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NUMERICAL MODELING OF GROUNDWATER FLOW IN AN URBAN ENVIRONMENT: INSIGHTS FROM N'DJAMENA, CHAD

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ABSTRACT

Groundwater flow modeling in urban areas is of great importance in the context of water level depletion due to the high population, unplanned urbanization and industrial growth. In N'Djamena, groundwater is the main source of drinking water. Under these conditions, groundwater flow modeling is essential to better understand the dynamics and behavior of the urban groundwater system of the city. The goal of this work is to analyze groundwater flow dynamics in the urban environment of N'Djamena using the well-known MODFLOW model. In this study, we combine field studies and modeling in order to reach this goal. Results of piezometric monitoring conducted across 200 boreholes and wells showed that the groundwater head ranging from 269.55 m to 304.01 m, with a general flow direction from southeast to northwest, confirming the direct influence of the Chari River on groundwater dynamics. The MODFLOW-based numerical model accurately reproduced the observed hydrodynamic response of the aquifer, as demonstrated by a coefficient of determination (R^2) of 0.95 obtained during model calibration. The results of the model developed could be used as an operational decision-making tool for the sustainable management of groundwater resources of N'djamena.

Keywords: MODFLOW, Groundwater Modeling, Urban Environment, N'Djamena

1 INTRODUCTION

Urban areas have grown rapidly worldwide in recent decades. People living in urban areas now account for 80% of the population according to United Nations (UN) report (United Nations, 2025). Therefore, rapid urban growth has an impact on the urban water balance (Bradley et al. 2002; McDonald et al. 2011; McGrane, 2016) and strongly affects people's needs. In urban areas, groundwater is a key resource for drinking water supply, industry, and ecosystem services (Howard, 2002; Griebler and Avramov, 2015; La Vigna, 2022). In many countries, including Chad, meeting water quality standards for groundwater remains challenging. This is due to high population growth, water quality deterioration, and unplanned and rapid urbanization (Dalin et al. 2019; Mishra, 2023). Among these, groundwater depletion is a global concern (Konikow, 2005; Schwartz and Ibaraki, 2011) that needs to be highlighted in order to take appropriate measures. According to Aeschbach-Hertig and Gleeson (2012), available groundwater volume globally is

restricted, with limited recharge ($\sim 12,600 \text{ km}^3/\text{yr}$) compared to recorded groundwater extraction ($\sim 1,500 \text{ km}^3/\text{yr}$). However, knowledge about groundwater and associated physical parameters that influence its dynamic is crucial for the sustainable management of aquifers. The problem is their accessibility because they are not visible like surface waters (Izady et al. 2017). In addition, Groundwater delineation is more difficult to delineate compared to surface water due to uncertainties in subsurface parameters, including groundwater hydraulic properties, human exploitation conditions, and elasticity properties (Lo et al. 2021). Through models, it is easy to understand regional flow and hydrogeological conditions and analyze recharge rates under climatic conditions of the groundwater system (Cao et al. 2013; Rao et al. 2020).

In recent years, several studies have used numerical models to assess groundwater flow in order to put policy tools for groundwater management. Groundwater modeling tools such as MODFLOW, FEFLOW, MIKE are often combined with Geographic Information System (GIS) to reach better results. Among these modeling tools MODFLOW is most popular (Wang et al. 2008; Khadri et al. 2016; Boufekane et al. 2019; Bailey et al. 2020; Lo et al. 2021; Gebru et al. 2025). For instance, Wang et al. (2008) applied MODFLOW model in North China Plain (NCP) to evaluate the groundwater resources of the NCP as an entire aquifer system. Mustafa et al. (2024) developed a three-dimensional groundwater flow model for the Erbil Basin utilizing the Groundwater Modeling System (GMS) and their results have provided valuable insights into the dynamics of groundwater flow in the study area. Groundwater flow models are also useful in different aquifer contexts as demonstrated by Boufekane et al. (2019) in the Jijel plain (Algeria) where the effect of groundwater pumping on subsidence in the Jijel plain in 2042 can be quantitatively projected with the integration of MODFLOW. El Alfy (2014) assessed the effectiveness of groundwater management in the arid areas (Nubia aquifer, Egypt) through groundwater modeling approach. Lo et al. (2021) studied groundwater flow in Semarang city (Indonesia), and their results revealed that implementing a groundwater model helps restore groundwater levels at the study site. For the site under consideration, no work has modeled the aquifer's hydrodynamic behavior, primarily because monitoring networks are inadequate and quantitative data are scarce. However, Abderamane (2012) developed a regional conceptual model of the Chari-Baguirmi Quaternary aquifer via MODFLOW, but this study does not allow for a detailed characterization of the groundwater flow in the city of N'Djamena. Therefore, a detailed study of groundwater flow in the urban environment of N'Djamena is needed to better understand the dynamics and behavior of the groundwater system.

The purpose of this study was to analyze groundwater flow dynamics in the urban environment of N'Djamena using the well-known MODFLOW model. We combined field studies and modeling in order to reach this goal. In particular, a steady-state flow is conducted to observe changes in groundwater level due to unplanned urban areas, private households, and farm development around N'Djamena.

2 MATERIALS AND METHODS

2.1 Study area

N'Djamena, the capital city of the Republic of Chad, is located between latitudes $12^{\circ}02' \text{ N}$ and $12^{\circ}12' \text{ N}$ and longitudes $14^{\circ}58' \text{ E}$ and $15^{\circ}10' \text{ E}$. The city lies in a marshy environment south of Lake Chad, at the confluence of the Chari and Logone Rivers (Fig. 1). Meteorological data, including precipitation and air temperature, were obtained from the National Agency of Meteorology for the period 1992–2022. The study area receives an average annual precipitation of approximately 586.50 mm, with the rainy season extending for up to eight months, from April to November. Air temperatures range from 27 to 41 °C, with a mean annual temperature of approximately 29.3 °C. The study area is characterized by a relatively low and gently varying topography, with elevations ranging from 280 to 320 m above sea level. From a geological perspective, the study area forms part of the Lake Chad Basin, a large intracontinental sedimentary basin characterized by a thick succession of Cretaceous, Tertiary, and Quaternary deposits (Louis, 1970; Ngounou Ngatcha et al., 2007; Ngounou Ngatcha and Djoret, 2010). The Quaternary deposits in the study area consist predominantly of sands, sandy-clay alluvium, clays, clayey-sandy alluvium, and silts (Schneider and Wolf, 1992). These unconsolidated sediments constitute the main hydrogeological units underlying N'Djamena and host the principal Quaternary aquifer system (Schneider and Wolf, 1992; Lemoalle and Magrin, 2014). The aquifer is of continental origin and is composed mainly of sandy deposits interbedded with discontinuous clay layers, resulting in spatially variable hydraulic properties and groundwater conditions (Schneider, 1989). Two main groundwater-bearing horizons have been identified within the Quaternary formations (Kadjangaba et al. 2017). The shallow aquifer occurs at depths of approximately 10 m and is primarily exploited through traditional wells for local water supply. A deeper aquifer, encountered at depths of around 60 m, is accessed through boreholes and is typically exploited by the Chadian Water Company for urban water supply.

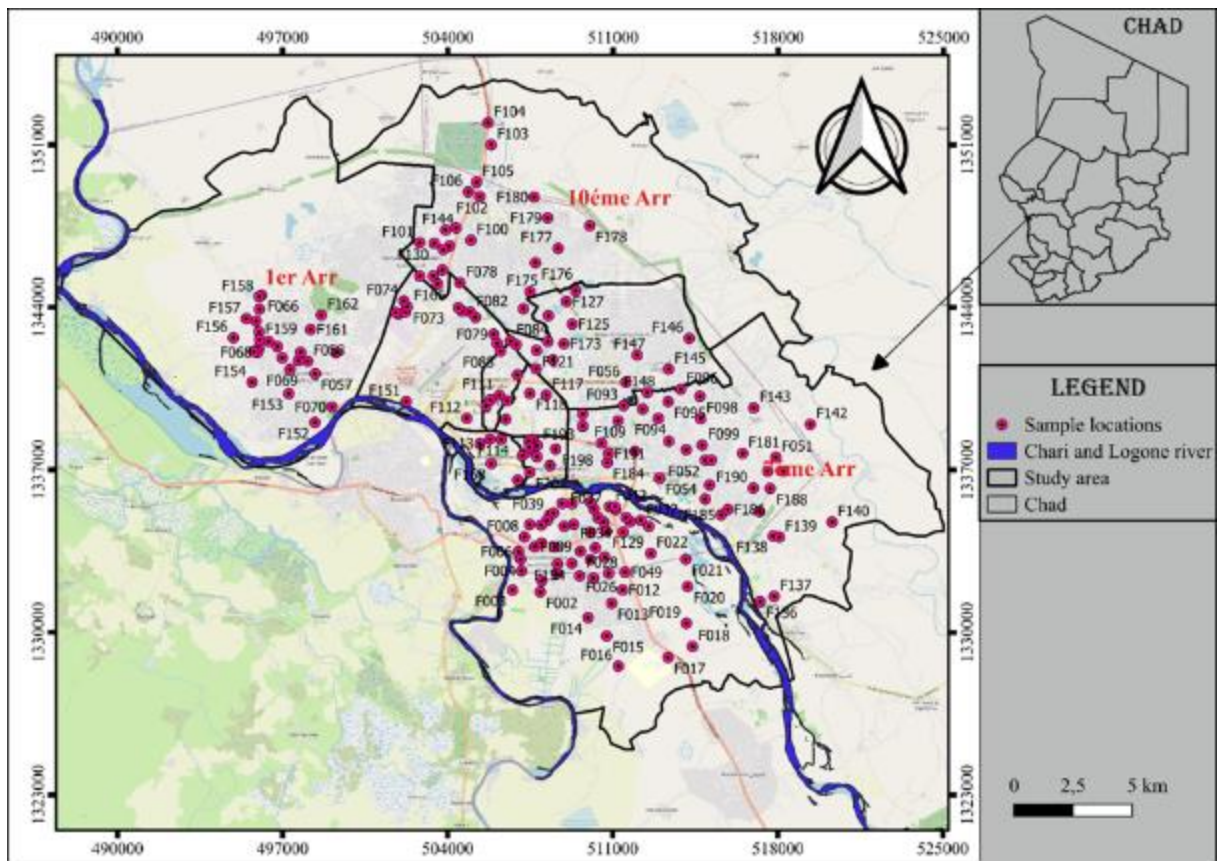


Figure 1: Location of the study site.

2.2 Data collection

Data collection conducted in this study consisted of measurements of groundwater head from boreholes and wells located inside N'Djamena. Field operations took place across all ten (10) districts of N'Djamena from April to June 2026. The primary objective of field-based piezometric measurements is to assess groundwater-level fluctuations in response to anthropogenic and climatic pressures and to generate a reliable dataset for calibrating the urban groundwater flow model. A total of 200 boreholes and wells were sampled for piezometric measurements, and these observation points serve to calibrate the hydrogeological model developed. Note that several materials were used during field measurements, such as multiparamètre, a piezometric probe, and a GPS (Fig. 2).



Figure 2: Field studies: (a) piezometric prob; (b) GPS (GARMIN); (c) and (d) water level measurements.

2.3 Groundwater flow modeling methodology

2.3.1 Description of Groundwater Flow Model

As mentioned earlier, Groundwater flow modeling can accurately describe underground flow channel behavior and guide better groundwater management. Several groundwater modeling tools have been developed based on various approaches. Among these modeling tools, MODFLOW has been widely used worldwide (Wang et al. 2008; Khadri et al. 2016; Boufekane et al. 2019; Bailey et al. 2020; Lo et al. 2021; Gebru et al. 2025).

In this study, the Groundwater Modeling System (GMS) is used due her user-friendly interfaces. The GMS software is a graphical user interface for MODFLOW model. It simulates the groundwater flow through a finite difference scheme for both steady-state and transient conditions. In the MODFLOW model, the governing equation is derived from the combination of two basic equations (the Darcy equation and the principle of conservation of mass). The three-dimensional groundwater movement can be described by the partial differential equation (Darcy's law) as follows:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial H}{\partial z} \right) - Q = S_s \frac{\partial H}{\partial t} \quad (1)$$

where: x, y, z = Cartesian coordinates in x, y , and z directions; H : hydraulic head; k_x, k_y, k_z : conductivity tensor in the x, y , and z direction; Q : sinks of water; S_s : specific storage;

2.3.2 Geometry of the model and grid preparation

The geometry of the model was made based on available lithological and hydrogeological data. The aquifer was modeled as a single layer representing the unconfined quaternary aquifer, in accordance with the hydrogeological characteristics

of the study area. The top of the aquifer was set at a depth ranging from 5 to 15 m below ground level, in accordance with data from the study area (Schneider and Wolff, 1992). The base of the aquifer consists of an impermeable clay formation located at a depth of 60 to 70 m (Schneider and Wolff, 1992).

The model has an area of approximately 533.85 km². It was discretized with a finite difference grid. The final grid contained 276 columns and 336 rows (276*336). In total, there are 92736 number of cells in the final grid of the model (Fig.3).

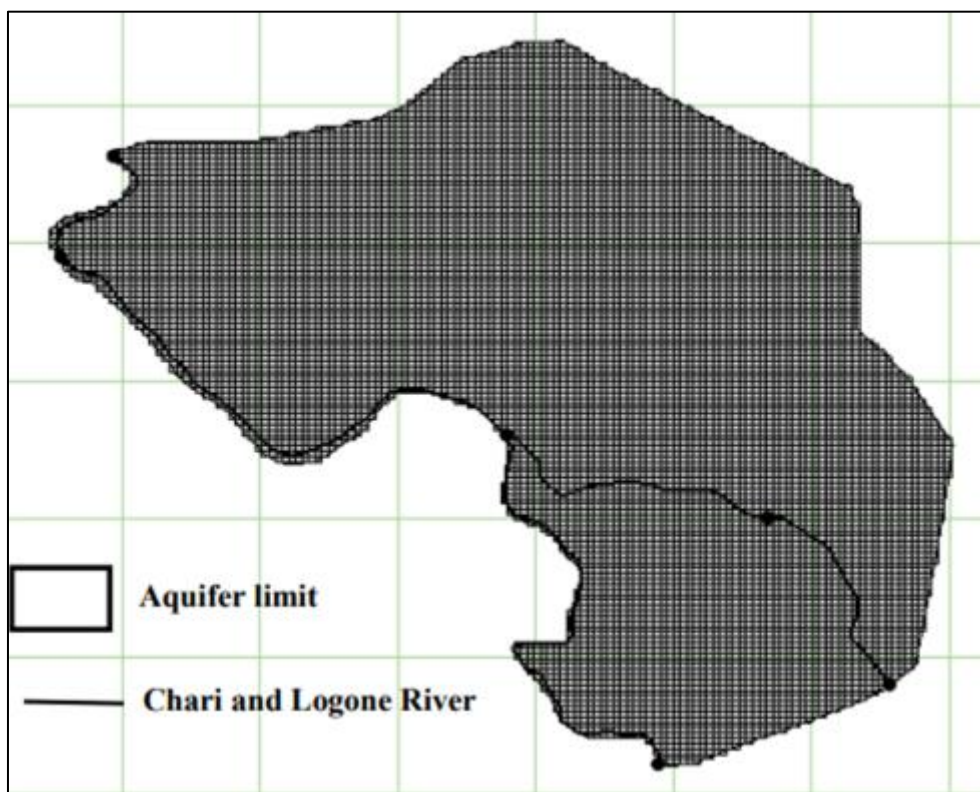


Figure 3: Model geometry and grid

The boundary condition types and hydrogeological properties range used in the model are summarized in Table 1.

Table 1: Boundary condition types and hydrogeological properties of the model

Number	Item	Detail
1	Hydraulic conductivity	64.10^{-4} - $1.4.10^{-2}$ m/s
2	Recharge	0 – 18 mm/year
3	Specific storage	0.25
4	Model simulation type	Steady state
5	Boundary package	CHD, RCH, EVT

2.3.3 Boundary condition

The boundary conditions of the model are defined according to lithological characteristics of the aquifer and specific context of N'Djamena which is crossed by two important rivers, namely the Chari and the Logone. There are two main boundary condition in the model, namely fixed hydraulic head-boundary and no flow-boundary or Neumann boundary (Fig.3). No flow- boundary condition is fixed because there are no hydraulic connections between the aquifer and its neighbors. Whereas fixed hydraulic head- boundary concern areas around Chari and Logone River.

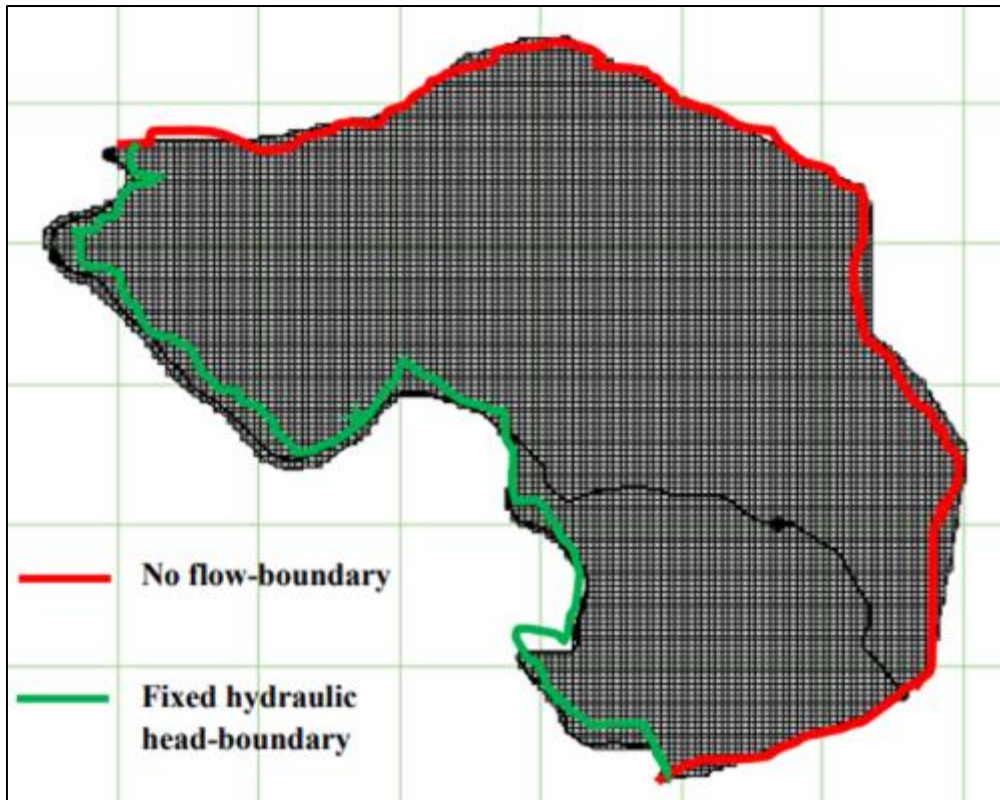


Figure 4: Model boundary condition

2.3.4 Initial hydraulic head

The initial hydraulic of the model was generated from static water level inventory, based on 200 borehole drilling reports collected form field studies. These data make it possible to set initial hydraulic head for the model. It is considered as one of the key parameters of the groundwater flow model.

2.3.5 Model calibration criteria

Before the use of the groundwater flow model, its calibration is a key step in the modeling process. The overall goal of the model calibration is to adjust the hydrogeological parameters until the simulated results math well with the fields data within acceptable error limits (Manghi et al. 2012).

In this study, the following statistic parameters we used to evaluate the goodness of groundwater flow model.

Mean error (ME):

$$ME = \frac{1}{n} \sum_{i=1}^n (h_{obs,i} - h_{sim,i}) \quad (2)$$

Mean absolute error (MAE):

$$RM = \frac{1}{n} \sum_{i=1}^n |h_{obs,i} - h_{sim,i}| \quad (3)$$

Root-mean-square error (RMSE):

$$RMSE = \frac{1}{n} \sqrt{\sum_{i=1}^n (h_{obs,i} - h_{sim,i})^2} \quad (4)$$

where n is the number of selected boreholes and wells to fit fields data, h_{obs} is the observed groundwater head and h_{sim} is the groundwater head from model.

To summarize modeling approach developed, a Methodological flow chart for groundwater flow modeling is defined and shown below:

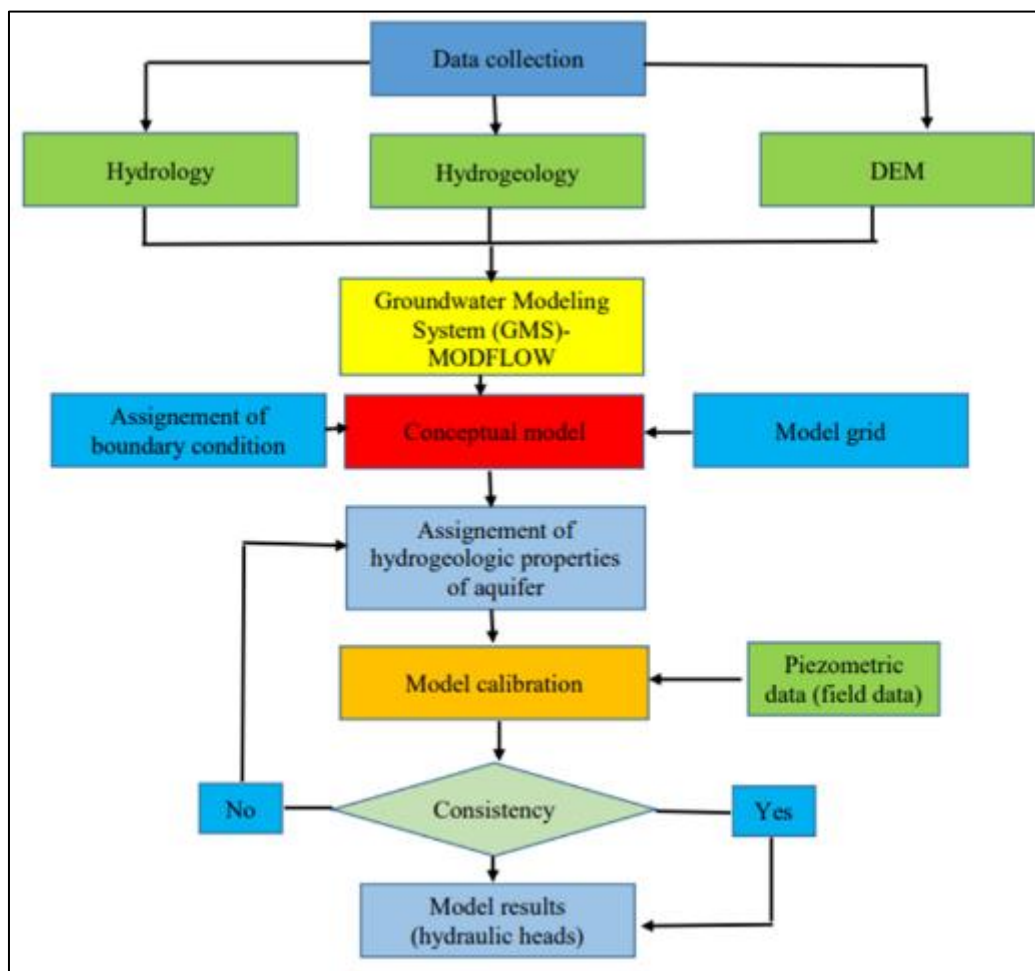


Figure 5: Methodological flow chart for groundwater flow modeling.

3 RESULT AND DISCUSSION

3.1 Piezometric of the study area

The establishment of a piezometric map via a piezometric study of an aquifer allows for a global assessment of groundwater flow Conditions, as well as their recharge conditions and the variation of their reserves (Gilli et al., 2012). The results of the piezometric survey conducted in the city of N'Djamena show that groundwater levels range from 269.55 m to 304.01 m, with an average of 285.32 m (Fig. 6). Groundwater flow is observed to be multidirectional, with a general trend from southeast to northwest as shown in the Fig.6. These findings are consistent with the results of Schneider and Wolff (1992) and Abderamane (2012), who observed the similar flow directions and in particular, described a regional flow converging towards Lake Chad.

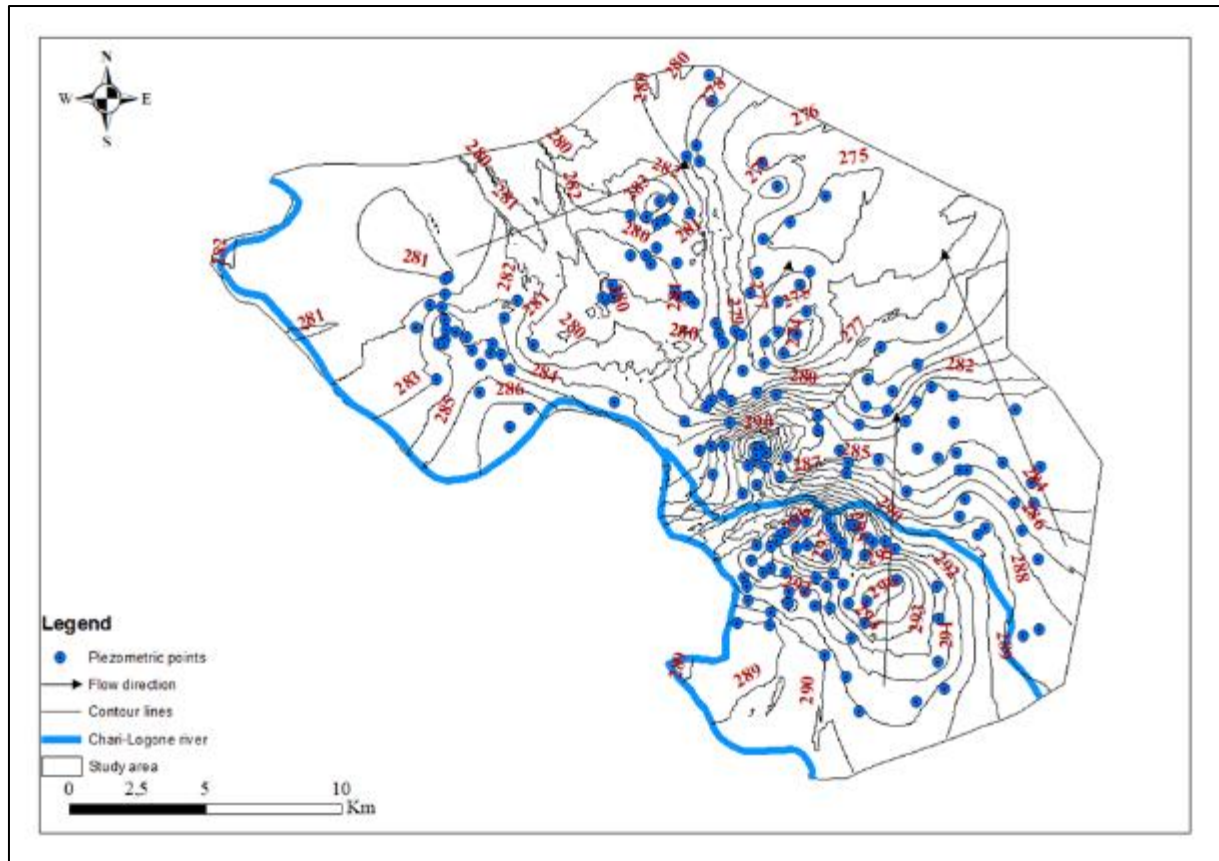


Figure 6: Observed groundwater head map (piezometric map) and flow direction of study site.

3.2 Analysis of groundwater level depletion

To understand piezometric fluctuations resulting from various stresses on the aquifer (whether caused by anthropogenic activities or climatic variations), we analyze groundwater-level depletion between 2024 and 2026 from data of 50 boreholes located in the city of N'Djamena. The piezometric data used in this study come from previous field studies (unpublished data). The results (Table 2) show relatively low groundwater depletion (less than 1 m) in N'Djamena, indicating regional stability of the groundwater level. This situation could be attributed to improved natural recharge conditions, particularly through rainfall and hydraulic exchanges with the Chari-Logone system. This stability is consistent with the observations of Kadjangaba (2018), who noted seasonal fluctuations in the range of 1 to 3 m, attributed to the combined influence of the Chari River and precipitation.

Table 2: Groundwater-level depletion (m/year) between 2024 and 2026 in N'Djamena.

Well identity	Year 2024	Year 2026	Depletion m/year (2024-2026)
F01	303.37	303.72	0.12
F02	285.72	286.26	0.18
F03	287.46	288.05	0.20
F04	290.29	290.75	0.15
F05	289.72	289.72	0.00
F06	288	288.47	0.16
F07	293.49	294.02	0.18
F08	295.15	295.71	0.19
F09	292.64	293.03	0.13
F10	295.45	295.81	0.12
F11	290.23	290.71	0.16

F12	294.99	294.68	0.10
F13	291.52	291.74	0.07
F14	288.85	288.57	0.09
F15	292.3	292	0.10
F16	291.33	290.92	0.14
F17	291.26	291.58	0.11
F18	288.54	289.11	0.19
F19	294.56	294.99	0.14
F20	291.01	291.36	0.12
F21	291.46	292.08	0.21
F22	301.52	302.05	0.18
F23	291.58	292.04	0.15
F24	290.52	290.81	0.10
F25	293.99	294.32	0.11
F26	288.54	287.86	0.23
F27	290.37	289.91	0.15
F28	295.61	296.07	0.15
F29	294.37	294.89	0.17
F30	292.28	292.77	0.16
F31	286.09	286.68	0.20
F32	289.53	290.11	0.19
F33	292.03	292.59	0.19
F34	291.42	292.12	0.23
F35	303.65	304.01	0.12
F36	303.03	303.55	0.17
F37	293.84	294.23	0.13
F38	296.08	296.68	0.20
F39	288.79	289.26	0.16
F40	288.94	288.56	0.13
F41	293.71	294.24	0.18
F42	286.39	286.9	0.17
F43	303.16	303.52	0.12
F44	292.05	292.42	0.12
F45	288.15	288.77	0.21
F46	303.03	303.62	0.20
F47	301.6	301.7	0.03
F48	298.57	298.95	0.13
F49	296.19	296.54	0.12
F50	295.8	296.42	0.21

3.3 Steady state flow simulation

In this study, the calibration of the model is performed for steady-state flow due to the lack of time-series groundwater flow data. The simulated groundwater head map (Fig.7) obtained after calibration showed that the model reproduced the hydrodynamic response of the aquifer compared to observed groundwater head map (Fig.7). Calibration on 200 observation points made it possible to reproduce satisfactorily the piezometry observed in the field with a coefficient of determination of $R^2=0.951$ (Fig.8). The final values of the statistic parameters obtained after calibration are shown in Fig.8. These results are consistent with the criteria usually adopted in the literature. Anderson and Woessner (1992) recommend that the Mean Absolute Error (MAE) be less than 5% of the total amplitude of the observed hydrodynamic loads. In the present study, the MAE was 0.96 over an amplitude of 34.46 m, which represents approximately 2.7%. This value of MAE is clearly below of that threshold. Results of groundwater budget in the steady-state regime obtained from calibration is showed in the Fig. 9. In steady state, the water flow entering the model must be identical to those leaving it. Flow balance errors, expressed as a percentage, must be less than 0.1% for the model to be considered numerically convergent (McDonald & Harbaugh, 1988). In the present study, the imbalance between inflows and outflows is 0.000023% confirming perfect numerical convergence of groundwater flow model developed.

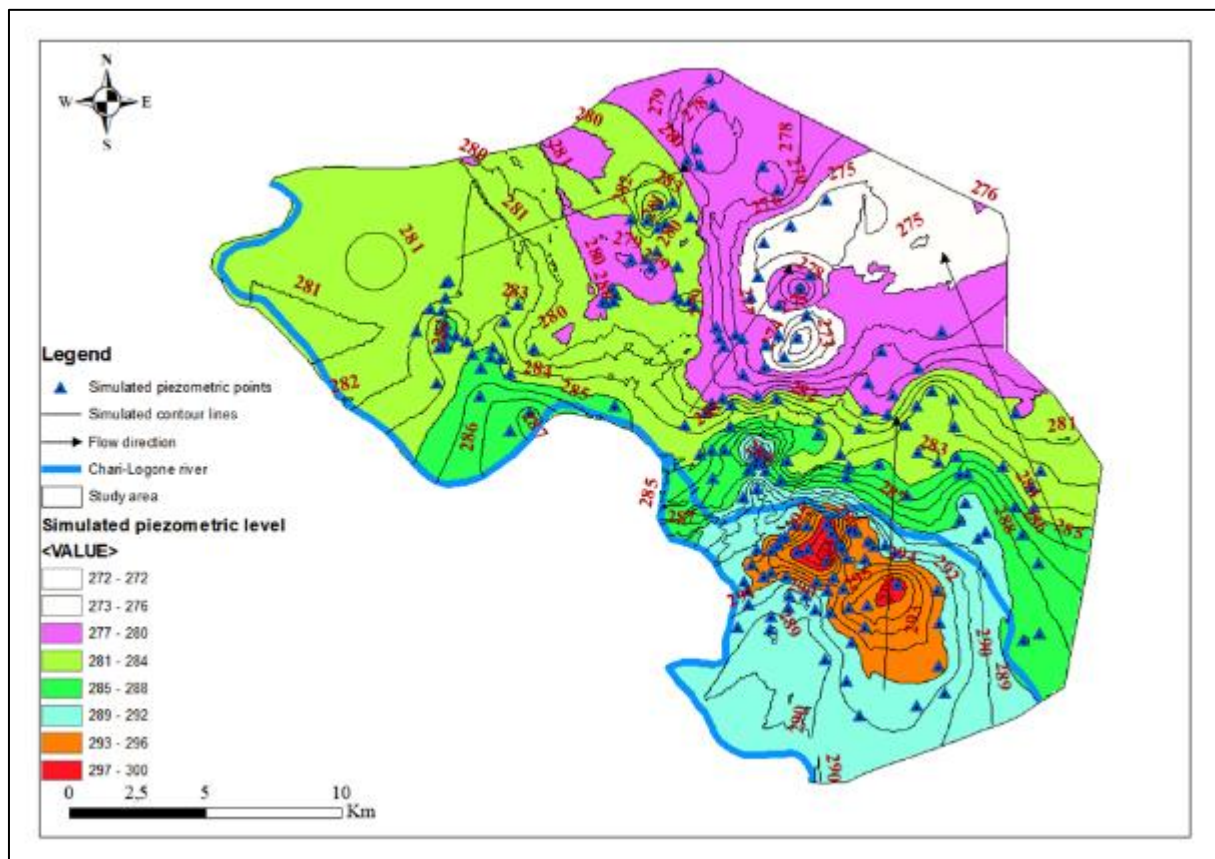


Figure 7: Simulated groundwater head map (piezometric map) and flow direction of study site.

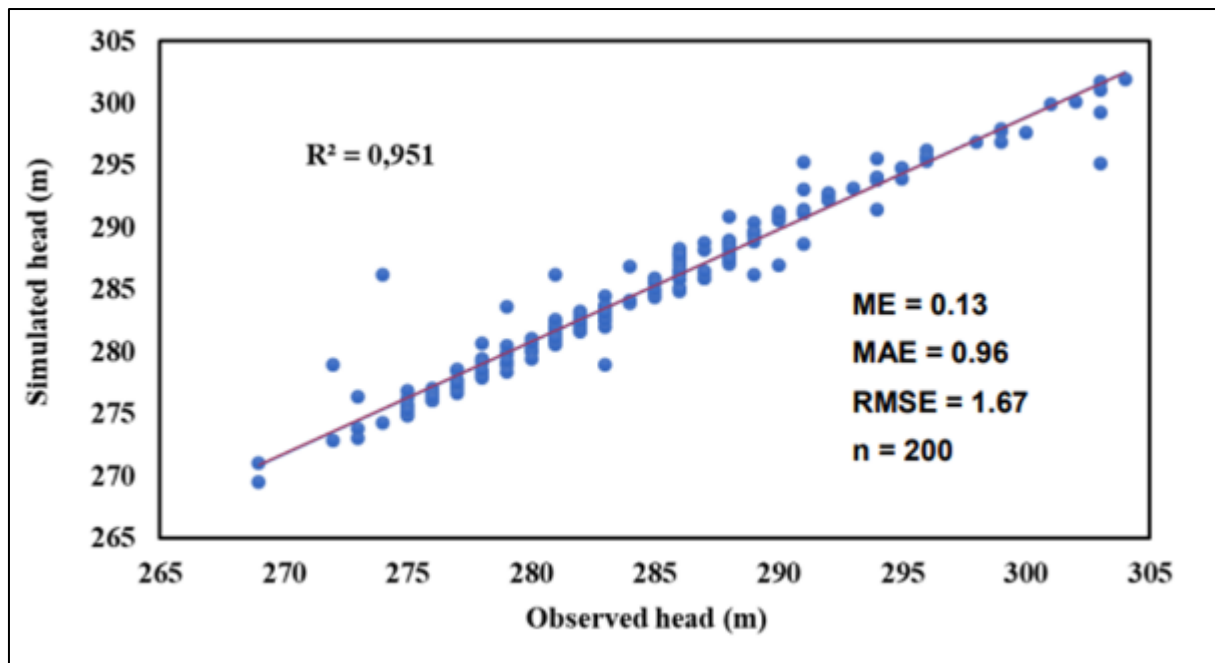


Figure 8: Scatter plot of observed and simulated groundwater heads.

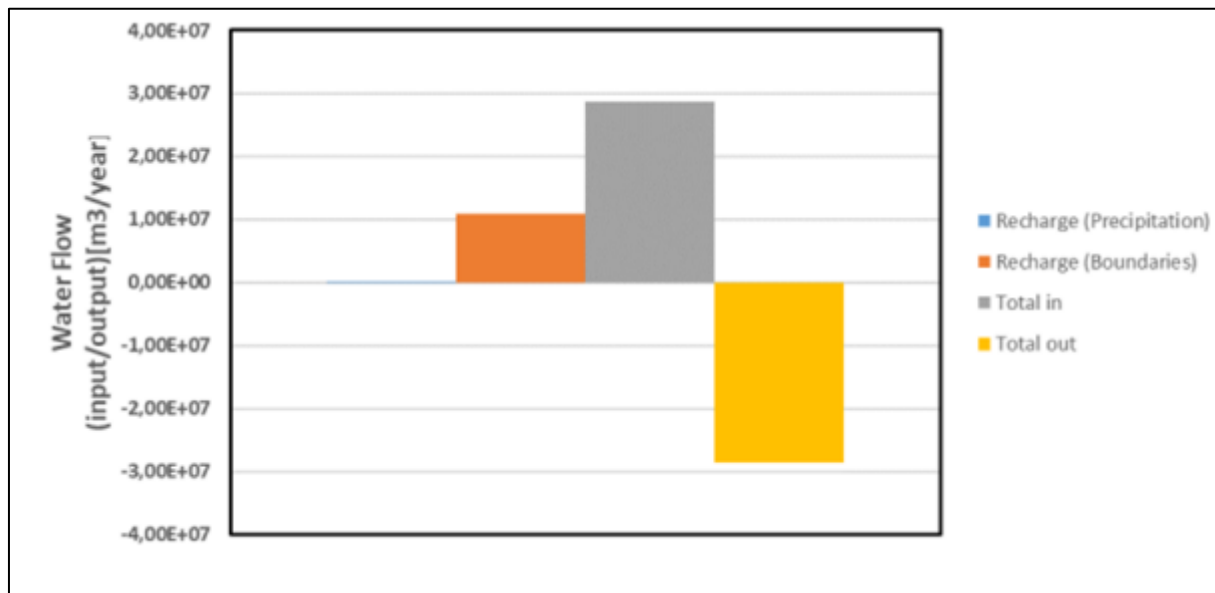


Figure 9: Groundwater budget in the steady-state flow regime of the study area

4 CONCLUSION

In urban areas, groundwater is a key resource for drinking water supply, industry and ecosystem services. In N'Djamena City (Chad, Central Africa), groundwater is the main source of drinking water. However, groundwater flow within the city is poorly understood due to the scarcity of hydrogeological data available for this complex aquifer system. The primary goal of this study was to analyze groundwater flow dynamics in the urban environment of N'Djamena, in response to growing concerns regarding the overexploitation of groundwater resources and the lack of scientific management tools at the urban scale. To do this, Combined approach including field studies and modeling are done. Field studies concerned monitoring of 200 boreholes and wells in order to obtain piezometric data. The Groundwater Modeling System (GMS) as graphical interface of MODFLOW is used to simulate the groundwater flow in the desired area. Piezometric monitoring conducted across 200 boreholes and wells made it possible to produce a representative piezometric map, showing levels ranging from 269.55 m to 304.01 m and a general flow direction from southeast to northwest, confirming the direct influence of the Chari River on groundwater dynamics. The model calibration is done

using steady-state and result showed that the model reproduced successfully the hydrodynamic behavior of the urban aquifer of N'Djamena. In addition, some evaluation indices such as mean error, mean absolute error, and root mean square error are calculated. According to these goodness statistic parameters, the performance of the model is promising. This study constitutes a first step towards the detailed and integrated hydrodynamic modeling of the water table at the urban scale of N'Djamena, thus filling an important scientific gap. It provides an operational decision-making tool for the sustainable management of groundwater resources in the face of increasing anthropogenic and climatic pressures.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare that they have no competing interests.

Author contribution

- Tidjani BAHAR: Conceptualization, Investigation, Resources, Supervision, Methodology, Writing-original draft & editing
- Djimadjimbaye Eraste: Conceptualization, Investigation, Data curation
- .Kaltouma Abakar: Investigation, Data curation

REFERENCES

- [1] Abderamane. H. (2012). Study of the hydrogeochemical functioning of the Chari-Baguirmi aquifer system (Republic of Chad) (Doctoral dissertation. Poitiers).
- [2] Aeschbach-Hertig. W.. & Gleeson. T. (2012). Regional strategies for the accelerating global problem of groundwater depletion. *Nature Geoscience*. 5(12). 853-861.
- [3] Anderson, M. P., & Woessner, W. W. (1992). *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*. Academic Press, San Diego, 381 p.
- [4] Bailey. R. T., Park. S., Bieger. K., Arnold. J. G., & Allen. P. M. (2020). Enhancing SWAT+ simulation of groundwater flow and groundwater-surface water interactions using MODFLOW routines. *Environmental Modelling & Software*. 126. 104660.
- [5] Borzì. I. (2025). Modeling groundwater resources in data-scarce regions for sustainable management: Methodologies and limits. *Hydrology*. 12(1). 11.
- [6] Boufekane. A., Saibi. H., Benlaoukli. B., & Saighi. O. (2019). Scenario modeling of the groundwater in a coastal aquifer (Jijel plain area, Algeria). *Arabian Journal of Geosciences*. 12(24). 799.
- [7] Bradley. R. M., Weeraratne. S., & Mediwake. T. M. (2002). Water use projections in developing countries. *Journal-American Water Works Association*. 94(8). 52-63.
- [8] Cao. G., Zheng. C., Scanlon. B. R., Liu. J., & Li. W. (2013). Use of flow modeling to assess sustainability of groundwater resources in the North China Plain. *Water Resources Research*. 49(1). 159-175.
- [9] Dalin. C., Taniguchi. M., & Green. T. R. (2019). Unsustainable groundwater use for global food production and related international trade. *Global Sustainability*. 2. e12.
- [10] El Alfy. M. (2014). Numerical groundwater modelling as an effective tool for management of water resources in arid areas. *Hydrological Sciences Journal*. 59(6). 1259-1274.
- [11] El Alfy. M. (2014). Numerical groundwater modelling as an effective tool for management of water resources in arid areas. *Hydrological Sciences Journal*. 59(6). 1259-1274.
- [12] Gebru. H., Gebreyohannes. T., Hagos. E., & Perilli. N. (2025). Hydrogeological assessment and steady-State groundwater flow modeling for groundwater management in the Golina River Sub-Basin. Northern Ethiopia. using MODFLOW 6. *Water*. 17(7). 949.
- [13] Gilli. É., Mangan. C., & Mudry. J. (2012). *Hydrogeology: Objects, Methods, Applications* (3e éd.). Dunod.

- [14] Gorelick. S. M. (1983). A review of distributed parameter groundwater management modeling methods. *Water Resources Research*. 19(2). 305-319.
- [15] Griebler. C.. & Avramov. M. (2015). Groundwater ecosystem services: a review. *Freshwater Science*. 34(1). 355-367.
- [16] Howard. K. W. F. (2002). Urban groundwater issues—an introduction. In *Current problems of hydrogeology in urban areas. urban agglomerates and industrial centres* (pp. 1-15). Dordrecht: Springer Netherlands.
- [17] Izady. A.. Abdalla. O.. Joodavi. A.. & Chen. M. (2017). Groundwater modeling and sustainability of a transboundary hardrock–alluvium aquifer in North Oman Mountains. *Water*. 9(3). 161.
- [18] Kadjangaba, E. (2007). Hydrochemical and isotopic study of the unsaturated zone-aquifer system in the urban area of N'Djamena: impact of pollution. (Doctoral dissertation. Avignon).
- [19] Kadjangaba. E.. Huneau. F.. Travi. Y.. & Djoret. D. (2017). Recharge and groundwater quality of an alluvial aquifer: case of the city of N'Djamena (Chad). *Journal of Environmental Science and Engineering B*. 6. 493-505.
- [20] Khadri. S. F. R.. & Pande. C. (2016). Ground water flow modeling for calibrating steady state using MODFLOW software: a case study of Mahesh River basin. India. *Modeling Earth Systems and Environment*. 2(1). 39.
- [21] Konikow. L. F.. & Kendy. E. (2005). Groundwater depletion: A global problem. *Hydrogeology journal*. 13(1). 317-320.
- [22] La Vigna. F. (2022). Urban groundwater issues and resource management. and their roles in the resilience of cities. *Hydrogeology Journal*. 30(6). 1657-1683.
- [23] Lemoalle. J.. Magrin. G. (2014). The Development of Lake Chad: Current Situation and Possible Futures. Marseille. IRD Éditions. "Expertise collégiale" series.. 21p + USB.
- [24] Lo. W.. Purnomo. S. N.. Sarah. D.. Aghnia. S.. & Hardini. P. (2021). Groundwater modelling in urban development to achieve sustainability of groundwater resources: A case study of Semarang City. Indonesia. *Water*. 13(10). 1395.
- [25] Louis. P. (1970). Contribution of geophysics to the geological knowledge of the Lake Chad Basin. ORSTOM Memoir No. 42. p. 303.
- [26] Manghi. F.. Williams. D.. Safely. J.. & Hamdi. M. R. (2012). Groundwater flow modeling of the Arlington basin to evaluate management strategies for expansion of the Arlington desalter water production. *Water resources management*. 26(1). 21-41.
- [27] McDonald, M. G., & Harbaugh, A. W. (1988). A Modular Three-Dimensional FiniteDifference Groundwater Flow Model. U.S. Geological Survey, Techniques of Water-Resources Investigations, Book 6.
- [28] McDonald. R. I.. Green. P.. Balk. D.. Fekete. B. M.. Revenga. C.. Todd. M.. & Montgomery. M. (2011). Urban growth. climate change. and freshwater availability. *Proceedings of the National Academy of Sciences*. 108(15). 6312-6317.
- [29] McGrane. S. J. (2016). Impacts of urbanisation on hydrological and water quality dynamics. and urban water management: a review. *Hydrological Sciences Journal*. 61(13). 2295-2311.
- [30] Mishra. R. K. (2023). Fresh water availability and its global challenge. *British journal of multidisciplinary and advanced studies*. 4(3). 1-78.
- [31] Mustafa. J. S.. & Mawlood. D. K. (2024). Developing three-dimensional groundwater flow modeling for the Erbil Basin using Groundwater Modeling System (GMS). *Journal of Groundwater Science and Engineering*. 12(2). 178-189.
- [32] Ngatcha. B. N.. & Daira. D. (2010). Nitrate pollution in groundwater in two selected areas from Cameroon and Chad in the Lake Chad basin. *Water policy*. 12(5). 722-733.
- [33] Ngatcha. B. N.. Mudry. J.. Aranyossy. J. F.. Naah. E.. & Reynault. J. S. (2007). Contribution of geology, hydrogeology, and environmental isotopes to the understanding of the "depressed aquifers" of the Grand Yaéré (Northern Cameroon). "Revue des Sciences de l'Eau". 20(1). 29-43.
- [34] Rao. Y. S.. & Prasad. Y. S. (2020). Groundwater flow modeling-A tool for water resources management in the khondalite and sandstone formations. *Groundwater for Sustainable Development*. 11. 100454.
- [35] Schneider. J. L.. Wolff. J. P. (1992). Carte géologique et cartes hydrogéologiques à 1/1.500.000 de la République du Tchad : Mémoire explicatif. Document du BRGM N° 209. Vol. 2. Éditions du BRGM.
- [36] Schneider. J.L. (1989). Géologie et hydrogéologie de la République du Tchad. Thèse d'état Univ. Avignon. vol 1 et 2. 818 p.

- [37] Schwartz. F. W.. & Ibaraki. M. (2011). Groundwater: A resource in decline. *Elements*. 7(3). 175-179.
- [38] United Nations. *World Urbanization Prospects 2025*. New York. 2025.
- [39] Wang. S.. Shao. J.. Song. X.. Zhang. Y.. Huo. Z.. & Zhou. X. (2008). Application of MODFLOW and geographic information system to groundwater flow simulation in North China Plain. China. *Environmental Geology*. 55(7). 1449-1462.
- [40] Zhou. Y.. & Li. W. (2011). A review of regional groundwater flow modeling. *Geoscience frontiers*. 2(2). 205-214.