mm/yr)	Total *R* Non-irrigated (mm)	Average *R* Non-irrigated (mm/yr)	Total *R* irrigated (mm)	Average *R* Irrigated (mm/yr)
Ground	2555	283.9	2244	250	90.8	10.0	302.1	33.5
Satellite	3754	417.1	3363	375	132.7	14.7	374.4	41.6
% of ground gauges	+46	+46	+33	+33	+46	+46	+23	+23

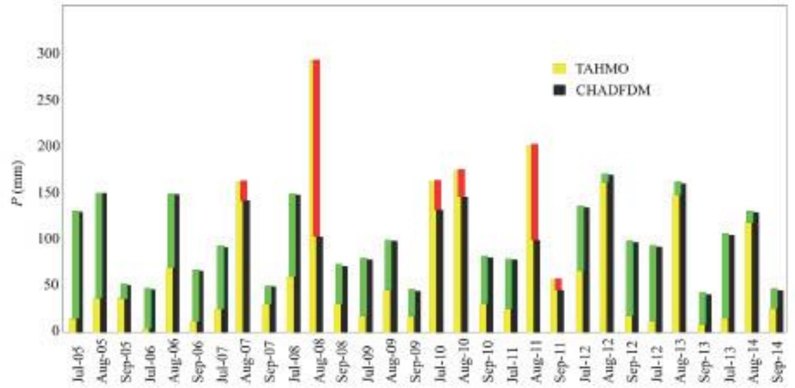

FIGURE 4 Monthly average precipitation (mm) from both ground-based stations and satellite-based data at the same locations (earth coordinates). Red bars indicate months with higher TAHMO values than CHADFDM ones. Green bars depict the opposite

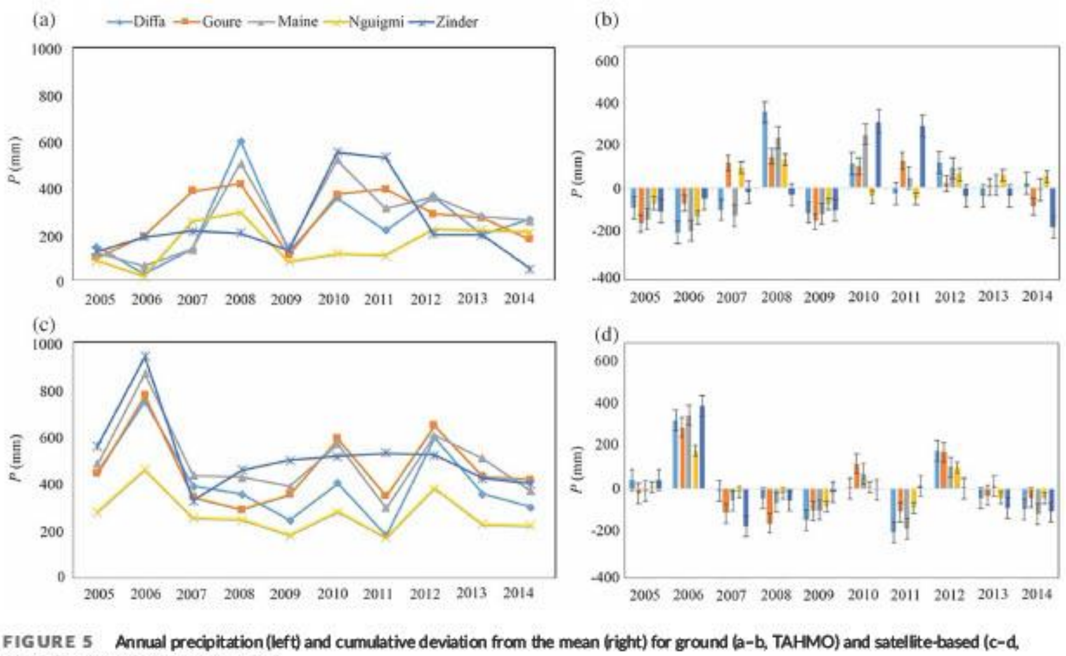

FIGURE 5 Annual precipitation (left) and cumulative deviation from the mean (right) for ground (a–b, TAHMO) and satellite-based (c–d, CHADFDM) data (2005–2014 period)

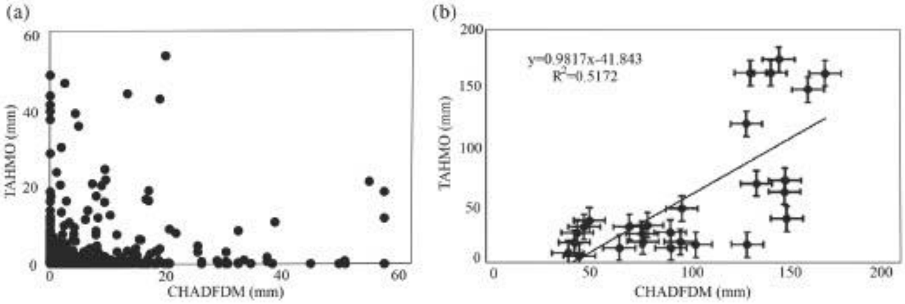

FIGURE 6 Rainfall data, ground (TAHMO) versus satellite (CHADFDM): (a) average daily data; (b) average monthly data for months with continuous rainfall (July to September)

from daily to monthly scales (change in time interval), and by focusing on months with high precipitation (July–August–September), scatter reduced, while the correlation increased ($R^2 = 0.51$). The data aggregation clearly smooths out the differences between both data sources. Moreover, it was noted that the performance of the products is largely scale and geographic location dependent. Most of the presently applied products showed comparatively good skills on the seasonal scale ($R^2 > 0.90$) rather than at annual scale (Atiah et al., 2020). This indicates that satellite data should be improved taking into account the type of precipitation (i.e., intensity), and for that a minimum of daily resolution is required.

4.2 | Recharge estimation

Two groundwater recharge types were assessed in the study area: (i) from precipitation; (ii) resulting from the precipitation and irrigation combination in irrigated areas. Calculated daily recharge and real evapotranspiration for irrigated areas and the study duration (2005–2014) are shown in Figure 7 from both ground-based stations and satellite results. The estimated mean annual recharge from precipitation equalled 10 mm/yr and 14.7 mm/yr for the ground- and satellite-based data, respectively (Table 1). Differences were marked in extremely dry and wet years, such as 2006 (9 and 20 mm/yr for the ground- and satellite-based data, respectively) and 2008 (15 and 12 mm/yr for the ground- and satellite-based data, respectively). The computed mean annual aquifer recharge in the irrigated areas ($P + I$) was 33.5 mm/yr and 41.6 mm/yr for the ground- and satellite-based data, respectively.

To better assess the recharge process, a daily recharge estimation in the area for the non-irrigated and irrigated areas, and from the two P and T datasets, was calculated for 2012 (Figure 8). Year selection was based on data availability, smallest gaps and amount of precipitation (282 mm), similarly to the average precipitation for all whole 2005–2014 period. In both the non-irrigated and irrigated areas, recharge takes place mainly during the wet season, between June and October. Recharge response to rainfall events was most variable (Figure 8(a),(b)), and somewhat independent of the amount of rainfall and changes over time, but was strongly conditioned by antecedent soil moisture condition, and highly dependent on precipitation distribution over both time and space. For the ground-based calculations, recharge only occurred after one important rainfall episode (more than 100 mm on 2 days, Figure 8(a)) with a peak after 3 days of continuous rainfall. Groundwater recharge differs spatially as a result of climatic and physical characteristics including precipitation pattern, soil type, porosity of vadose zone, depth to groundwater and hydrogeology. In arid and semiarid environments, groundwater recharge appears to occur during intense precipitation events as compared to other environments described as having a mix of constant-rate and episodic behaviours and often conditioned by preferential flow (De Vries & Simmers, 2002).

4.3 | Sensitivity analysis

A series of simulations were performed by perturbing (were multiplied by 10%, 15%, 20% and 25% test-factors, from −25% to +25% in magnitude) the model parameters. The test included: field capacity, wilting point, soil thickness, soil porosity, soil hydraulic conductivity, curve number and initial conditions (initial soil water content) to evaluate the impact on aquifer recharge estimates. The model was run repeatedly changing each test-factor to evaluate the impact on aquifer recharge estimates by relative change in each input parameter.

For the loamy sand soil in the area, the initially considered parameters were: field capacity, 0.1 (m^3/m^3); wilting point 0.05 (m^3/m^3); soil thickness, 6 m; soil total porosity, 0.42; soil hydraulic conductivity 2×10^{-5} (m/s); curve number (CN), 77. The boundary conditions (temperature, precipitation, irrigation) were left at the baseline values. Then the effect of perturbations on estimated aquifer recharge in relation to the baseline estimation was evaluated (Figure 9).

The results showed for both the ground- and satellite-based data that only the changes or uncertainties in field capacity, wilting point, and curve number led to significant changes in the aquifer recharge estimations (Figure 9). A 25% increase in wilting point led to a 1.6%

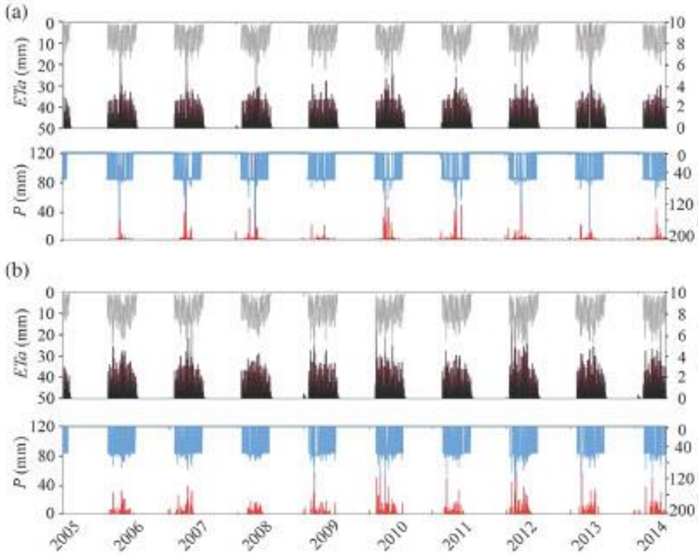

FIGURE 7 Calculated daily recharge (*R*, black) and actual evapotranspiration (*ETa*, grey) for irrigated areas and the study period (2005–2014) from the (a) ground-based stations and (b) satellite-based data. Daily precipitation (*P*, red) and irrigation (*Ir*, blue) are also shown. The irrigation applied according to crop water needs and data provided for the study area

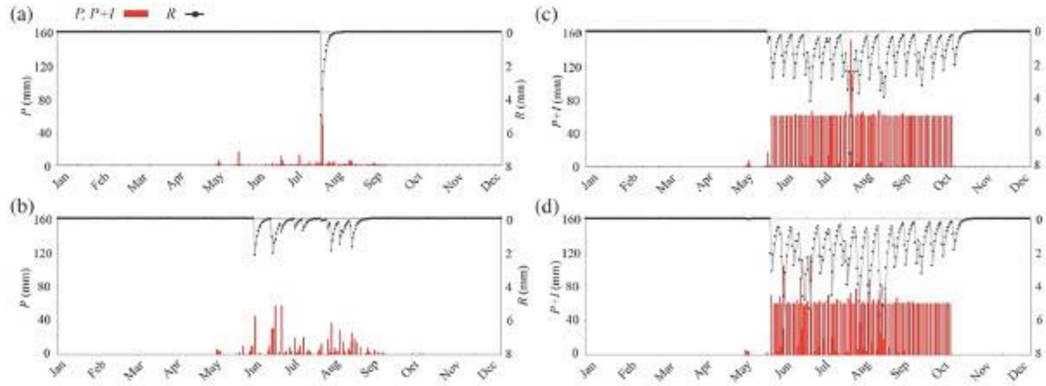

FIGURE 8 Computed daily recharge (mm) for the non-irrigated (a, b) and irrigated (c, d) areas for 2012 from the ground-based stations (upper row) and satellite-based data (lower row)

increase in recharge for the ground and 4.4% for the satellite data. The perturbation of the curve number resulted in a different magnitude of recharge and differed depending on the magnitude of the perturbation between the ground-based stations and satellite-based data. Changes in porosity (soil thickness and hydraulic conductivity; neither is shown here) had a much less impact on computed recharge.

5 | DISCUSSION

Climate forcing functions (precipitation and temperature, important system driving forces), soil and vegetation variables availability and the non-linearity of recharge processes are the most important obstacles for recharge estimations in arid and semiarid areas, where they predominantly concentrated in the short term.

The comparison between the two rainfall dataset sources (ground and satellite) showed that a bigger amount of precipitation and a relatively time-homogeneous precipitation distribution occurred from the satellite data source in relation to the ground data. Satellite derived data estimates may provide uncertain rates even when they contain information on spatial patterns and relative spatial distributions (Lucas et al., 2015). One explanation could be accounting for cloud microphysical processes (liquid water content, effective radius, and radar reflectivity) in the satellite-based data, and the moisture distribution

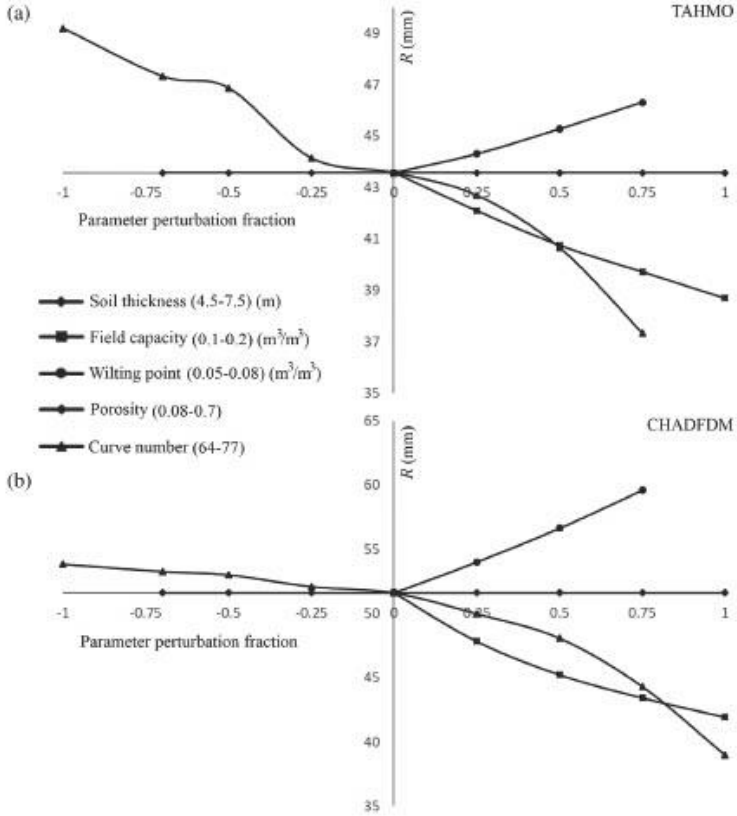

FIGURE 9 Irrigated area. Sensitivity analysis of aquifer recharge to the soil parameters for the ground-TAHMO (a) and satellite-based-CHADFDM (b) data. The numbers in brackets are the range of variation for parameters

of the environment (Gao et al., 2014; McCollum et al., 1999). In particular, the overestimation by infrared-based satellite retrieval algorithms (which contribute to MSWEP) was attributed to rainless cirrus with a cold cloud-top temperature (Young et al., 2014). For the ground-based data, misleading results cannot be ruled out due to possible changes in observation practices, equipment, and location. Systematic biases are possible in rain gauge-based gridded precipitation products. Wind-induced precipitation under gauge catchment, evaporation losses and wetting losses are examples of estimation biases. In general, the bias due to wind-induced precipitation under catchment is the most important (Masuda et al., 2019). The air temperature from satellite and field observations presented a high degree of similarity.

The annual and total recharges (dryland) estimated on the daily scale by VisualBALAN from the satellite data were 46% higher than the results obtained from ground stations. As expected, the highest rates for the recharge from the satellite-based data were primarily due to more abundant precipitation, while the amount of evapotranspiration was similar, which resulted in much more readily available water to infiltrate. Nevertheless, owing to the episodic aspect of recharge in arid areas, small changes in precipitation rate may affect groundwater recharge (Thomas et al., 2016), besides in non-vegetated areas vapour diffusion in the soil may overcome plant root transpiration. An attempt of recharge estimation after bias-correction of CHADFDM precipitation data set (only one gauge station,Supplementary material) shows that obtained result is 9% greater than the obtained from ground-based data, for Diffa location. As regards the annual ground-based recharge results (Table 1), values ranging between 15 mm/yr and 50 mm/yr have been obtained by other authors who worked in this area (Edmunds et al., 1998; Leblanc, 2002; Ngounou Ngatcha, Mudry, & Sarrot-Reynauld, 2007) mainly based on isotopic and numerical methods. Between 5% and 10% of the rainfall by Leduc and Desconnets (1994), and also from running the numerical groundwater flow model of the Basin for the same time period (WB, 2020). The data also agree with the aquifer recharge estimations (1–30% of precipitation) in arid and semiarid regions worldwide (Carter et al., 1994; de Vries et al., 2000) as found 14.89% and 13.53% of the rainfall in Brazil (Coelho et al., 2017), 10.8% of total rainfall in Iran (Ebrahimi et al., 2016).

In the irrigated areas, with irrigation applied to account for 5000 mm/yr, while the precipitation from the ground- and satellite-based data remained invariant (Table 1), the recharge difference from both datasets was ~23%, which was much lower than between the precipitation values (46%), a finding that evidences the non-linearity of recharge processes. Although precipitation from the satellite-based data, and therefore $P + I$, were higher, the actual evapotranspiration was almost double compared to the values computed from the ground data (Figure 7; *ETa*, grey). A detailed observation of the process that controlled recharge indicated that most important parameters were irrigation dose and application frequency (Figure 8(c),(d)). Cyclical variability was also observed as a response of irrigation application. The effect of rainfall events was less influential in irrigated than on the - non-irrigated areas.

Previous studies conducted in irrigated zones for semiarid climates have shown that irrigation return can vary between 1% and 25% of the applied water, with an average of ~15% (Scanlon et al., 2006). The values herein obtained fell within this range (1–13%). Genthon et al. (2015) have also demonstrated that this recharge was supposed to take place during the irrigation cycles. The effect of irrigation methods on groundwater recharge is critical and generally under the water conservation methods, only after a very significant rainfall occurrence deep drainage contributing to groundwater recharge occurs (Porhemmat et al., 2018). Under water-saving irrigation systems in arid and semiarid zones, the absence of significant rainfall occurrences between irrigations reduced recharge (Jiménez-Martínez et al., 2010).

Sensitivity analysis identified the effects of different input parameters helping to elucidate potential uncertainties on obtained recharge. Wilting point and field capacity are key parameters of water holding capacity and depending on soil texture. Spatial variability of soil texture (sands or clay-silt soil type) would imply different recharge rates areal distribution. Although changes in the mean annual recharge due to perturbations in wilting point and field capacity were linear and quasi-linear, showing positive and negative slope as perturbation increases, respectively, magnitude was not the same for the ground stations and satellite-based data. Curve number, for runoff estimation, exhibited different behaviour for both data source; recharge dependence on *CN* was higher for the ground-based data characterized by wider precipitation variability and the existence of rainfall events. The Curve Number equation empirically describes the runoff amount from a rainfall event and potential soil water retention. It is based on data collection from different sites, and published values can only approximate actual runoff conditions at field sites being the *CN* appropriate for use at watershed scale (Westenbroek et al., 2018). In the area, gauged watersheds do not exist and field data measurement are not available for runoff validation.

Uncertainties from input datasets could affect model final results. Lack of groundwater level observations in the area to assess the relation between the simulated aquifer recharge and observed groundwater levels did not allowed for model calibration and model performance assessments. Nevertheless, as the vegetation and soil-aquifer parameters remained invariant to run the model independently of the data base, recharge dependence relied on mainly climate parameters (*P* and *T*) and related soil water conditions. Therefore, the obtained results did not invalidate the findings.

6 | CONCLUSIONS

Reliable aquifer recharge estimations are crucial for assessing and managing groundwater resources, and their role will become even more important if further climate change and variability impacts restrain increasing demand. Since groundwater is one of the key sources of irrigation in arid and semiarid regions, the recharge estimation is also crucial for ensuring future groundwater supply and usage.

Climate, vegetation and soil-related parameters are the most important parameters to condition groundwater recharge. Precise ground-based daily data on amount of precipitation and temperature are difficult to obtain in some areas, while remote sensing data sources can provide continuous estimates of these variables. However, the differences in precipitation rates and rainfall distribution, and therefore on recharge estimates, between weighted-ensemble satellite-based data and ground-based data indicate that a comparative analysis is needed to establish a range of possible real values; beyond the uncertainty related to the considered model parameters, it may provide initial estimations for groundwater numerical modelling, among other applications.

For the Lake Chad aquifer system, one of the largest aquifers of the world, groundwater has a significant importance as a source for water supply and irrigation, especially in the northern part. For the basin-wide, diffuse recharge of aquifer system from precipitation is the main water source and it mainly takes place on southern margins and in the dune systems. Estimates for the Basin ranges between 0% and 13% of total precipitation (WB, 2020), with important spatial variability. Assessment of the groundwater renewal and vulnerability of the system involves recharge quantification from rainfall to the groundwater system. At regional level, the field data scarcity from unevenly distributed weather ground-based stations, its availability and possible related uncertainties to measured series, make the information from satellite products a useful data source for recharge estimation. As accurate assessment of recharge is limited by uncertainties derived from satellite data in a wide dry region where rainfall is localized and sporadic, development of user-friendly platforms providing relatively wide range of improved observations may constrain associated uncertainty.

In the semiarid Lake Chad Basin part, the analysis focused on understanding how different data sources could affect the amount of recharge because of the highly non-linear behaviour of the recharge process through soil. Aquifer recharge concentrates predominantly during short periods of time (rainy season from June to October) and is controlled mainly by climate factors such as precipitation, evapotranspiration and the few intense rainfall events, together with applied irrigation in agricultural areas. More precipitation does not necessarily imply a proportional increase in recharge as the actual evapotranspiration rate would also rise. As agricultural irrigation is generally carried out from surface water, implying more water availability from an external source, the obtained amount would reflect the combined effect (from dryland recharge plus irrigation return flow). Note that in those areas where water depth was close to the ground, the surface water table could also provide an additional source of water for evapotranspiration. As recharge very much depends on changes in the soil moisture condition over time, the almost uniform rainfall distribution with time from satellites also implies computing higher soil water content and a bigger amount of recharge.

In the Lake Chad Basin region and in other arid zones, where groundwater is the main water resource, accurate recharge estimates are essential for the knowledge of system hydrologic dynamics (input–output) and water availability. Also it is essential for establishing guiding planning and policy water management and ecosystems protection for sustainable long-term water resources management. A better understanding of recharge mechanisms will enormously contribute to the sustainability of groundwater exploitation rates across the basin. This fact is especially important if future land use changes and new agricultural developments require increased surface water and groundwater withdrawal.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

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Paper 2. The Lake Chad transboundary aquifer. Estimation of groundwater fluxes through international borders from regional numerical modeling

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

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ABSTRACT

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

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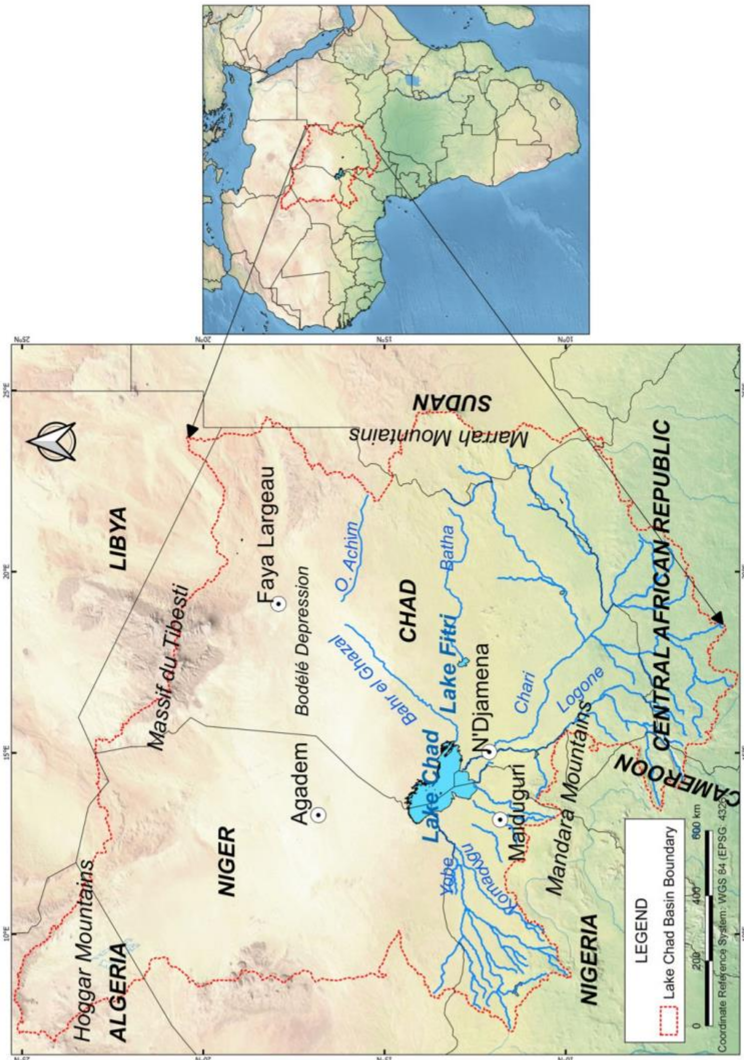

Fig. 1. The Lake Chad Hydrologic Basin (BGR-LCBC, 2009). Present day Lake Chad boundary.

1. Introduction

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

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

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

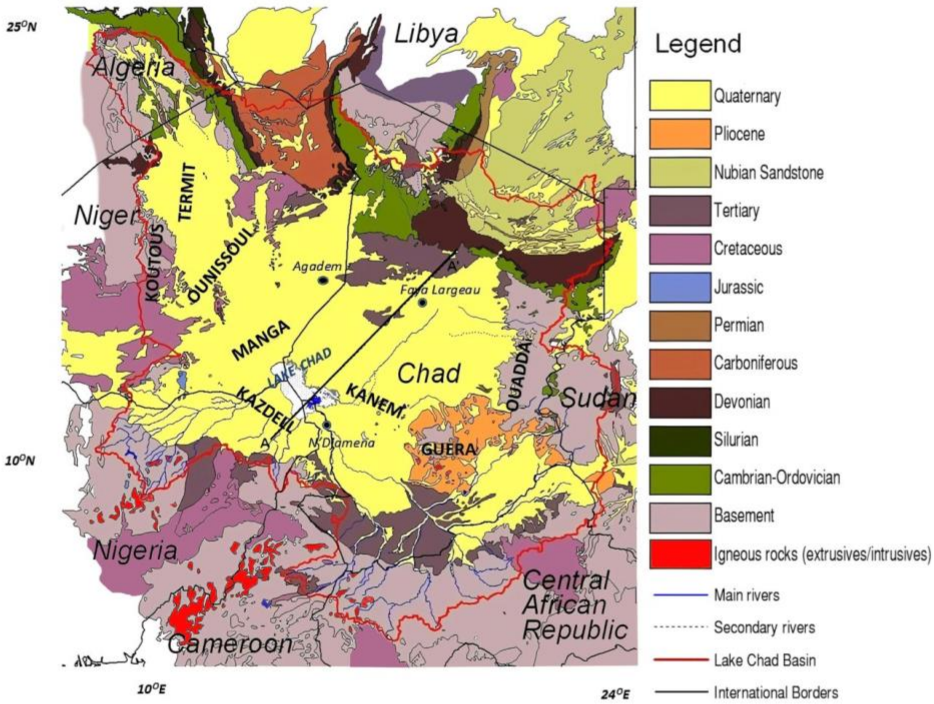

Fig. 2. The red line indicates the Lake Chad Hydrologic Basin limits. Geology of the basin area; geological formations and age (modified from Schneider, 1989; BGR-LCBC, 2009).

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

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

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

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

2. Study area. The Lake Chad transboundary aquifer

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

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

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

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

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

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

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

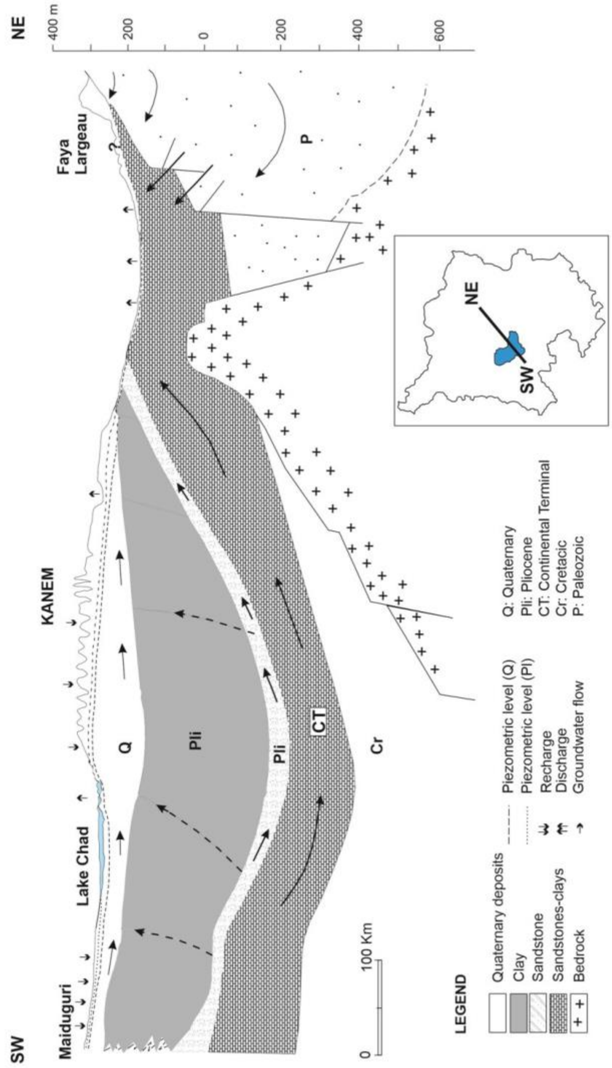

Fig. 3. Cross-section of the basin (after Schneider, 1989). See inset map and Fig. 2 for location.

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

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

2.1. Groundwater hydrology

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

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

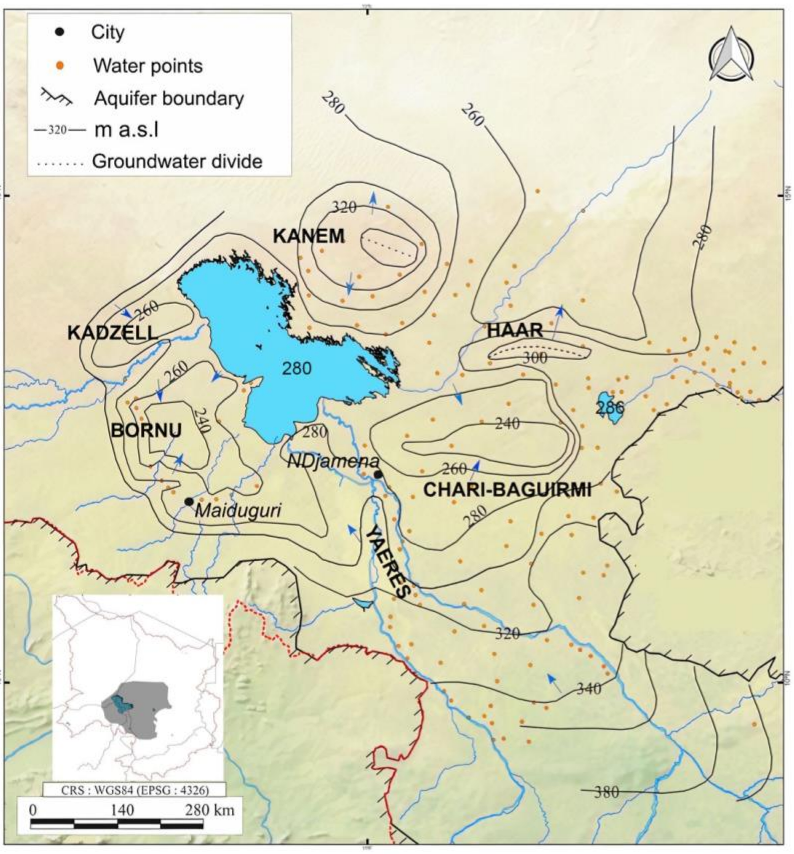

Fig. 4. Upper aquifer potentiometric surface (2008–2011); major rivers within the aquifer boundaries are shown (blue line). Lake Chad reference level 280 m. The inset map (bottom left) shows the location of piezometric map coverage in the Lake Chad Basin areal extension.

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

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

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

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

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

2.2. The conceptual hydrogeological model

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

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

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

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

Table 1

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

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

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

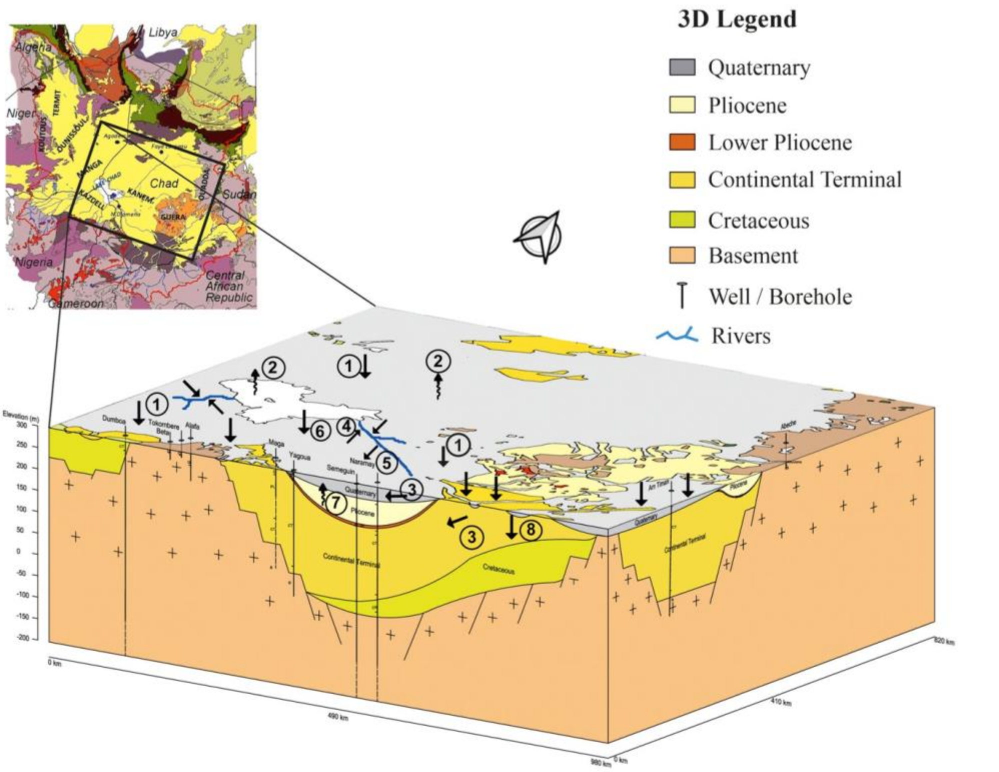

Fig. 5. Input-output hydrologic processes in the aquifer basin. 1) Natural recharge; 2) Evapotranspiration; 3) Groundwater inflow; 4) Recharge from rivers; 5) Discharge from rivers; 6) Recharge from Lake; 7) Upflow from deep aquifers; 8) Vertical recharge from shallower aquifers to deeper ones. Major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

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

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

3. Methodology

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

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

3.1. Data source and tools

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

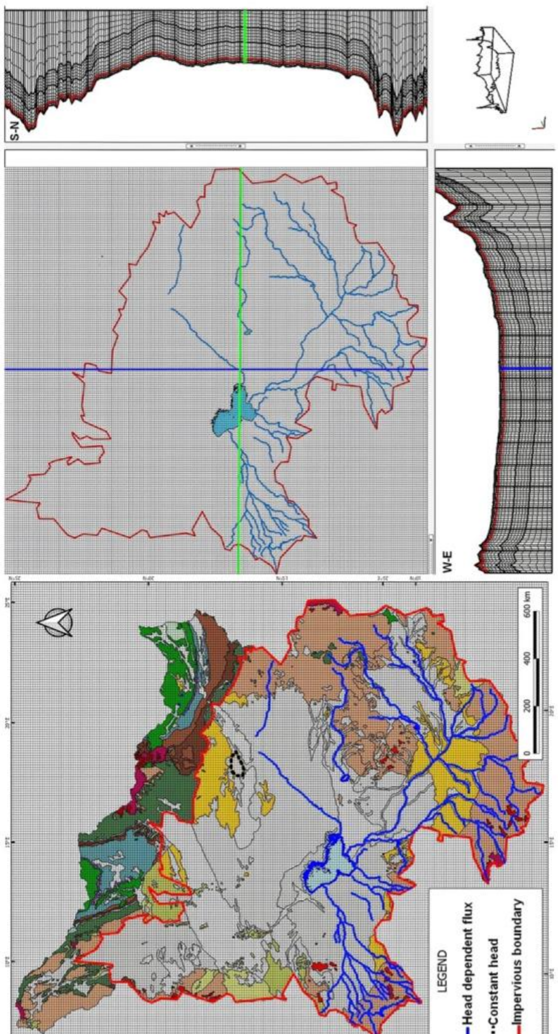

Fig. 6. Model domain, finite differences mesh and vertical layer definition cross-sections (output from MODFLOW).

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

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

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

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

3.1.1. Applied tools

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

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

3.2. Groundwater modeling

3.2.1. Regional model definition/modeling approach

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

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

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

Layer 1: Unconfined, five sublayers, 8 m thick (40 m total thickness).

Layer 2: Confined/unconfined, five sublayers, 30 m thick (150 m total thickness).

Layer 3: Confined, five sublayers, 28 m thick (140 m total thickness).

Layer 4: Confined, five sublayers, 40 m thick (200 m total thickness).

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

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

3.2.2. The initial and boundary conditions

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

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

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

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

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

3.2.3. Hydraulic parameters

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

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

3.2.4. Model calibration and sensitivity analysis

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

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

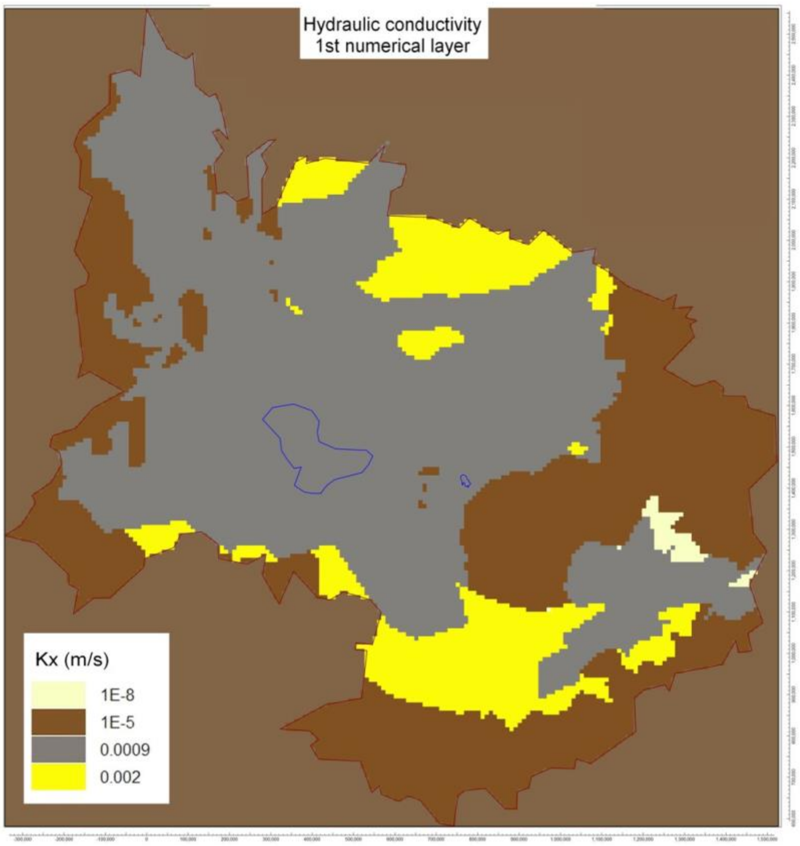

Fig. 7. Initial hydraulic conductivity values distribution (k, m/s) for the top numerical layer (unconfined top layer).

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

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

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

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

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

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

where O_i is the measured head at n locations, p_i is the predicted value and O_m is the observations mean.

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

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

3.3. Transboundary simulation

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

4. Results and discussion

4.1. Regional model

4.1.1. Model calibration

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

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

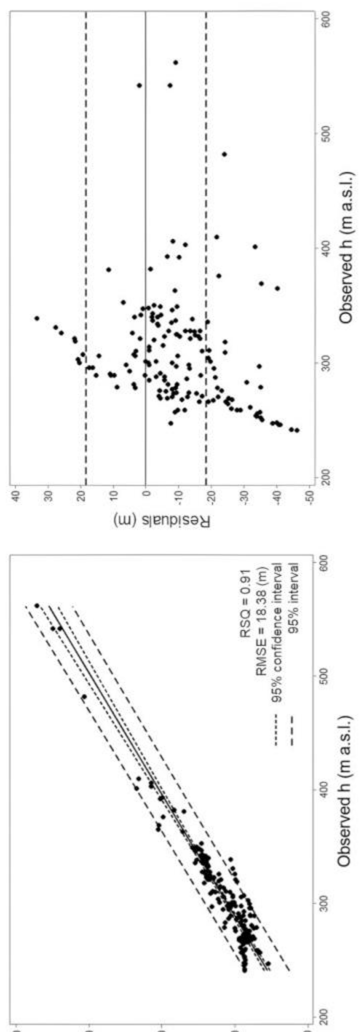

Fig. 8. Hydraulic head observations vs. the simulated values by the model (left). Residuals vs. the observed hydraulic head values (right).

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

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

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

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

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

4.1.2. Water balance

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

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

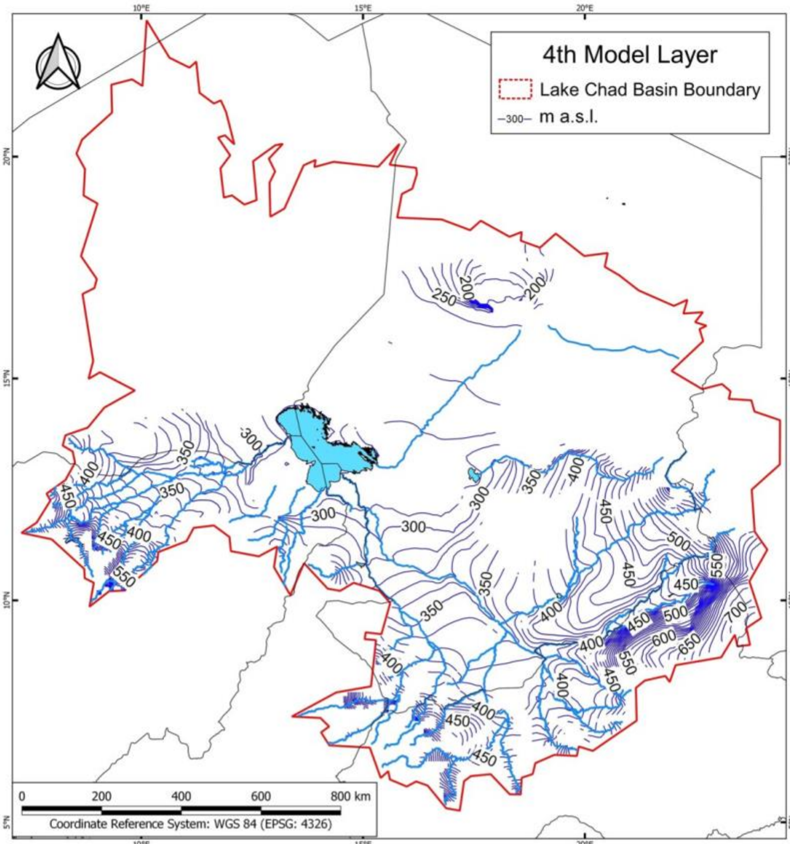

Fig. 9. Upper aquifer. Simulated piezometric level.

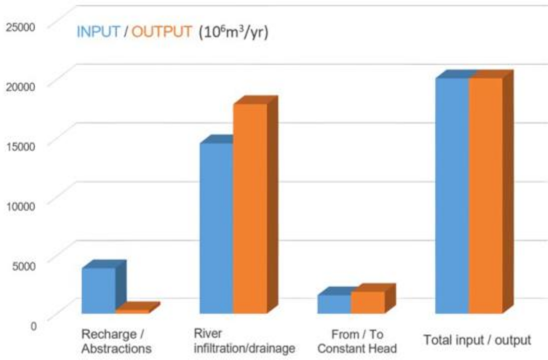

Fig. 10. Groundwater 3D model budget results (10^6 m^3).

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

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

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

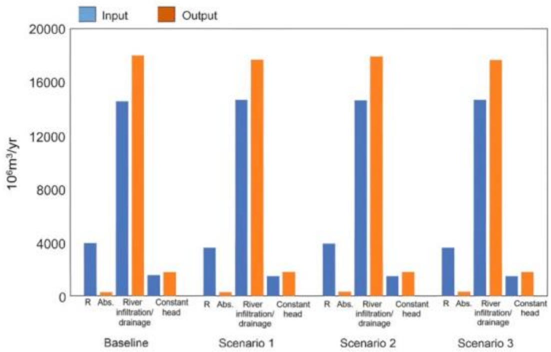

Fig. 11. Average annual water balances in each scenario (R: recharge; Abs: abstraction). Scenarios: 1) 10% recharge reduction; 2) 10% increase in water abstractions; 3) 10% recharge decrease and 10% increase in water abstraction.

4.1.3. Sensitivity analysis

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

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

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

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

4.2. Fluxes to transboundary countries

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

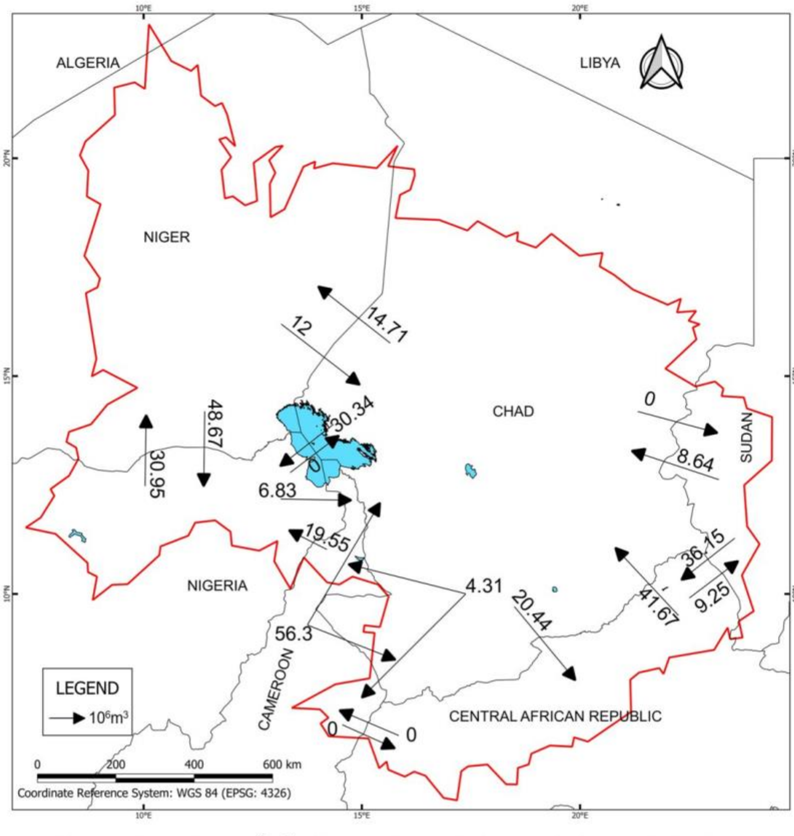

Fig. 12. Modeled groundwater fluxes (10^6 m^3/yr) between the TBA-sharing countries (average for the 2008–2011 period).

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

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

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

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

5. Discussion

5.1. Conceptual model

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

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

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

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

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

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

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

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

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

5.1.1. Modeling for transboundary issues

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

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

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

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

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

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

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

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

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

6. Conclusions

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

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

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

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

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

CRediT authorship contribution statement

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

Declaration of Competing Interest

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

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Appendix A. Supporting information

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

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Paper 3. Modeling vadose zone hydrological processes in naturally-occurring piezometric depressions. The Chari-Baguirmi region, southeastern of the Lake Chad Basin, Republic of Chad.

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Modeling vadose zone hydrological processes in naturally-occurring piezometric depressions. The Chari-Baguirmi region, southeastern of the Lake Chad Basin, Republic of Chad.

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Abstract

The Chari-Baguirmi region, southeastern of the Lake Chad (Africa), has a wide naturally-occurring piezometric depression with values deeper than the expected regional groundwater level. To date, the most widely accepted hypotheses to explain its origin and dynamics are based on lack of rainwater infiltration and exfiltration processes. The code HYDRUS-1D is applied to numerically simulate the hydrological flow processes along the unsaturated zone in two soil profiles located in the central part and on the boundary of this piezometric depression under bare and vegetated soil coverage. The simulated time-period is 2004-2015 with 715 mm annual rainfall average. The computed recharge with respect to total precipitation accounts for 21% on the boundary and 12% in the central part, which is limited by thick silty low permeability layer on the top surface. Considering modelling uncertainty and limitations under the simulated climatic conditions, the rainfall effect is observed only at upper soil layers, which leads to low aquifer recharge, while the upward water flux to condition water table evaporation is very low. Past climate conditions, capable of developing a drying front to reach the water table after thousands of years of drying and geological structural constraints, may explain the current depressed area.

Keywords: Hydrus 1D, vadose zone, piezometric depression, Chari Baguirmi

1. Introduction

Large closed piezometric depressions, manifested by closed curves and depths attaining tens of meters lower than the regional groundwater level, also known as "*hollow aquifers*", are naturally-occurring phenomena in some area of the subSaharan Africa aquifers, i.e.: Senegal (Dieng et al., 1990), Niger (Favreau et al., 2002), Cameroon (Ngounou Ngatcha and Reynault, 2007), Chad (Durand, 1982; Schneider, 1989; Leblanc, 2002; Boronina and Ramilien, 2008; Abderamane et al., 2016) and Mauritania (Lacroix and Semega, 2005).

Different hypotheses about hydrological mechanisms have been proposed to give an explanation on the origins of these depressions: aquifer overexploitation, land subsidence, deep drainage conditioned by geological structures, seawater level changes and/or high evapotranspiration rates (e.g. Durand, 1982, Dieng, et al., 1990). Aranyossy and Ndiaye (1993) suggested that Sahel piezometric depressions occur in areas characterized by low natural recharge due to the outcropping of impervious geological materials where evapotranspiration is not compensated by other water inputs.

In arid and semi-arid areas similar to the study area, a number of methodologies are currently applied to estimate both recharge and soil-water balance and reviews on aquifer recharge quantification have been conducted in the past (Scanlon et al., 2002). Among them, modelling upward and downward transport of tritium with the code SOLVEG was applied in southeastern Spain for natural recharge estimation (Jiménez-Martínez et al., 2012), based on data from vadose zone monitoring. Quantification of diffuse recharge in the Chari-Baguirmi area has been carried out by Salehi Siavashani et al., (2021) from a soil–plant-atmosphere model (VisualBALAN) based on the water balance and with ground and satellite-based meteorological input datasets. At Lake Chad basin level, based on Meteosat thermal findings and numerical modelling Leblanc et al., (2003) conclude that depressions present low rainwater infiltration, as very little precipitation is available for aquifer recharge. Exfiltration or other processes capable of extracting groundwater from the aquifer media founded on isotope data, are a process that has been previously assumed in the area by some authors (Eberschweiler, 1993; Coudrain-Ribstein et al., 1998; Gaultier, 2004; Ngounou Ngatcha and Reynault, 2007). To date, a comprehensive model for the existence of piezometric depressions cannot explain their formation, and the most accepted approach considers negligible recharge (from natural infiltration) due to the scarce presence of permeability materials, along with considerable evapotranspiration rates.

Within the endorheic Lake Chad Basin area, according to Maley (2010) and Armitage et al., (2015) superimposed millennial and centennial rainfall changes have been documented for more than 11.5 kyr (thousand years ago). During the Holocene, the existence of a Mega Chad, with more than 350,000 km^2, and a level rising to 325 m.a.s.l., have been identified by Schuster et al. (2005), among other researchers, to evidence the changes in lake extension over time. Since the last wetter period (6000 AD, Kröpelin et al., 2008), which has led to important groundwater recharge, a significant reduction in rainfall has occurred, which has resulted in the current Lake extension.

In the Quaternary aquifer of the Chad Formation Aquifer System-CFA, extending along all the Basin area (FAO, 1973), naturally-occurring wide piezometric depressions are found in Cameroon (Yaéré), Chad (Bahr El Ghazal, Chari-Baguirmi), Niger (Kadzell) and Nigeria (Bornu). In the Chari-Baguirmi region of Chad Republic, the wide piezometric depression in the eastern part of the Lake Chad Basin presents a groundwater level that is between 40 m and 60 m deeper than expected. Despite its importance, its genesis is not yet known and several hypotheses have been proposed. One is the importance of the evapotranspiration phenomenon in the region, where only a scanty amount of rainwater constitutes aquifer recharge, which is underlined by isotopic data, piezometric studies and mathematical modeling (Eberschweiler, 1993; Schneider, 1989; Leblanc, 2003). Deep groundwater flow drainage (Arad and Kafri, 1975; Abderamane, 2012; Vaquero et al., 2021) is another proposed hydrological mechanism because the flow direction is expected toward the North discharging to the basin’s lowest elevation point (the Lowlands, Bodelé, northern Chad) and apparently, regional groundwater levels lower with time. According to Abderamane et al. (2016), the structural geology of bedrock characterized by horsts and grabens may control the depression genesis, which is favored by the presence of a top thick silt low permeability layer with clay minerals content that impairs high evaporation rates from the groundwater level.

The objective of this research is to investigate the different hydrological processes that take place in the vadose zone of the piezometric depression area based on numerical simulations with HYDRUS, a variable-saturated vadose-zone numerical flow model. Simulation was carried out during the 2005-2014 period in two different areas of the Chari-Baguirmi depression: Bokoro (boundary of the depression) and Amdedoua (center of the depression).

2. Study area

The Chari-Baguirmi region, a broad plain, located in Chad (Africa), on the boundary of the paleo-Chadian basin of the Lake Chad Basin (Figure 1), extends over an area of 45,000 km². Its population is around 621,785 inhabitants. The surface height varies from 200 m to 400 m above sea level. Several kinds of rubber, vine and rice are common vegetal species. Acacia, the doum palm, and *Ziziphus* (spiny shrubs and small trees) species (Mallon et al., 2015) dominate the sparse woody community. *Acacia Tortilis* (umbrella thorn) is a small-medium sized evergreen tree or shrub with high tolerance to strong salinity and seasonal waterlogging and drought-resistant. Acacias generally grow in open dry forests that consist exclusively of acacias (pure acacias stand), or is mixed with other species. This plant develops long lateral roots and a deep taproot system that enable the limited soil moisture existing in arid areas to be obtained (Heuzé and Tran, 2015). During dry season the woody vegetation loses its leaves, and grasses dry up and may burn in winter.

The region lies in the Sudano-Sahelian climatic zone. The hottest months are May and April, and the coldest month is January. The mean annual temperature is 29.5ºC, with a maximum between 34ºC and 43ºC, and a minimum between 17ºC and 23ºC. Three weather stations, Ndjamena, Bokoro, and Bousso, exist in the area (Figure 1). For the 2005-2014 period the average annual rainfall was 700 mm/year (715 mm/year in Bokoro, 890 mm/year in Bousso and 648 mm/year in N'Djamena), (Figure 2). The air humidity range for Bokoro is 12-75%. Most rain falls in summer months from May to September, followed by a 6- to 8-month dry season; extreme events occur during the rainy season. The Harmattan hot dry wind blows from the north, and often bring dust and sand from the Sahara Desert.

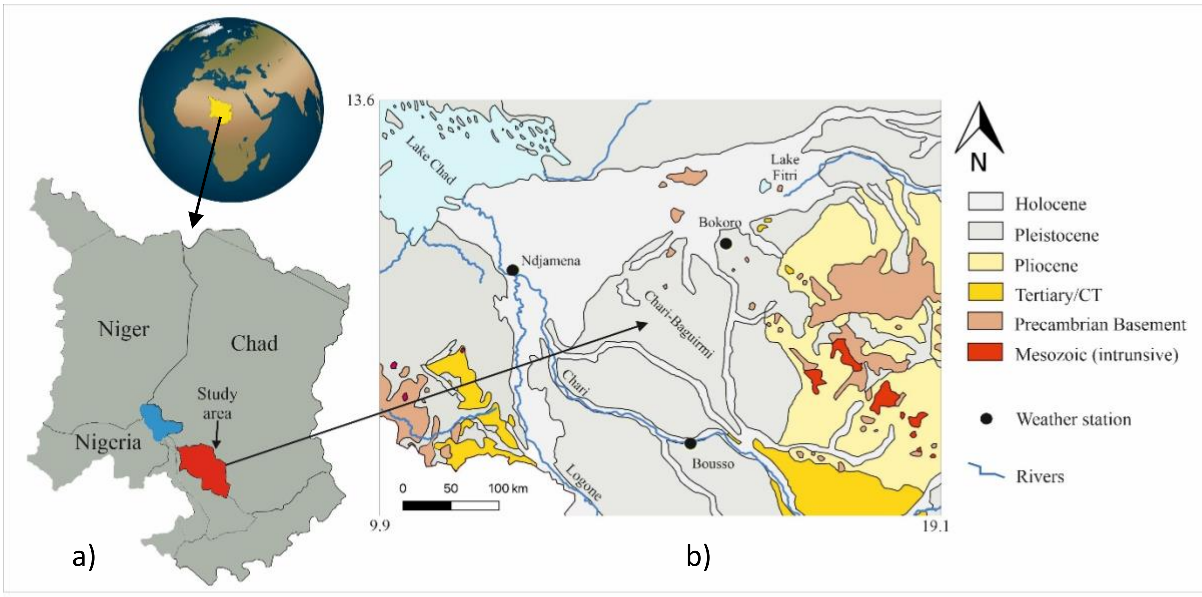

Figure 1. a) The Chari-Baguirmi area (Chad Republic, Africa). b) Geographic location and geological map of the area (modified from Schneider, 1989)

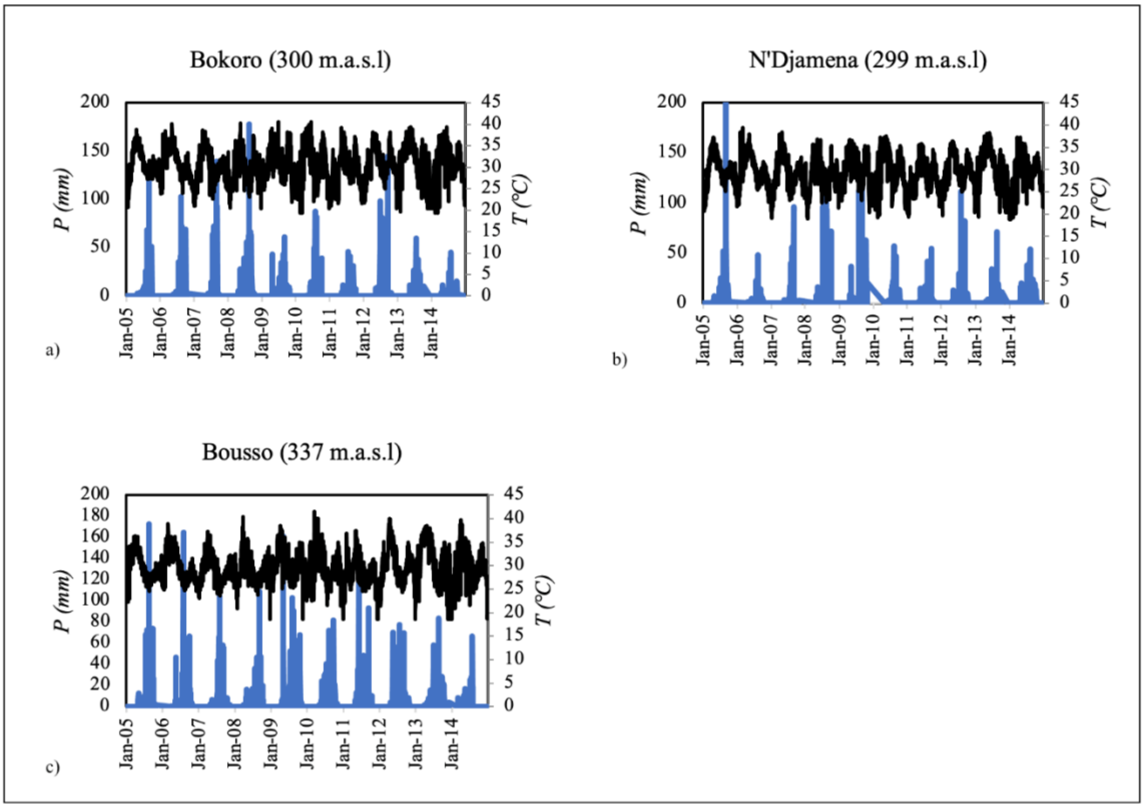

Figure 2. Precipitation (blue bars) and temperature (black line) from the a) Bokoro, b) N'Djamena and c) Bousso weather stations for the 2005-2014 period

According to literature, different geological materials (Figure 1) make up the sedimentary basin and its basement (Genik, 1992; Schneider and Wolf, 1992; Moussa, 2010): to the Northeast and Northwest, the crystalline basement (granite) outcrops (Kusnir, 1995); in the central part, the Pliocene deposits of the paleo-Chadian sedimentary basin cover almost the entire area. The geological composition corresponds to detrital series with sandy clay intercalations and a thick layer of lake sediments with sandy and gypsiferous clays with diatomites intercalations. The overlying Quaternary deposits are composed of sandy-clayey sediments of fluvial, lacustrine, deltaic and eolian origin. They present frequent lateral and vertical changes of facies (Abderamane et al., 2016). Soils are composed mainly of sandy- and clay-rich materials.

The surface hydrology is composed by a channel network of the two main rivers, Chari and Logone, flowing into the lake.

At the Basin level, the aquifer system known as the Chad Formation Aquifer System-CFA (FAO, 1973) is the main source of freshwater. From the hydraulic point of view, an upper unconfined aquifer of Quaternary age and a deeper confined-unconfined aquifer of the Lower Pliocene and the Continental Terminal are defined (Supplementary material). The connection between the upper and lower multilayer aquifers in almost the whole area is conditioned by the clay impervious layers of the Upper Pliocene. However, they are hydraulically connected in the basin's southern area where the deeper aquifer outcrops. According to Maley, (2010) and Abderamane (2012) the current groundwater level of the Basin upper aquifer (Quaternary) is the consequence of a groundwater level drop from the aquifer replenishment time during last pluvial Holocene period (around 6000 years ago).

At Chari-Baguirmi, the upper aquifer groundwater level is characterized by a wide piezometric depression of 17,761 km², which extends from the border of the Lake to Bokoro (see Figure 3). The groundwater depth ranges from a few meters in the lowland area close to the Lake Chad to around 50 m in the central part of the depression (Abderamane et al., 2016; Leblanc, 2002). From a hydrochemical point of view, groundwater presents stratification: it has a calcium bicarbonate type at a shallow level, but in deeper groundwater, it is sodium carbonate-type water. According to Abderramane et al. (2013), the origin of the different groundwater salinities, with chloride concentration between 0.2 and 9 meq/L, is related to lithology, and also to the mixing of waters from the recharge areas near the Lake and the eastern bedrock. In the piezometric depression, the δO^{18} isotopic composition is -8‰ and -0.12‰, with the lowest values in the central part. This process has led to a mixture of water recharged near the lake and in the eastern part, with different isotopic signatures flowing through the aquifer to the central part of the depression (Abderramane et al., 2013).

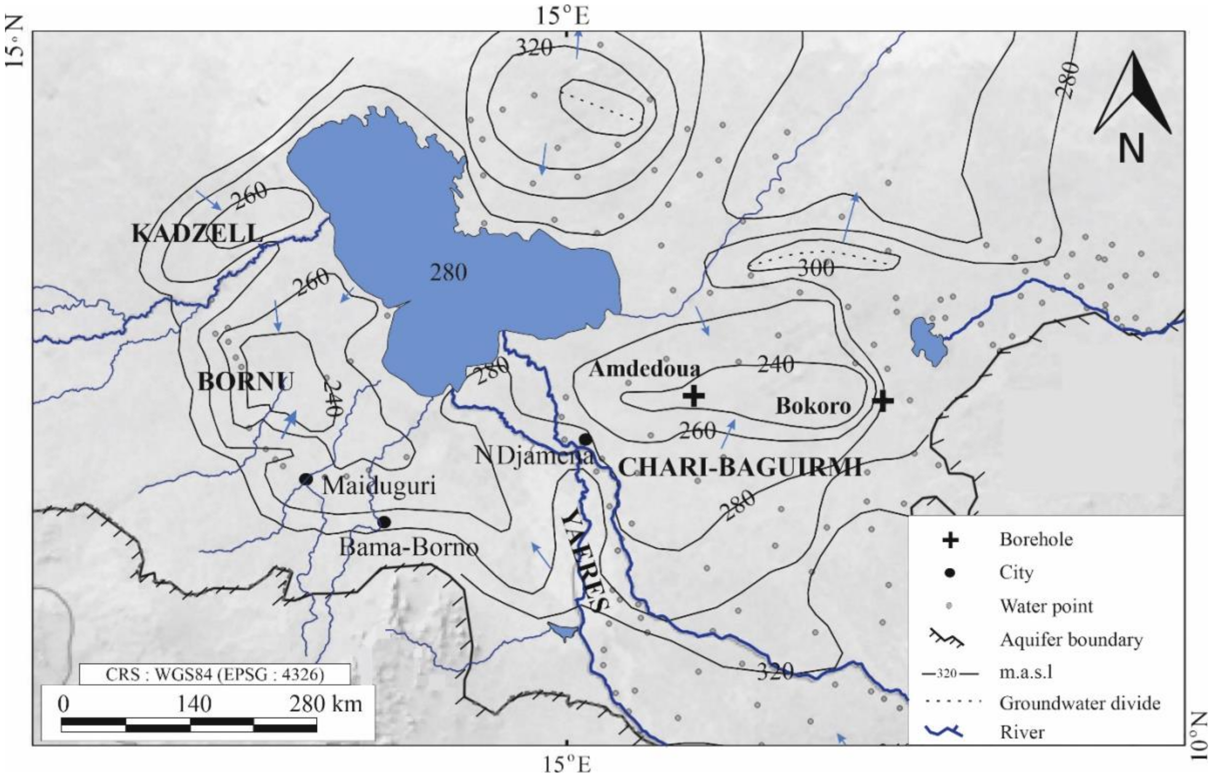

Figure 3. Piezometric map (2008-2011) of the Chad Formation upper aquifer showing the Chari-Baguirmi depression and other existing depressions (after Vaquero et al., 2021).

3. Materials and methods

For the selected period (2005-2014), two sites with existing lithological logs were considered for the simulation (Figure 3, Figure 4b). One is located in the central part of the depression (Amdedoua) and one on the eastern boundary of the aquifer and depression (Bokoro).

To simulate the hydrologic processes taking place in the entire unsaturated zone, the Hydrus-1D (Simunek et al., 2015) code was applied for the 2005-2014 time period (3651 days). Simulation of the water balance components for both sites included the running numerical model for bare soil conditions, as well as the *Acacia Tortilis* land cover to assess changes driven by plants.

To obtain a better knowledge of the soil water fluxes process, a last run with no precipitation was included by considering the existing setup to provide further information. To estimate the hydrological processes along the soil profile, several monitoring points were set up at different depths of both the available geological logs (Bokoro and Amdedoua, Figure 4) following code capabilities.

To identify the parameters that have or do not have a significant impact on the model simulation of real-world observations, and to assess the relevance of the uncertainty parameters on recharge (Jiménez-Martínez et al., 2010), a sensitivity analysis was performed.

3.1. Modeling the unsaturated zone. Numerical model

For the simulation of the one-dimensional water flow through the vadose zone, the HYDRUS-1D was selected; as presence of desiccation cracks has not been documented double porosity/permeability system was not considered. This well-known numerical model implemented in many different regions allows for water flow, heat and solute calculations in variably saturated porous media. The principles, main features and detailed presentation of model are given in Simunek et al. (2015).

In the current code, water flow, vapor flow, heat transport and root water absorption are simulated under saturated and unsaturated conditions in a water-soil-plant system based on a gridded soil profile distribution. HYDRUS input includes: geometric data, climatic data (precipitation, potential evapotranspiration), soil hydraulic properties, geological profile (layers setting) and vegetation parameters. The model also allows for up to six observation nodes definition along depth for which the values of the pressure head, water content, temperature and carbon dioxide are calculated and saved at each running time level. Outputs are evapotranspiration from soil and plants, the water flux along the top and bottom boundaries, and the soil water content and soil pressure head in the profile for each time step.

3.2.1 Governing equations

The Darcy-Richards equation is the governing equation for water flow. The Richards equation (Richards, 1931) in the one-dimensional mode is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K(\theta)\left(\frac{\partial h}{\partial x} + \cos\beta\right)\right] - S \qquad (1)$$

where θ is the volumetric soil water content, h is the soil matrix pressure head (L), S is the water uptake by roots ($L^3\ L^{-3}\ T^{-1}$), $K(\theta)$ is the unsaturated hydraulic conductivity ($L\ T^{-1}$) as function of θ, β is the angle between the flow direction and the vertical axis, x is distance (L) and t is time (T). The relationships between saturated and unsaturated hydraulic conductivity are defined by:

$$K(h,x) = K_s(x) \cdot K_r(h,x) \tag{2}$$

where K_r is the relative hydraulic conductivity (dimensionless) and K_s is the saturated hydraulic conductivity ($L\ T^{-1}$). HYDRUS solves the equation using a linear finite elements pattern.

The equation for unsaturated hydraulic conductivity, based on soil-water retention parameters, is obtained from the soil-hydraulic functions of van Genuchten (1980) and the statistical pore-size distribution model of Mualem (1976):

$$\theta(h) = \begin{Bmatrix} \theta_r + \frac{\theta_s - \theta_r}{[l + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{Bmatrix} \tag{3}$$

$$K(h) = K_s S_e^l \left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{4}$$

where

$$m = 1 - \frac{1}{n} \tag{5}$$

and

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{6}$$

where α is the inverse of the air-entry value (or bubbling pressure) (L^{-1}), n is pore-size distribution index of soil (dimensionless), l is pore-connectivity parameter (dimensionless), S_e is effective saturation (dimensionless), and θ_r and θ_s are residual and saturated water content, respectively (dimensionless). Parameters α, n and l are empirical coefficients describing the shape of hydraulic functions.

3.2. Climatic data

For the 2005-2014 considered period, daily data of precipitation, wind direction and velocity, relative air humidity, and air minimum and maximum temperature from the existing meteorological stations in the area, were downloaded from the Trans-African Hydro-Meteorological Observatory-TAHMO (Van de Giesen et al., 2014). The existing records from Bokoro field site are used in all the simulations after checking their accuracy and considering that observations are representative to further simulations in both boreholes.

3.3. Evapotranspiration estimation

Daily potential evapotranspiration (*PET*) is estimated based on the Hargreaves method (Hargraves and Samani, 1985), which requires average, minimum, and maximum air temperatures and radiation. Selection was based on its applicability in arid and semi-arid regions and at non-irrigated sites. For vegetated soil with acacias crop plants, the potential evapotranspiration (ET_c) and crop-specific coefficient (K_c) values were independently estimated according to Ringersma and Sikking (2001), Ghebremicael (2003), Descheemaeker et al. (2011) and Allen and Pereira (1998, 2009). Calculation is based on crop coefficients defined for this vegetation type and geographical area (plant development, canopy, leaf area index, surface area cover). For the bare soil scenarios, only actual evaporation estimates are computed, while for vegetated soil with acacias, HYDRUS allows independent estimation of actual evaporation and actual transpiration by plants; calculations are based on water availability in the soil profile.

To assess the effect of plants on the evapotranspiration component along depth for two different climatic seasons (dry, wet), simulations of water processes in the Amdedoua site for two different climatic days were performed. The comparison of the potential water demand by plant and water uptake is done by HYDRUS for computational day 1340, with 23ºC as the maximum temperature during the 2008-2009 wet period, and for computational day 3564 with the maximum temperature of 35.5ºC during the 2013-2014 dry period.

3.4. Geological data

The soil profiles and geohydrologic parameters from the geological logs in Bokoro and Amdedoua, gathered from Abderramane (2012), were used to infer all the water processes (flow, vapor) in simulations. According to soil texture and composition, and as shown in Figure 4b, soil materials consist in loamy sand, sand and silty loam. Soil profiles discretization was made according to the distribution of soil layers. The soil profile definition includes definition of observation nodes for Bokoro and Amdedoua at six and five depths, respectively, as depicted in Figure 4. Selected location corresponds to depth of existing boundaries between permeable and low permeability materials.

Groundwater depth (LCBC-BGR, 2010; Abderramane, 2012) is around 40 m beneath land surface in the eastern part of the depression (Bokoro), and can be as high as 60 m in the central part of the depression (Amdedoua).

3.5. Soil hydraulic parameters and root water uptake

The initial input for the five independent parameters used in the simulation, θ_r, θ_s, α, K_s and n, according to defined types of geological materials at Bokoro and Amdedoua (Figure 4), were obtained from the textural analysis of the geological samples (Abderramane, 2012). The adopted average pore connection parameter l in the hydraulic conductivity function, 0.5, is according to literature a value applied for most soils (Mualem, 1976). The selected van Genuchten parameters are found in Table 1.

For root water uptake (RWU), the Feddes model (Feddes et al., 1978) was adopted. This approach is macroscopic and considers the whole root system as a diffuse sink that removes water from soil at each depth layer and at varying rates.

The actual root water uptake term, $S(h)$, is expressed as:

$$S(h) = \gamma(h)S_p$$

where Sp is the potential root uptake rate ($L^3\ L^{-3}\ T^{-1}$) and $\gamma(h)$ (dimensionless) is a function of the soil water pressure head ($0 \leq \gamma(h) \leq 1$). RWU is zero when soil is near to saturation and lower than the wilting point (*P3*) for pressure head values; this RWU decline is due to a reduction of oxygen availability and unsaturated hydraulic conductivity, respectively. Water uptake is optimal between the pressure heads in which roots extract water (*Popt)* and cannot extract water (*P2)* at the maximum possible rate. To allow *P2* to act as a function of potential transpiration rate, the model uses two additional parameters for the limiting pressure head value (*P2H* and *P2L)*, which vary according to potential transpiration rates (*R2H* and *R2L)*.

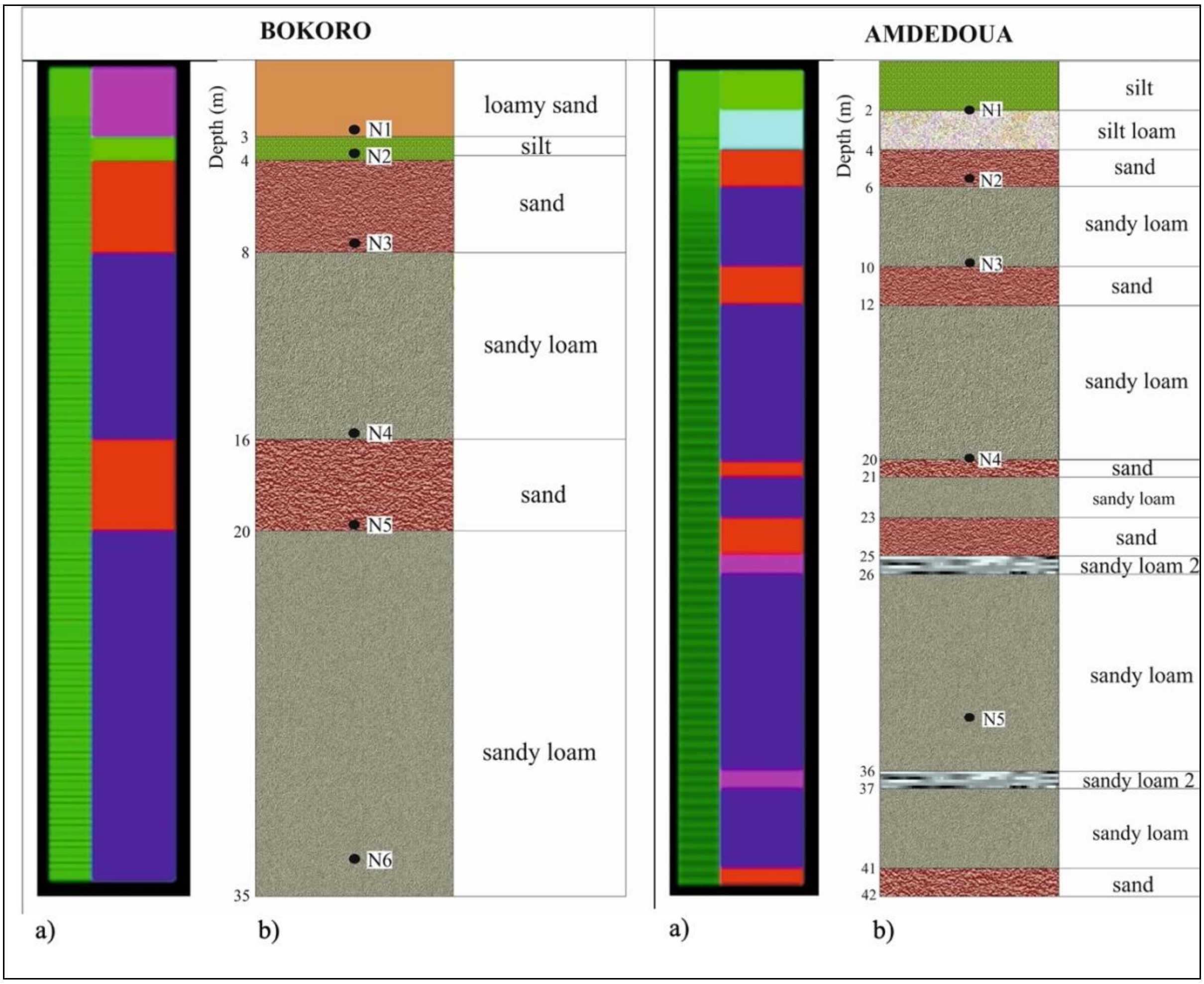

Figure 4. a) HYDRUS input. b) The Bokoro and Amdedoua distribution of geologic materials and control points along depth (N1-N5 or N6). The adopted discretization of the geological logs and materials (red, blue, purple, green and turquoise) for HYDRUS input is jointly shown on the left side of the Bokoro and Amdedoua geological logs description.Green column shows the number of defined nodes used in HYDRUS to discretize soil profile

Table 1. Soil hydraulic parameters adopted for different soil textures

Soil type	$\boldsymbol{\theta_r}$	$\boldsymbol{\theta_s}$	**$\boldsymbol{\alpha}$ (1/cm)**	$\boldsymbol{n}$	**$\boldsymbol{K_s}$ (cm/day)**
Sandy loam*	0.034/0.065	0.41/0.47	0.0183/0.075	1.266/1.89	60/106
Sand*	0.04/0.67	0.41/0.46	0.01246/0.145	1.227/2.68	712.8
Silt	0.034	0.46	0.016	1.37	6
Silt loam	0.067	0.45	0.02	1.41	10.8

θ_s: saturated water content; θ_r: residual water content; Ks: saturated hydraulic conductivity; α: inverse of the air entry value;(n: pore size distribution index. For sandy loam and sand, the two values represent the maximum and minimum values finally adopted in the simulation for the Bokoro and Amdedoua boreholes*

The *Acacia tortilis* parameters definition corresponds to a 79-year-old tree, 25 m high, with a distributed root density along a 25-meter depth, 25 mm x1mm leaf dimension, a leaf area index of 0.5 and a crop specific coefficient (K_c) of 0.95. These average parameters are selected according to Canadell et al. (1996), De Boever (2015), and Do et al. (2007): *P0* = 0 cm, *P3* = −16,000 cm, *Popt* = −400 cm, *P2H* = −4000 cm, *P2L* = −4000 cm, *R2H* = 0.5 cm/day, and *R2L* = 0.1 cm/day.

3.6. Initial and boundary conditions

Precipitation, runoff and potential evapotranspiration fluxes constitute the upper boundary condition. A free drainage condition is considered at the bottom of the model domain by considering that groundwater level is deep enough to not interfere with recharge processes in the simulated domain. To achieve the steady-state condition, a 10-year warm-up run was performed; the resulting profile of soil pressure head at the end of the warm-up run is the model initial condition. With this approach, possible impacts on model results by assumed boundary conditions are lessened.

4. Sensitivity analysis

Computing the effect of parameter uncertainties on recharge and evapotranspiration outputs is obtained by running HYDRUS. For this purpose, simulations are run considering individual model parameters. The analysis is performed by perturbing the original value of hydraulic conductivity (K_s) and the pore size distribution (*n)* parameters up to ±10% (Tables 2 and 3). The model is run several times with each changed factor to see how the input parameter can affect estimations. The impact of perturbation on the baseline calculation (simulation with the original values) in the recharge and the actual evapotranspiration is analyzed.

Table 2. The range of K_s used for the sensitivity analysis

Layers	**K_s (cm/day)**	**+10%**	**-10%**
Sandy loam*	60/106.1	66/116.7	54/95.5
Sand*	712.8	784.08	641.52
Silt	6	6.6	5.4
Silt loam	10.8	11.88	9.72

*As data correspond to both boreholes, two values are provided

Table 3. The range of n numbers used for the sensitivity analysis

Layers	***n***	**+10%**	**-10%**
Sandy loam*	1.266/1.89	1.38/2.08	1.13/1.7
Sand*	2.68	2.94	2.41
Silt	1,37	1.5	1.23
Silt loam	1.41	1.55	1.26

*As data correspond to both boreholes, two values are provided

5. Results and Discussion

For the simulated 2005-2014 period (10 years), the water budget for the two sites under bare soil and acacias land cover is shown in Table 4, which summarizes the unsaturated zone hydrological system components (precipitation, recharge, runoff, evapotranspiration) and interactions. According to the results, the relative error (%) of water balance for the entire flow domain accounts for values that are much lower than the recommended threshold value.

Table 4. Water balance results from 2005 to 2014 (10-year simulated period)

Parameters	**Amdedoua bare soil**	**Amdedoua acacias**	**Bokoro bare soil**	**Bokoro acacias**
Precipitation (*P*) (cm)	715	715	715	715
Recharge (*I*), (cm)	86	83	152	149
Runoff (*R*), (cm)	78	86	0.08	0.08
Transpiration (*T*), (cm)	0	66	0	107
Evaporation (*Ev*) , (cm)	556	484	644	552
HYDRUS relative water balance error (%)	0.001	0.2	0.002	0.1

For the 715 cm precipitation (corresponding to a mean of 715 mm/yr), deep recharge (*I*) occurs at both sites, and is lower at Amdedoua (86 cm and 83 cm for bare soil and acacias, respectively) as a result of a thick silty loam layer present at a 2-m depth of the soil surface, which favors runoff (Figure 4). Bokoro site, at the depression area boundary, presents higher recharge values (152 cm and 149 cm for bare and acacias coverage, respectively) than Amdedoua. The infiltration values account for 12% and 21% of the total precipitation for Amdedoua and Bokoro, respectively. For the local hydrological cycle, the Acacia cover contribution to final recharge values is not significant compared to the bare soil results, as also stated for other regions (Leduc et al., 2001). According to model with vegetation, plant roots obtain the infiltrated water at upper layers due to the reduced evaporative demand. The infiltration rate and changes along time are conditioned by the initial water content, and on the texture, structure and layering order of soil profile. Obtained values are consistent with the recharge results estimated in the MODFLOW modeling of the Quaternary aquifer (WB, 2020).

The runoff calculated by HYDRUS is higher at Amdedoua (70-77 cm) than at Bokoro (0.08 cm). The low runoff values at Bokoro *versus* Amdedoua can be explained by the existence of a slightly permeable layer on the topmost soil surface profile, followed by low permeability materials in depth (Figure 4). When a high precipitation event takes place, water initially infiltrates through the upper permeable layer, remains held in the interface with the beneath less permeable layers until it slowly infiltrates deeper, leading to a temporal perched aquifer.

Potential evapotranspiration (*PET*), estimated by the Hargreaves method, accounts for 2214 cm for the 10-year study period. This method is recommended by the FAO (Allen et al, 1998) instead of Penman-Monteith when insufficient meteorological data are available and for its good performance in arid and semi-arid regions. According to Allen and Stott (2003) however, uncertainty of daily estimates may occur because of changes in temperature, wind speed or cloud cover. Regarding the evapotranspiration results obtained at both sites, potential demands are much higher than total precipitation, which reveals clear plant water stress. Evaporative demand is slightly higher for bare soil and dominates over the transpiration effect by plants in vegetated soil, which is a particular feature of warm areas with sparse vegetation. This can be explained by the fact that the impact on the hydrological system of insolation reduction due to the presence of vegetation is stronger than the increase in the plant transpiration rate. According to Dong et al. (2022), plant transpiration generally takes place for air temperatures above 10ºC, depending on the growing conditions. The actual transpiration values in similar climatic areas (Do et al., 2007; Chavarro-Rincon, 2009) range from 0.7 cm/year to about 6 cm/year, following seasonal fluctuations, which are consistent with the obtained values. According to the results, plant water stress is significant because it is only capable of meeting 25% of the water demand, which will undoubtedly affect its development.

The results of the actual (*ETa*) and potential (*PET*) transpiration for a dry humid season along depth for Amdedoua (center of the depression) are plotted in Figure 5a,b. Water uptake by *Acacia Tortilis* follows its double root system distribution and root length density, and is always limited to a maximum root depth of 25 m. For both seasons, transpiration takes place preferentially at the 5.0 m upper most soil depth where root density is higher. According to estimations, during the 'dry period' (day 3583 of the 2013-2014 period) values are higher, and total *ETa* amounts to 2.40 cm. For the humid and colder period, it accounts for 0.49 cm (day 1340 of the 2008-2009 period). During the humid season, plant water needs are completely met at some depths, but water stress remains.

Water uptake and hydraulic lift, a wet to dry soil layers water movement through plant roots, generally occurs at nighttime (Richards and Caldwell, 1987; Caldwell et al., 1998). Acacia trees can lift up a meaningful volume of water to at least 10 m from the tree base. For *Acacia*

Tortilis water uptake by tree roots can happen at depth when the matric potential equals or is higher than -1.6 MPa (Do et al, 2007). Data suggest that when the soil water potential drops below -5.0 MPa, the hydraulic lift no longer operates (Ludwig et al., 2003). During the dry period, deep taproots (up to 25 m deep, considered selected root length) supply most of the plant water needs. During the wet period, lateral roots obtain water mainly from the recent precipitation stored in the upper soil layers.

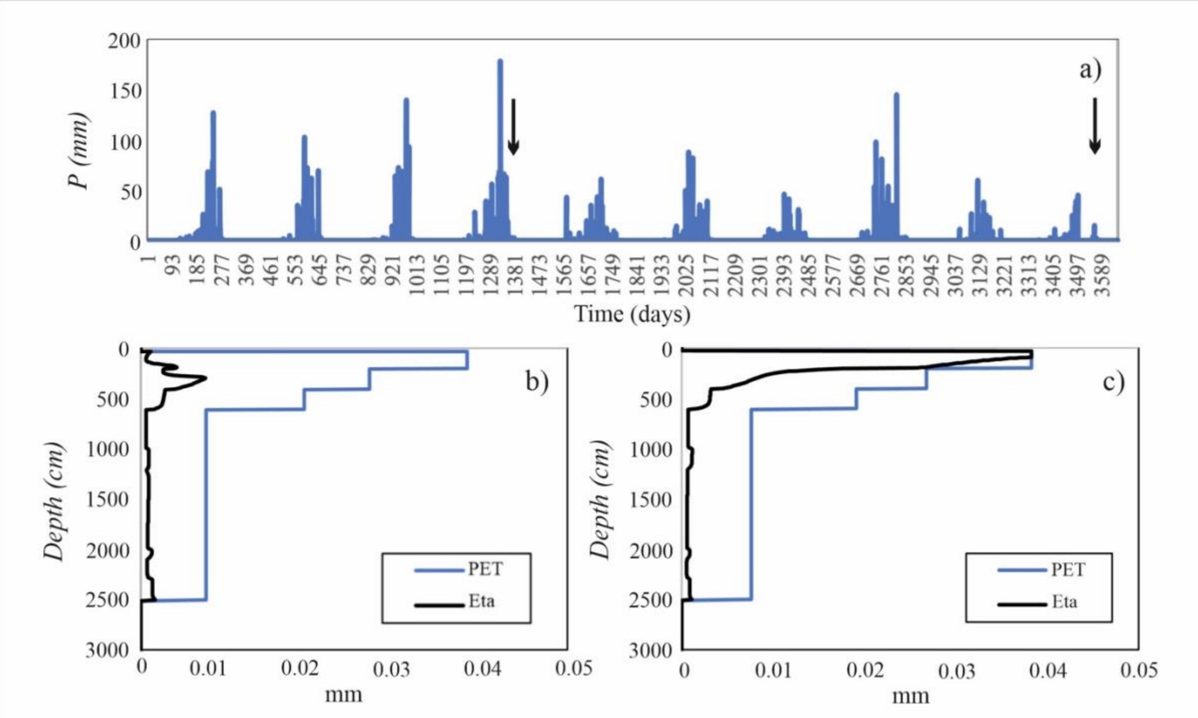

Figure 5. Amdedoua site. (a) Precipitation P; Simulation of PET *and ETa along depth for day 1340 (b) humid season, total ETa 0.49 mm and (c) day 3583 dry season, total ETa 2.40 mm.*

For the prevailing simulated conditions (steady-state) and parameters at Bokoro bare soil, the consequence of a lack of precipitation (simulations not shown here) is an evaporation reduction to about 1-2 mm/year. This outcome illustrates the limited effect of evaporative demand on controlling the present groundwater level in the depression. Also, vapor flux estimation and its contribution to water balance calculations is meaningless and does not lead to changes in the final balance. Moreover, according to HYDRUS modeling, the system seems to incorporate atmospheric air humidity amounts in the water balance due to the low soil pressure head. Air humidity is controlled by temperature in HYDRUS simulations.

Figures 6 and 7 plot HYDRUS simulations of water content and water flux over time in the bare and vegetated soil at the control points distributed along the soil depth profile for Bokoro and Amdedoua, respectively (left bare, right acacias). At both sites, the recharge values are generally higher for vegetated soil, while they present a similar pattern flux and water content along depth.

The recharge from the precipitation at Bokoro mainly takes place during intense rainfall periods at the three shallowest layers of the soil profile (Figure 6, N1 to N3), For the deepest layers, from 15 m deep to the lower boundary, the effect of main recharge events is barely observed as high downward water fluxes are buffered by intermediate layers. For Amdedoua (Figure 7), soil water content changes and the recharge flux occur mainly in the shallowest layers of the soil profile at 2 m from the soil surface. At the N2 monitoring point (Figure 7, 5.59 m), changes occur when major precipitation takes place. However, no recharge effect is observed from N4 (Figure 7, 19.5 m) and with both simulations. For the deepest layers (N3, N4), the maximum water recharge value can account for less than 0.1 cm/day and is observed only after intense rainfall for a long time-delay period. However, it is important to note that these results may lie within error limits. The existence of low to moderate hydraulic conductivity layers, interbedded in soil profile and defined observation points, is the main reason to explain this fact.

The regional groundwater level is around 40 m below ground surface at Bokoro and more than 50 m deep at Amdedoua, far below the root zone to enable evapotranspiration. Recharge to aquifer from rainfall (12% at Amdedoua, Table 4) appears to be very limited according to the results obtained for the water that reaches deep layers. Under the present climatic conditions and the estimated recharge rates, no major changes for the groundwater level in the piezometric depression are expected.

Simulation shows that the response to precipitation mainly affects shallow upper soil layers. Limited aquifer recharge in the depression has also been proposed by Abderramane (2012) from groundwater isotopic data, and by Leblanc et al. (2003) based on Meteosat thermal data. Similar unsaturated zone results obtained at four different arid and semi-arid sites have been obtained with the modeling by Scanlon et al. (2003). Further simulations of these sites from the pluvial Pleistocene to the dry Holocene past climate conditions (changes from mesic to xeric vegetation) indicate the importance of the upper water flux reduction to create a drying front (and an upward water flux) that propagates more deeply into the profile and reaches the water table after several kyr of drying.

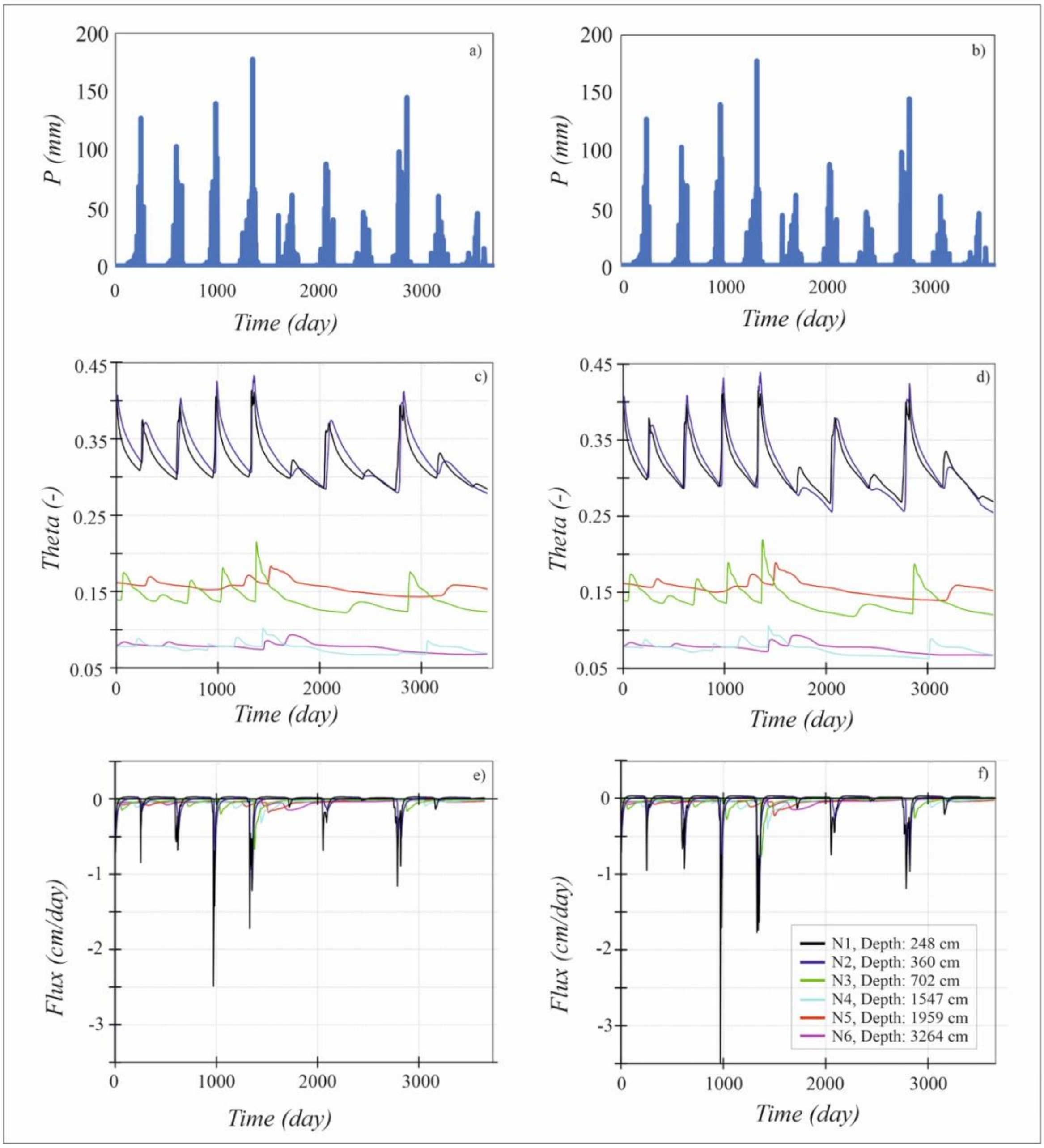

Figure 6. (a,b) Precipitation P. Results of water content (c and d) and recharge (e and f) for the control points at Bokoro (left bare, right acacias); HYDRUS outputs.

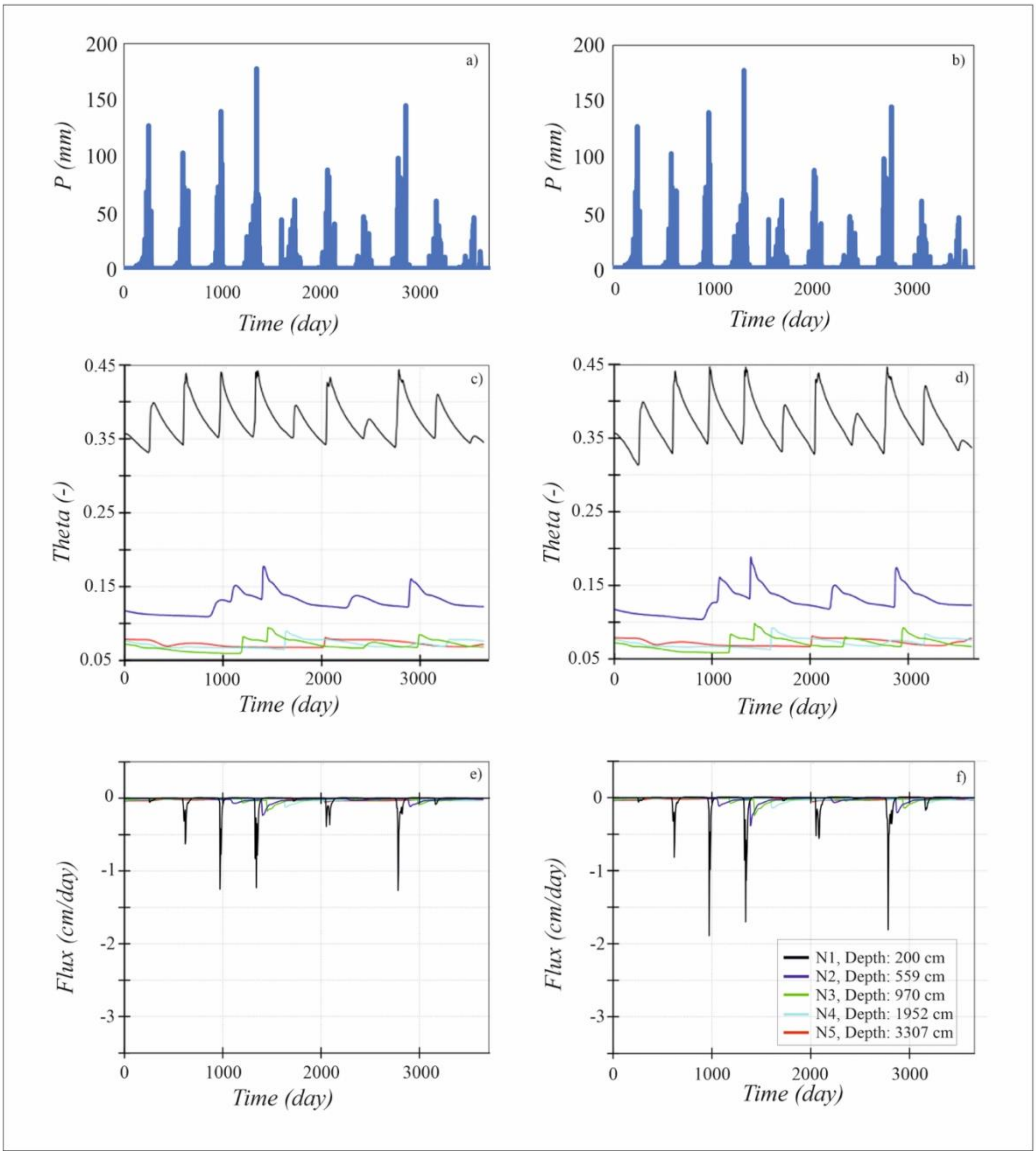

Figure 7. (a,b) Precipitation P. Results of water content (c and d) and recharge (e and f) for the control points at Amdedoua (left bare, right acacias); HYDRUS output.

The results are considered satisfactory and consistent with what can be expected for this zone. However, as sources of uncertainty of hydrological components and parameters may exist and besides, external piezometric data are lacking for model calibration and validation, the predicted hydrologic values should only be considered as an indication of current hydrologic process taking place in the area.

5.1. Sensitivity analysis results

The sensitivity analysis of the fluxes to a 10% change in the soil hydraulic parameters for both sites (Amdedoua and Bokoro) were carried out; only forAmdedoua bare soil is presented in Table 5 and Figure 8. For the hydraulic conductivity parameter K_s and *n*, analysis shows that for the cumulative actual surface flux the least sensitivity is linked with K_s, and the greatest sensitivity corresponds to *n* (porosity). Under unsaturated conditions, the K_s (saturated soil water permeability) importance for controlling groundwater recharge process (or generally, porous water) is very limited. This is a basic concept from the soil water flow theory in variable-saturated porous media. When unsaturated conditions prevail, the main leading parameters controlling the water flow are related with the soil water retention curve, and hence, the *n* and α shape parameters, according to the van-Genuchten model to describe the soil, water-head and water-content relationships. Generally, no significant change appears for other fluxes (Table 5). These results indicate that the cumulative actual surface flux is the most sensitive to parameter changes.

Table 5. Sensitivity analysis results

	Recharge (cm)	**Runoff (cm)**	**Cum. Evaporation (cm)**
Baseline	86	78	556
10% increase in K_s	92	70	562
10% decrease in K_s	79	87	552
10% increase in *n*	65	70	583
10% decrease in *n*	17	98	598

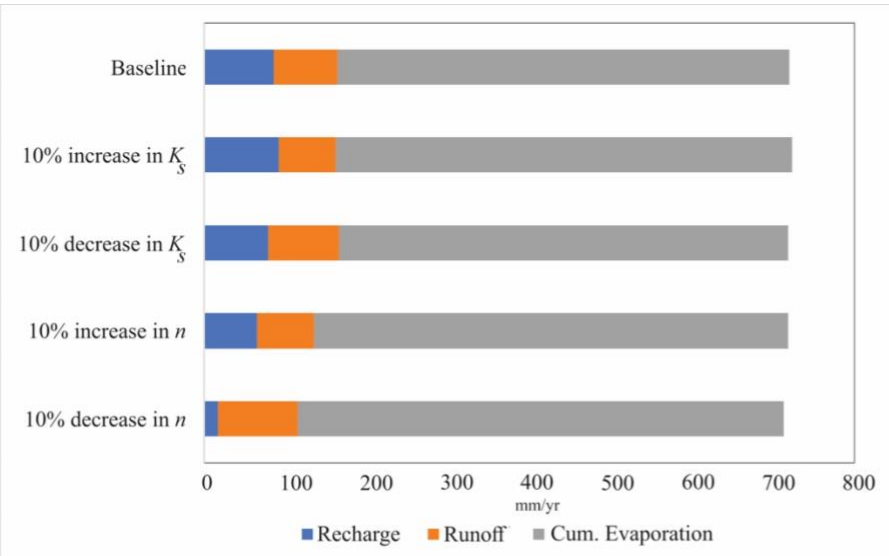

Figure 8. The sensitivity analysis results of changes in K_s and n in recharge, runoff and evapotranspiration (mm/yr)

The analysis shows that climate is the main driving force of soil water fluxes, and soil hydraulic properties are less sensitive. The most sensitive parameter is *n*. A reduction in *n* in relation to fine-grained sediments leads to a major decrease in the total water volume held by soil.

6. Conclusions

Under natural conditions, large piezometric depressions as regards the regional groundwater level exist in the Lake Chad Basin area, including the Chari-Baguirmi in the Chad Formation Aquifer.

Presently, the most accepted explanations for the origin and dynamics of such singularities are high evapotranspiration (exfiltration) combined with low natural recharge. Nevertheless, exfiltration processes or other approaches able to extract groundwater from the system (i.e., evapotranspiration from the saturated zone) are not completely able to naturally explain the current process when the water level is at more than 40 m below ground surface. Our results show that for a water table depth of 35 m and below, the evaporation rates are very low, which implies a negligible contribution to the groundwater depression process. For saturated porous media and bare soil, when groundwater level is greater than 10 m deep generally, the water table is not under direct evapotranspiration. In this research and for the area covered by acacia trees, this depth is controlled by a maximum acacia root depth of up to 25 m. The recharge process is very sensitive to parameter *n* (pore size distribution).

From the present model outcomes, no upward water flux (positive outputs) is observed under the present climate conditions, which highlights the existence of previous climatic setups when the groundwater depression process should have appeared. The soil profile results support the previous hypothesis by indicating that above the depression, the rainfall effect is only observed at the upper soil layers, may accumulate on the soil surface and does not infiltrate deeply into the ground, which all lead to low aquifer recharge. From the numerical modeling in the semiarid areas, performed to evaluate the system's response to paleoclimatic fluctuations under transient flow conditions, the effect of the past drying climate over millennia could create an upward flux regime throughout the unsaturated zone that could reach the groundwater level (Scanlon et al., 2003). For the Chad Basin, the changing climate timescales are probably shorter than the necessary time to reach the steady state, which would condition the subsurface flow and the actual depression pattern. The study of the Cl^- concentration profile in soil, supported by spatially distributed experimental research plots for vadose zone monitoring, would provide very useful information to validate the climate change hypothesis and its effect on soil water fluxes.

Finally, although the obtained results highlight the governing role of recharge and evaporation in the depressed area, the development of the current depression is also conditioned by structural constraints according to the sediment deposition sequence. Maintaining the groundwater regional equilibrium also implies that the horizontal flow is very small. Although simulations provide information on the current hydrologic process, the model's outcomes and quantitative values should be carefully considered because a calibration of the simulated domain is lacking. Quantitative results need to be considered as estimations of simulated hydrologic process; lack of observations, computing issues or intrinsic uncertainties in model development are generally translated to final results.

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