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ORIGINAL RESEARCH ARTICLE

Dynamic monitoring of unconfined and semi-confined aquifers in the Quaternary system of N'Djamena, Chad

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Abstract: This study investigates the spatiotemporal variability of unconfined and semi-confined aquifers in N'Djamena, Chad, based on dynamic monitoring conducted from 2020 to 2024. A total of 40 boreholes—18 in unconfined aquifers and 22 in semi-confined systems—were monitored using piezometers, probes, and GPS instruments during two key periods each year: May (end of the dry season) and November (post-rainy season). Groundwater depths exhibited marked seasonal fluctuations, ranging from 13.5 m to 4.1 m in unconfined aquifers and from 29.1 m to 6.3 m in semi-confined aquifers. Pearson correlation analysis revealed only a moderate relationship with temperature (r = 0.582) and a weak correlation with precipitation (r = 0.390), suggesting that groundwater level variations are not solely or linearly governed by climatic parameters. Instead, they likely result from a combination of thermal influences, delayed infiltration, and lateral recharge through semi-permeable layers**.** A comparative analysis with the Lake Chad Basin highlighted distinct recharge mechanisms shaped by geological and hydrological contrasts. These findings support differentiated aquifer management strategies—such as using unconfined aquifers for emergency supply and preserving semi-confined aquifers for long-term needs—as well as urban planning interventions, including improved drainage in flood-prone areas such as Sabangali and Gassi. This study contributes to the development of adaptive groundwater governance frameworks in water-stressed and rapidly urbanizing Sahelian environments.

Keywords: Surface water; Renewable aquifer; Quaternary aquifer; Dynamic monitoring; Groundwater levels; Climatic variability

1. Introduction

Water is essential for all living organisms and plays a crucial role in environmental sustainability and socio-economic development. In semi-arid regions such as the Lake Chad Basin in Central Africa, surface water availability is highly variable and often insufficient to meet the growing demands of rapidly expanding urban populations.[1]-[5] This variability, combined with climate change[6],[7] and increasing anthropogenic pressures such as urbanization and land-use change,[8]-[11] has made groundwater the primary source of freshwater for domestic, agricultural, and industrial use.[12]-[15]

The city of N'Djamena, the densely populated capital of Chad, has experienced significant urban growth over recent decades and now houses over three million inhabitants.[16]-[18] Despite the presence of extensive Quaternary aquifers beneath the city,[19],[20] access to safe and reliable drinking water remains a major challenge, with more than half the population experiencing inadequate access for at least 1 month/year.[14],[21] Seasonal rainfall fluctuations, unsustainable abstraction practices,[22]-[24] rapid land-use transitions,[25] and inadequate water management infrastructure[26] have placed these groundwater resources under significant stress.[27],[28]

Previous studies in the region emphasize that focused recharge from high-intensity rainfall events is a dominant mechanism of aquifer replenishment.[29],[30] However, the spatial and temporal dynamics of unconfined and semi-confined aquifers within N'Djamena remain insufficiently understood, particularly in response to urban expansion and changing land-use practices.[31]-[33] There is an urgent need for detailed monitoring and analysis to inform sustainable groundwater management and borehole siting.[34]-[36]

Studies on groundwater quality reveal the vulnerability of the Quaternary aquifers to both natural contamination and anthropogenic pollution, an issue exacerbated by unregulated urban waste and surface runoff.[21],[37] In addition, global research confirms the critical influence of climate change on groundwater recharge and sustainability, underscoring the need for locally tailored investigations.[38],[39]

The objective of this study is to analyze the dynamic behavior of the unconfined and semi-confined aquifers of the Quaternary system in N'Djamena, based on groundwater level monitoring between 2020 and 2024. The goal is to provide data-driven insights that can guide hydrological engineers and policymakers in optimizing groundwater exploitation while preserving resource sustainability.

Specifically, the study seeks to (1) characterize temporal and spatial variations in groundwater levels across key monitoring points; (2) investigate the influence of seasonal rainfall patterns on aquifer recharge processes; and (3) compare the hydrodynamic responses of unconfined versus semi-confined aquifers to environmental and anthropogenic factors.

Correspondingly, the study proposes three hypotheses. First, groundwater depth fluctuations are primarily controlled by rainfall seasonality and aquifer permeability. Second, unconfined aquifers respond more quickly and strongly to rainfall events than semi-confined aquifers. Third, spatial heterogeneity in land use and water abstraction significantly affects recharge patterns and groundwater level trends.

To verify these hypotheses, the study employs (1) statistical analysis of correlations between rainfall and groundwater level time series; (2) comparison of time lags and amplitude of responses between unconfined and semi-confined aquifers; and (3) spatial analysis integrating land use and abstraction data to assess their impact on aquifer behavior.

2. Materials and methods

2.1. Geographical location of the study area

The study was conducted in N'Djamena, the capital of Chad, located at geographical coordinates 12°06'36''N and 15°03'00''E (Figure 1), with an average altitude of 294 m.[11] This city is situated in the far west of Chad, at the confluence of the Chari and Logone rivers. Although geographically eccentric, it is bounded to the west by Hadjer-Lamis, to the east by the Dababa department, to the south by the Chari River, to the southwest by the Cameroonian division of Kousseri (across the Logone River), and to the north by the Chari-Baguirmi region. It is located about 470 km from Moundou, the country's industrial capital, and 800 km from Abéché, the historical capital and the largest city in the country.

2.2. Geology of the region

This study focuses on observations and measurements related to the dynamic monitoring of water tables, specifically within the Quaternary geological formations of the region. These formations, comprising clayey, sandy, and mixed clay-sandy deposits, span three eras: Holocene, Upper Pleistocene, and Late Lower Pleistocene.

2.2.1. Quaternary geological formation

The city of N'Djamena lies entirely within the watershed and sedimentary basin of Lake Chad. The Quaternary formations in this area reflect the broader lithostratigraphic dynamics of the Lake Chad Basin, shaped by the infill of the Chadian basin depression and by eustatic movements associated with the mega, medium, and small Lake Chad episodes up to the Holocene.

According to borehole technical sheets—including those from sites where dynamic monitoring was conducted—the stratigraphy of the study area reveals several distinct layers, as summarized in Table 1.

Sedimentological analysis distinguishes two principal aquifers within the Quaternary system,

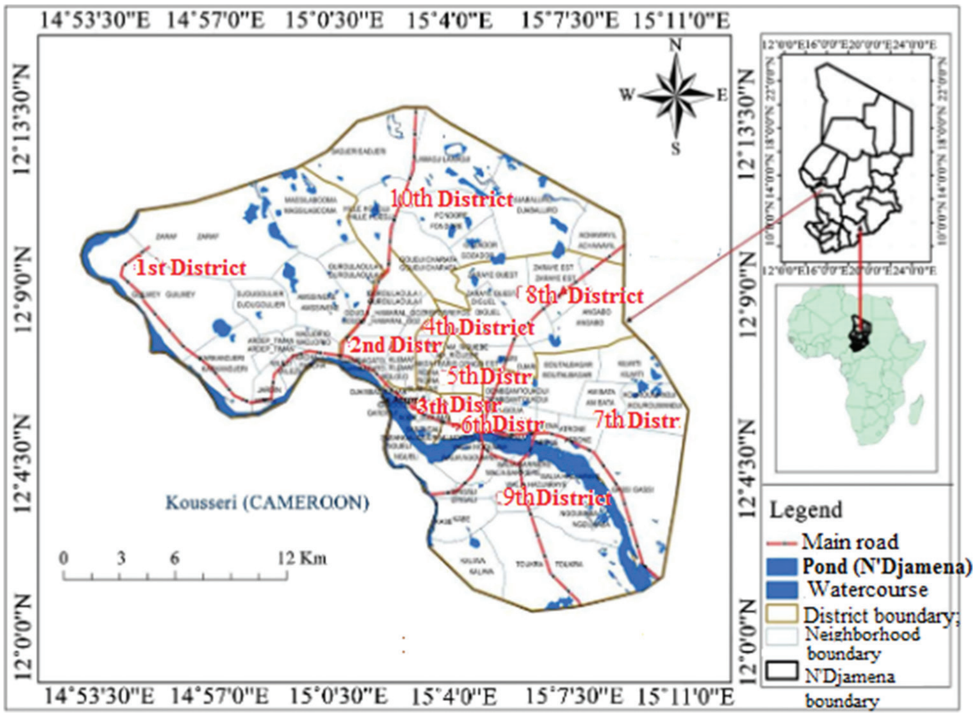

Figure 1. Geographical location of the study area.[11] Copyright © 2025 by Deubalbe *et al*. and Scientific Research Publishing Inc.

Table 1. Soil types encountered at different depths in the city of N'Djamena

Depth (m)	Soil type
0–3	Alluvium, sand, and clay of Holocene age
3–8	Sand of Holocene age
8–14	Sand of Upper Pleistocene age
14–16	Clayey-sandy, semi-impermeable layer; forms the bedrock of the unconfined water table of Upper Pleistocene age
16–20	Yellow sand of Upper Pleistocene age
20–40	White sand of Upper Pleistocene age
40–55	Pink sand of Lower Pleistocene age
55–250	Impermeable clay layer; forms the bedrock of the semi-confined aquifer of Neogene age

each with unique hydrodynamic properties related to permeability. The deep boreholes in the area typically reach depths of 45–50 m in semi-confined aquifers and 10–15 m in unconfined aquifers, as shown in Table 2.

The hydrological processes in the study area exhibit a dynamic relationship between surface water and groundwater, governed by the geological context and aquifer characteristics. The unconfined aquifers are predominantly recharged by direct rainfall infiltration through permeable sandy and clay-sandy layers, mostly associated with the Holocene and Upper Pleistocene formations. This process is subject to temporal lag effects caused by soil moisture retention and seasonal variability in precipitation.

In contrast, the semi-confined aquifers, located at greater depths within the Late Lower Pleistocene formations, are primarily recharged via lateral flow and riverbank infiltration from the adjacent Chari and Logone rivers. This lateral recharge pathway is influenced by the hydraulic connectivity between surface water bodies and the aquifer system, and is modulated by the semi-permeable clay layers acting as partial confining units.

This conceptual hydrogeological model illustrates distinct recharge mechanisms for the two aquifer types, highlighting the role of geological stratification in controlling recharge sources and flow dynamics. Furthermore, the interplay of these recharge pathways contributes to the observed temporal variations in groundwater levels, as recorded by piezometric monitoring across the study area.

Overall, understanding these mechanisms is critical to assessing the sustainability of groundwater resources in N'Djamena, particularly given the region's climatic variability and anthropogenic pressures. Table 1 thus provides not only a stratigraphic framework but also a functional context for interpreting aquifer recharge dynamics in the study area.

Table 2. Lithostratigraphy at different borehole sites in N'Djamena[11]

Era	Epoch	Layer thickness (m)	Thickness at boreholes (m)	Lithology	Types of aquifers
Quaternary	Holocene	0–8	0–3	Alluvium, sand, or clay	Unconfined aquifer
			3–14	Sand	
	Late Pleistocene	8–20	14–16	Clay-sandy (semi-impermeable layer)	Semi-impermeable base of the unconfined aquifer
			16–20	Yellow sand	Semi-confined aquifer
		20–40	20–40	White sand	
	Lower Pleistocene	40–55	40–55	Pink sand	
Tertiary	Neogene	55–250	55–250	Clay (impermeable layer)	Impermeable base of the semi-confined tablecloth

2.2.2. Geomorphology of the region

N'Djamena lies on a gently inclined plain, sloping at approximately 2° towards the northeast. The city exhibits a bowl-shaped topography and is extensively influenced by surface water flow from surrounding watercourses. Historical overflows from these watercourses have left geomorphological traces still evident today, such as depressions and ponds that now function as natural retention basins.

The region contains several small watersheds located near the banks of the Chari and Logone rivers. These include the Air Base watershed, Star watershed, Saint Martin watershed, Gardener watershed, and the Amriguebé Slope watershed.[12]

All these watersheds discharge into the adjacent riverbank. Due to the dense urban occupation of N'Djamena, natural surface runoff pathways are often obstructed or diverted, contributing to the risk and occurrence of flooding.

Some of these depressions align with the surface flow trajectory toward Lake Chad. Once these depressions are filled, part of the overflow continues toward the Barh El Gazel. These basin areas are characterized by a combination of spongy and impermeable clay soils, which favor the retention of enormous masses of water during the rainy season and contribute to seasonal flooding.

2.3. Materials

2.3.1. Piezometers

Piezometers (iLevelGW, KISTERS AG, Germany) are essential hydraulic instruments designed to observe the variation of groundwater levels over time. They were installed in boreholes or wells and are used to assess fluctuations in the water table. The measurement process involves inserting a water level probe into the structure until it comes into contact with the water, at which point the device emits a visual or audible signal. The depth was then read directly from the graduated tape. By subtracting this reading from the coping elevation (the top of the well or borehole), the exact groundwater depth was determined. This method offers precise tracking of level changes, enabling reliable interpretation of recharge and drawdown events within the aquifer.[1],[4]

2.3.2. Water level probe and GPS receiver

The water level probe (GoudaGeo standard waterlevel meter, Gouda GeoEquipment B.V., Netherlands) consists of a graduated cable integrated with an electrical circuit that activates a sound or light signal upon contact with water. This mechanism allowed accurate detection of groundwater depth during field investigations. In parallel, the geographic coordinates of each structure were recorded using a GPS receiver (CHCNav I76 GNSS RTK receiver, CHC Navigation, China) to ensure accurate spatial positioning. This step is crucial for mapping and for establishing spatial correlation between groundwater behavior and site characteristics.[2],[31]

2.4. Groundwater dynamics data acquisition

A total of 40 observation boreholes were selected for continuous monitoring of groundwater dynamics, including 18 wells tapping the unconfined aquifer and 22 targeting the semi-confined system. These sites were chosen to evaluate temporal variations in aquifer levels in response to climatic variability and anthropogenic pressures.

The monitoring network was strategically distributed across multiple sectors of N'Djamena, including residential districts, industrial areas, peri-urban zones, and sites near the Chari River. In addition, the boreholes were located within distinct geological formations such as clay-sand layers, alluvial zones, and silty deposits. This spatial heterogeneity was necessary to ensure that the dataset reflects the diversity of hydrogeological conditions and urban land uses, thereby improving the relevance and generalizability of the results.[3],[13],[17]

2.4.1. Acquisition of existing digital databases

From 2020 onward, the Ministry of Water and Energy of Chad, through the Documentation and Geographic Information Center, has undertaken the compilation and digitization of groundwater monitoring data. These datasets document seasonal and interannual fluctuations in aquifer levels up to 2024. Upon collection, the data were subjected to verification procedures, including consistency checks and critical comparison of annual trends. Each time-series record was geo-referenced and linked to the corresponding land use and hydrogeological environment, enabling a more integrated interpretation of the data. Any variations or inconsistencies in recorded data were analyzed to identify their underlying causes, which ranged from reduced rainfall and drought events to overexploitation of groundwater resources.[5],[7],[8]

This spatialized approach allowed for the detection of contrasting behaviors, with more pronounced declines in groundwater levels observed in densely urbanized and industrialized zones, while more stable trends were recorded in peripheral or river-adjacent areas. These evaluations also contributed to refining future measurement planning and improving data collection strategies.[10]

2.4.2. Field data acquisition via dynamic monitoring

In addition to the historical records, new in situ measurements were conducted throughout 2023 to assess the current status of both aquifer types. To capture seasonal variability, two strategic periods were selected: November, which follows the rainy season and typically reflects maximum recharge, and May, the height of the dry season when groundwater levels tend to reach their lowest point. These periods were selected to maximize observation of aquifer responses to both natural recharge and anthropogenic extraction pressures. This approach allowed for comparison of groundwater behavior in various sectors, revealing differences between zones benefiting from natural recharge and those suffering from urban sealing or over-pumping.[1],[17],[39] The seasonal observations thus provided valuable insights into aquifer dynamics, particularly in terms of their vulnerability and recharge capacity under diverse environmental and urban conditions.[4],[9]

2.5. Dependency of groundwater depths on temperature and precipitation: Pearson correlation coefficient

The Pearson correlation coefficient (r) quantifies the linear association between two quantitative variables. It is calculated by dividing the covariance of the variables by the product of their standard deviations, as shown in Equation I.[40],[41]

$$r = \frac{\sum_{i=1}^{n}(\mathrm{x_i}-\overline{\mathrm{x}})(\mathrm{y_i}-\overline{\mathrm{y}})}{\sqrt{\sum_{i=1}^{n}\left(\mathrm{x_i}-\overline{\mathrm{x}}\right)^2}\sqrt{\sum_{i=1}^{n}\left(\mathrm{y_i}-\overline{\mathrm{y}}\right)^2}} \tag{I}$$

Where x_i and y_i are paired observations, $\overline{x_i}$ and $\overline{y_i}$ are the respective means, and n is the number of observation pairs.

The coefficient r ranges from −1 (perfect negative correlation) to +1 (perfect positive correlation), with 0 indicating no linear relationship. The magnitude describes the strength of the correlation, and the sign indicates the direction of the relationship.

3. Results

3.1. Preliminaries

The unconfined (free) water table corresponds to the subsurface layer consisting of two parts: the unsaturated zone, where pores are partially filled with air, and the saturated zone, where pores are fully saturated with water—also known as the phreatic zone. Horizontal groundwater flow occurs when rainfall infiltrates and percolates vertically through the unsaturated zone, recharging the saturated zone aquifer (the free water table). The observed water movements were processed and interpreted as hydrogeological information, including both vertical and horizontal flows. A synthesis of these findings is presented in Table 3.

3.2. Dynamics of the quaternary aquifers of N’Djamena

From 2020 to 2023, the free water table of N’Djamena exhibited marked fluctuations. During the dry season (May), the water table depth increased, while in the rainy season (November), the water table rose closer to the surface (Figure 2). This indicates the presence of a recharge reserve replenishing the aquifer, consistent with findings reported by Bada.[42]

In 2021, fluctuations were minimal due to low rainfall. By May 2022, the water table had deepened significantly, but following heavy rains in November 2022, the water table rose from 11.00 m to 1.40 m

Table 3. Dynamic groundwater level monitoring of quaternary aquifers in N'Djamena (2020–2024)

No.	Locality	Alt	Sub-division	Groundwater depths (m)								
				2020		2021		2022		2023		2024
				May	November	May	November	May	November	May	November	May
1	Farcha	297	1st	8.35	4.10	8.20	7.70	13.50	8.90	10.50	8.90	12.95
2	Milezi	292	1st	8.35	4.00	7.95	5.00	12.70	7.50	8.80	7.95	11.00
3	Karkand	293	1st	8.65	5.90	9.80	8.60	14.00	8.80	10.80	9.95	12.90
4	Madjorio	292	1st	12.50	8.00	12.10	11.40	19.30	12.40	14.00	13.10	17.00
5	Farcha. In	293	1st	12.65	8.50	12.60	11.70	19.50	12.60	14.00	13.80	17.50
6	Amsinené	292	1st	17.50	14.90	17.95	16.96	24.90	17.95	18.98	16.00	19.60
7	Abourdja	295	1st	17.50	14.85	18.80	17.90	25.90	18.99	20.00	18.90	22.10
8	Goudji.H	293	2nd	21.02	18.60	22.70	21.90	28.90	24.90	26.50	24.90	28.90
9	Sabangali	297	3rd	10.50	6.30	10.20	9.80	18.00	11.20	12.80	10.20	14.60
10	Repos	292	4th	21.25	17.10	21.20	20.00	27.80	21.40	23.00	21.40	25.45
11	Repos	310	4th	22.04	19.75	23.90	22.30	29.10	23.50	21.00	18.60	22.65
12	Ridina	290	5th	17.94	13.65	17.75	15.25	23.05	16.25	17.85	15.45	19.60
13	Atrone	294	7th	6.17	1.85	6.00	5.10	13.00	6.80	8.50	6.40	10.90
14	Gassi1	295	7th	6.75	2.70	6.70	6.00	13.50	6.80	9.50	7.50	11.30
15	Gassi2	288	7th	8.00	3.90	7.61	6.50	7.64	2.00	6.80	5.10	8.30
16	Gassi3	295	7th	8.37	4.20	8.60	7.00	13.10	8.00	10.70	9.10	13.20
17	Gassi4	297	7th	8.67	4.60	9.00	8.10	13.60	8.20	11.30	10.50	14.10
18	Gassi5	297	7th	10.24	7.90	11.90	10.00	18.20	8.50	13.10	11.00	15.10
19	Gassi6	292	7th	11.20	6.90	12.00	11.10	19.00	9.00	13.60	11.50	15.50
20	Chagoua	293	7th	11.52	7.50	11.60	10.80	18.90	9.80	13.20	11.90	16.00
21	Boutal1	293	7th	12.67	8.30	12.20	10.80	18.50	10.30	12.90	11.10	15.10
22	Boutal2	293	7th	15.50	11.10	15.50	14.20	22.80	11.50	16.90	14.10	18.00
23	Angabo	291	8th	13.75	8.90	13.90	12.50	20.80	13.10	14.80	12.70	16.50
24	Diguel.K	292	8th	18.60	14.50	18.90	17.10	24.90	17.60	18.70	15.90	19.10
25	Darassalam	301	8th	18.67	13.90	17.20	16.90	23.10	15.80	16.90	14.90	18.10
26	Angabo	291	8th	19.30	15.20	18.90	17.70	25.00	16.80	18.20	16.50	20.60
27	Ndjari.K	297	8th	19.45	14.80	18.30	17.10	25.20	17.60	18.20	17.5	22.60
28	Kabé	293	9th	6.00	2.10	5.40	3.00	11.00	1.40	4.00	1.30	6.80
29	Walia.B	296	9th	6.10	2.50	5.70	3.10	11.10	1.40	4.60	2.00	7.80
30	Ngueli	296	9th	6.20	2.10	5.80	3.20	11.30	1.50	5.10	2.30	9.80
31	Walia.H	297	9th	6.30	2.50	6.00	3.00	11.00	1.50	4.80	2.50	7.95
32	Toukra2	295	9th	6.35	2.70	6.10	3.30	11.10	1.60	5.00	3.00	8.00
33	Kaliwa	291	9th	6.90	2.85	6.95	5.10	13.50	1.80	7.60	6.30	10.40
34	Ngonba.S	295	9th	7.00	2.50	6.00	5.00	11.10	2.80	6.30	5.20	9.80
35	Toukra1	299	9th	7.20	2.80	6.10	5.90	11.80	2.00	6.75	5.90	10.95
36	Walia.N	294	9th	7.30	3.00	6.50	6.10	12.90	2.20	7.90	6.85	11.10
37	Ngonba	293	9th	7.80	3.00	7.10	6.80	12.10	2.50	7.50	7.00	11.20
38	Gaoui	294	10th	15.20	10.90	13.80	12.60	20.60	14.50	15.85	14.00	18.00
39	Goudji.C1	291	10th	20.20	15.70	19.60	17.80	24.10	14.90	18.70	17.60	10.90

(Cont'd...)

Table 3. ***(Continued)***

No.	Locality	Alt	Sub-division	Groundwater depths (m)								
				2020		2021		2022		2023		2024
				May	November	May	November	May	November	May	November	May
40	Goudji.C2	293	10th	20.45	15.90	20.30	18.10	25.00	15.20	19.10	18.10	11.20
				12.25	8.26	12.17	10.81	18.01	10.24	12.87	11.17	14.81
				5.37	5.51	5.59	5.71	6.01	6.66	5.65	5.69	5.18

Note: Groundwater depth measurements (in meters) at selected boreholes from the Documentation and Geographic Information Center of the Ministry of Water and Energy (CDIGMEE).

Abbreviations: Alt: Altitude; Boutal: Boutalbagara; Diguel.K: Diguel Koudou; Farcha.In: Farcha Industrial; Goudji.C: Goudji Charafa; Goudji.H: Goudji Hamralgoz; Karkand: Karkand jeri; Ndjari.K: Ndjari Kwass; Ngonba.S: Ngonba Sara; Walia.B: Walia Barrière; Walia.H: Walia Hadjarai; Walia.N: Walia Ngoussou.

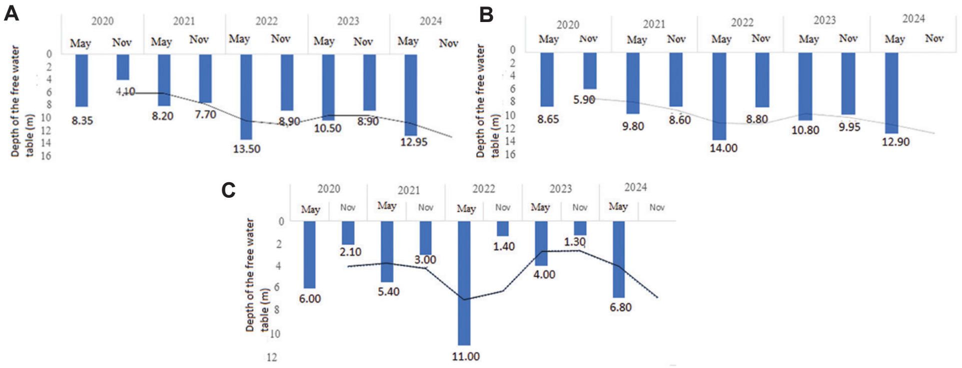

Figure 2. Dynamics of the quaternary free water table at N'Djamena from 2020 to 2024 at three monitoring piezometers. (A) NEWB050, Farcha (1st district). (B) NEWB046, Karkandjeri (1st district). (C) NEWB091, Kabé (9th district).
Note: The blue bars indicate measured average depths during May and November of each year, while the dashed line represents the average trend.

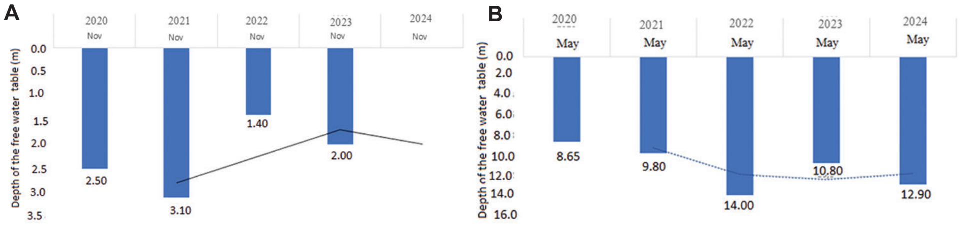

Figure 3. Variation in the minimum depth of the unconfined aquifer during recharge periods in N'Djamena at two piezometers. (A) NEWD074, Walia Barrier (9th district). (B) NEWB046, Karkandjeri (1st) district.
Note: The blue bars indicate measured average depths during May and November of each year, while the dashed line represents the average trend.

(Figure 2C). This pattern illustrates how lower precipitation and higher temperatures enhance surface water evaporation, reducing recharge and increasing aquifer depth. For example, between November 2021 and May 2022, the aquifer level deepened from 3.00 m to 11.00 m, reflecting insufficient recharge linked to poor rainfall in 2021 (Figures 2-4). Similar dynamics were observed in the semi-confined aquifer.

It is important to highlight that these groundwater fluctuations are driven not only by climatic factors but also by human influences, such as water extraction and urban land sealing. Urban expansion reduces infiltration and alters recharge regimes, which may explain abrupt local variations and drawdowns observed in densely populated and industrialized areas.[3],[5]

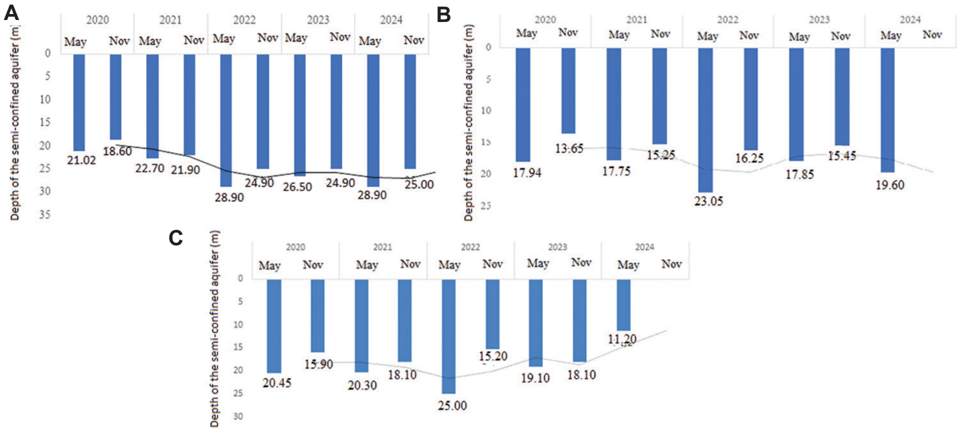

Figure 4. Dynamics of the semi-confined Quaternary aquifer in N'Djamena from 2020 to 2024 at three monitoring piezometers. (A) NEWB075, Goudji Hamralgoz (2nd district). (B) NEWD061, Ridina (5th district). (C) NEWB076, Goudji Charafa (10th district).

Note: The blue bars indicate measured average depths during May and November of each year, while the dashed line represents the average trend.

To ensure data reliability, rigorous quality control procedures were applied, including systematic outlier detection, regular calibration of water level probes, and the exclusion of readings influenced by pumping activities. These measures enhance confidence in the observed trends of seasonal recharge and discharge (Figures 2 and 3).

3.2.1. Minimum recharge depth

The minimum recharge depth of the unconfined aquifer reflects the extent to which the aquifer has been recharged. When the aquifer is overloaded, groundwater can emerge at the surface, contributing to flooding. The minimum recharge depth recorded in November 2022 was 1.40 m (Figure 3A), indicating very shallow groundwater access during high rainfall years such as 2022 and 2024.

3.2.2. Maximum depth of discharge

The maximum discharge depth indicates periods of aquifer depletion. In May 2022, following low rainfall in 2021, the free water table at Karkandjeri (1st district) was completely depleted, with groundwater levels reaching 14 m—the full depth of the borehole (Figure 3B). Typically, the maximum depth to access the free water table ranges between 14 and 16 m.

3.3. Dynamics of the semi-confined aquifer

The semi-confined aquifer consists of a water-bearing porous layer capped by a semi-impermeable clay-sandy layer approximately 2 me thick, dated to the Upper Pleistocene. Similar to the unconfined aquifer, the semi-confined system exhibited seasonal fluctuations during the dry (May) and wet (November) periods (Figure 4). In the N'Djamena area, this aquifer is typically encountered at depths of 40–50 m.

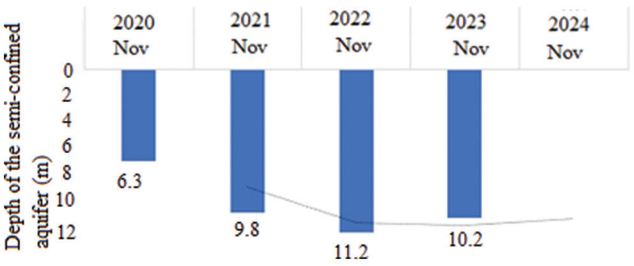

Figure 5. Variation in the minimum depth of the semi-confined Quaternary aquifer during recharge periods in N'Djamena at the NEWD050 piezometer (Sabangali, 3rd district).

Note: The blue bars indicate measured average depths during November of each year, while the dashed line represents the average trend.

3.3.1. Minimum recharge depth

The minimum recharge depth observed for the semi-confined aquifer was 6.30 m (Figure 5), which is considerably deeper than the 1.40 m found for the free water table (Figure 3B).

3.3.2. Maximum depth of discharge

The maximum depth of discharge for the semi-confined aquifer reached 29.10 m, significantly exceeding the 14 m maximum depth observed in the free water table

(Figure 6). This finding suggests a greater storage capacity and resilience of the semi-confined aquifer, although it also indicates a greater vulnerability to deep drawdowns under prolonged stress conditions.

3.4. Climate impact on renewable groundwater in N'Djamena

Climatic variables, particularly temperature and rainfall, exert a major influence on the behavior of shallow aquifers in N'Djamena. In 2022, a year marked by elevated average temperatures (33°C) and abundant precipitation exceeding 1000 mm, significant groundwater recharge was observed. This was reflected in a relatively shallow groundwater depth of 3.8 m, suggesting enhanced infiltration. In contrast, the year 2021 recorded lower temperatures (~31.7°C) and reduced rainfall (~645.7 mm), resulting in a deeper groundwater table of around 5.2 m, indicative of limited recharge. These interannual variations are detailed in Table 4.

The trends are visually presented in Figure 7, showing the relationships between average groundwater depth and temperature or rainfall, as well as the annual evolution of groundwater depth, temperature, and total rainfall. The patterns suggest that rainfall remains the dominant factor in aquifer recharge, while high temperatures can either promote or hinder infiltration depending on soil saturation and surface conditions.

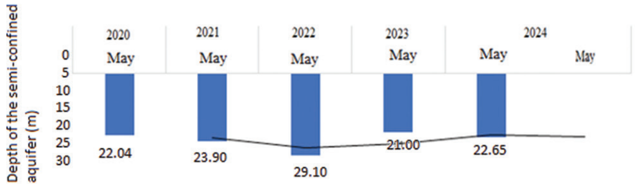

Figure 6. Variation in the maximum depth of the semi-confined quaternary aquifer during discharge periods in N'Djamena at the NEWD065 piezometer (Repos, 4th district).

Note: The blue bars indicate measured average depths during May of each year, while the dashed line represents the average trend.

Urbanization further complicates the recharge process. As land surface sealing increases due to urban expansion, natural infiltration pathways are obstructed, reducing groundwater recharge even in years of high rainfall. This leads to persistently deeper groundwater levels during dry periods and modifies the aquifer's natural response to climatic variability.[3],[5]

Pearson correlation analysis, calculated using Equation I and the average values presented in Table 4, shows a moderate positive correlation ($r = 0.582$) between aquifer depth and temperature. This suggests that thermal effects—potentially from geothermal gradients or urban heat island phenomena—may influence groundwater distribution. In contrast, the correlation between groundwater depth and rainfall was weaker ($r = 0.390$), indicating that recharge processes are not governed by direct precipitation alone but also by delayed infiltration and lateral recharge through semi-permeable geological layers.

4. Discussion

The groundwater depth patterns observed in N'Djamena broadly align with regional hydrogeological trends documented in Chad. The unconfined water table exhibited significant seasonal fluctuations, ranging from approximately 0.5 m in January to around 14 m in May–June. Similar variations were observed in adjacent aquifer systems, including polder areas (0–3 m) and perched aquifers (0–5 m), which are sensitive to seasonal recharge processes near lake margins. These fluctuations are largely governed by soil texture and proximity to Lake Chad, consistent with prior findings.[13]

Seasonal peaks in groundwater levels were closely linked to hydrological inputs from the south, primarily the Chari and Logone rivers. Originating from the humid southern regions, these rivers typically reach peak discharge in October and contribute to Lake Chad's recharge cycle in January.[14] Within the Lake Chad basin, aquifers benefit from dual recharge mechanisms:

Table 4. Average climatic parameters and groundwater depth in N'Djamena (2020–2024)

Parameter	2020		2021		2022		2023		2024	Average
	May	November	May	November	May	November	May	November	May	
GWD (m)	12.25	8.26	12.17	10.81	18.01	10.24	12.87	11.17	14.81	12.29
Temperature (°C)	25.80	30.00	34.50	30.00	35.00	29.80	36.50	30.50	36.80	32.10
Precipitation (mm)	4.40	0	42.70	0	12.50	0	11.90	0	20.50	10.22

Abbreviation: GWD: Groundwater depth in N'Djamena.

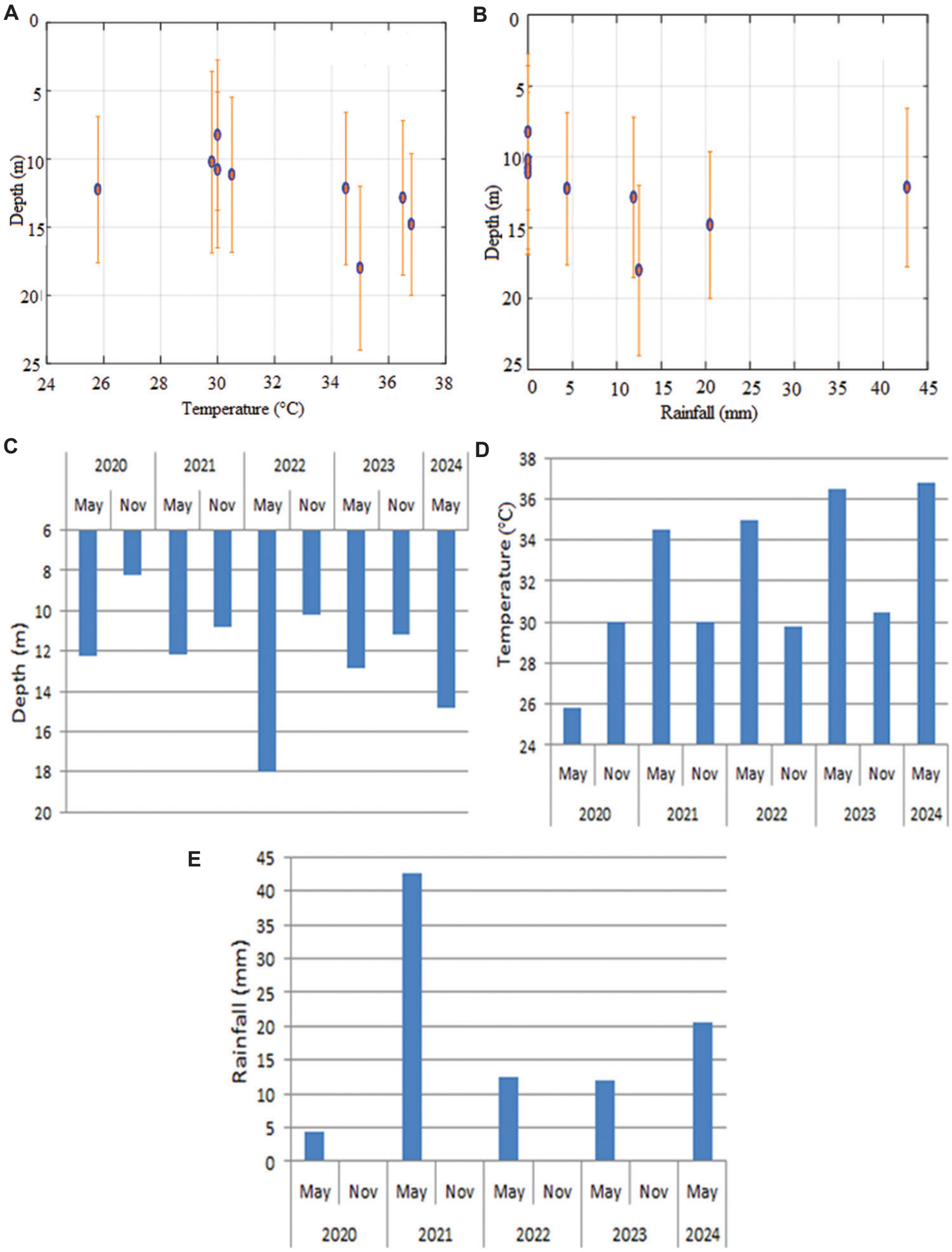

Figure 7. Influence of climate parameters on groundwater levels in N'Djamena, based on data from the Water Resources Department. Relationship between average aquifer depth and temperature (A) and average rainfall (B); data are presented as mean ± standard deviations. Average depth to the water table from May 2020 to May 2024 (C), and corresponding average temperature (D) and rainfall (E) during the same periods.

direct infiltration of rainfall during the wet season (August–September) and lateral inflow from the lake. The dominance of coarse sandy lithology in these areas promotes rapid infiltration and supports relatively stable moisture conditions.

In contrast, the hydrogeological context of N'Djamena appeared more constrained due to the predominance of clayey soils interbedded with sandy layers, which limit vertical recharge and slow infiltration. Although the Chari and Logone rivers lie at elevations higher than the city, their contribution to local groundwater recharge is limited, especially during low-flow periods. In addition, rising temperatures between March and June exacerbate evapotranspiration, leading to drying of shallow wells and increased vegetation stress, thereby amplifying the impact of climatic variability on aquifer behavior.

Notably, flood events in October 2024 revealed the dynamic interaction between surface water and groundwater. Elevated river levels caused groundwater resurgence in low-lying urban neighborhoods such as Sabangali, Moursal, and Klemat, where piezometric levels temporarily exceeded ground surface elevations, resulting in localized flooding. This phenomenon highlights the vulnerability of urban aquifers to extreme hydrological events.

While the present study did not implement a formal, rigorous data quality control protocol, future investigations should adopt such procedures. These include systematic outlier detection, regular instrument calibration, and the exclusion of data affected by anthropogenic activities (e.g., pumping), to enhance the reliability of groundwater fluctuation analyses.

From a socio-economic perspective, the escalating issue of water scarcity in Chad—especially in rapidly urbanizing N'Djamena—underscores the importance of understanding groundwater dynamics. Urban expansion and surface sealing reduce natural recharge areas, while rising water demand intensifies pressure on subsurface resources. These factors collectively alter the natural balance between recharge and exploitation, calling for integrated management approaches that combine continuous hydrogeological monitoring, sustainable urban planning, and climate adaptation strategies.

In this context, integrating artificial intelligence (AI) into groundwater monitoring—particularly for predicting water quality indices (WQI)—offers promising advances in forecasting, early warning systems, and decision-making. Recent studies have demonstrated that AI models, such as artificial neural networks, support vector regression, and explainable AI techniques like SHAP and LIME, can enhance the accuracy, interpretability, and spatial resolution of groundwater quality predictions.[43]-[46] Such developments align directly with the United Nations Sustainable Development Goals (SDGs), including SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities), and SDG 13 (Climate Action).

5. Conclusion

This study provides a detailed characterization of the recharge dynamics and seasonal variability in the Quaternary aquifers of N'Djamena, highlighting distinct behaviors between unconfined and semi-confined systems. By integrating field observations with historical data, the analysis reveals how climatic variability and anthropogenic pressures jointly influence aquifer responses in an urban Sahelian setting. A key contribution of this work lies in its comparative perspective with the Lake Chad basin, demonstrating contrasting recharge mechanisms within a relatively short distance (<200 km), primarily driven by differences in stratigraphy, soil texture, and hydrological connectivity.

The results demonstrated pronounced seasonal variability in unconfined aquifers, with water table depths ranging from 13.5 m in May to 4.1 m in November at Farcha, consistent with patterns observed across other monitored sites. Semi-confined aquifers exhibited fluctuations between a minimum recharge depth of 6.3 m in November and a maximum discharge depth of 29.1 m in May, reflecting their heightened sensitivity to climatic and anthropogenic factors. Compared to prior studies based on limited point observations or short-term dataset, this research provides a more comprehensive spatial and temporal perspective on groundwater behavior in N'Djamena, thereby filling an important gap in regional hydrogeological knowledge.

Looking forward, the implementation of a national groundwater monitoring protocol is essential. This should include procedures for outlier detection, routine instrument calibration, and the exclusion of data influenced by anthropogenic activities. Furthermore, the development of a robust hydrogeological conceptual model is recommended to distinguish vertical recharge from precipitation and lateral inflows from surface water bodies. From a management standpoint, unconfined aquifers should be prioritized for short-term or emergency water supply, whereas semi-confined aquifers ought to be preserved for long-term, sustainable use. In addition, urban planning strategies must integrate improvements in drainage infrastructure, particularly in flood-prone areas such as Sabangali and Gassi. These actions require an integrated groundwater governance framework that combines enhanced monitoring, predictive modeling, and adaptive policies tailored to the climatic and urban realities of the Sahel region.

Incorporating AI into groundwater monitoring—particularly for WQI estimation—can significantly enhance prediction accuracy, system resilience, and evidence-based decision-making. These technological advancements support the implementation of adaptive and integrated groundwater governance frameworks that are well-aligned with the SDGs.

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Conflict of interest

The authors declare that they have no competing interests.

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All data generated or analyzed during this study are included in this published article. No additional datasets were used or generated.

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