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SPATIO-TEMPORAL ANALYSIS OF GROUNDWATER LEVEL IN KADUNA METROPOLIS, KADUNA, NIGERIA

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ABSTRACT

This study investigates the spatial and temporal variations in groundwater levels across Kaduna Metropolis, Nigeria. As urban development accelerates and climate conditions shift, understanding how groundwater responds to these changes is essential. The research involved a combination of field measurements from six monitoring wells, meteorological data, satellite-based land use analysis, and statistical techniques such as regression and correlation. Results indicate a consistent decline in groundwater levels throughout the study period. The dry season saw significant drawdowns, while the rainy season offered only limited recovery. Urban centers like Barnawa and Malali recorded the most severe reductions, largely due to increased water extraction and a lack of natural recharge caused by impervious surfaces. Temperature showed a stronger correlation with groundwater fluctuations than rainfall, suggesting that rising temperatures and evaporation rates are playing a greater role in water loss. The land-use analysis revealed growth of over 31 square kilometers in the urban area, further limiting the ground's ability to absorb rainfall. These findings highlight the urgent need for improved groundwater governance. Key recommendations include stricter borehole regulations, encouragement of artificial recharge practices, and integration of water sustainability into urban planning. The study contributes valuable insights for policymakers and stakeholders aiming to ensure long-term water security, aligning with national priorities and global objectives such as Sustainable Development Goal 6, advocating for resilient groundwater systems amidst the challenges posed by climate change and urban encroachment.

Keywords: Groundwater fluctuation, Groundwater assessment, Groundwater management, Kaduna Metropolis

INTRODUCTION

Groundwater is a valuable resource in arid and semi-arid regions where surface water is unreliable (Taylor *et al*., 2013). The overreliance on groundwater in urban areas, driven by rapid population growth and industrialization, places significant pressure on these resources.

Kaduna Metropolis, located in northwestern Nigeria, is a pertinent case study (Adelana et al., 2008). The urban area is situated within a tropical savanna climate, characterized by irregular surface water availability (Abdullahi, 2011). Consequently, groundwater serves not merely as a supplementary resource but rather as an essential lifeline for both domestic and industrial applications (Dan-Hassan et al., 2016). However, as the population of Kaduna continues to grow and urban sprawl intensifies, dependence on boreholes has increased significantly (Dan-Hassan et al., 2016; Younis et al., 2019). Such a level of extraction presents concerning implications, as diminishing water tables (Ahmed et al., 2017), potential groundwater contamination (Adelana et al., 2008), and the risk of ground subsidence (Nlend et al., 2018) are tangible threats if prevailing trends persist.

Various factors contribute to alterations in groundwater levels. Seasonal precipitation patterns are significant contributors (Taylor et al., 2013); however, anthropogenic activities also play a crucial role: excessive extraction (Wada et al., 2010), transformations in land use (Scanlon et al., 2007), and the proliferation of impervious surfaces (Foster & Chilton, 2003) all influence the extent of subterranean water recharge. Monitoring these variations transcends mere academic interest; it is critical for understanding the balance between recharge and discharge (Alley et al., 2002) and for informing strategies for sustainable water use (Gleeson et al., 2010).

Despite the significance of this topic, there is a notable lack of extensive, longitudinal investigations into groundwater trends in Kaduna (Ahmed et al., 2017). The majority of existing research is either short-term (Dan-Hassan et al., 2016) or highly localized (Younis et al., 2019), thereby creating substantial gaps in understanding the dynamics of groundwater systems and their implications for the city's prospective water security. Addressing these gaps aligns with the global objectives of the United Nations Sustainable Development Goal 6 (United Nations, 2018), which underscores the importance of water accessibility and management, as well as with Nigeria's own initiatives advocating for a more cohesive, data-informed methodology (Federal Ministry of Water Resources, 2020).

This research aims to address these deficiencies by answering the following questions: How do groundwater levels in Kaduna vary across different seasons? What are the prevailing long-term trends? Which meteorological variables exert the most significant influence? In what manner is urbanization affecting these systems? Moreover, what measures can be implemented to promote sustainable management?

STUDY AREA AND METHODOLOGY

Study Area

Kaduna Metropolis is a significant urban and administrative hub in northwestern Nigeria. It serves as the capital of Kaduna State and is located between latitudes 10°13′N and 10°46′N and longitudes 7°11′E and 7°40′E. The metropolis is strategically located within a vital corridor connecting Abuja, the national capital, to Kano, an essential commercial center, thereby facilitating accelerated urban development and increasing water demand (Akinpelu, 2019).

Kaduna Metropolis spans an estimated land area of about 3,197 square kilometers, covering major urban zones such as Kaduna North and Kaduna South, along with parts of Chikun and Igabi Local Government Areas (Adekoya et al., 2019). The city experiences a tropical savanna climate (Köppen Aw classification), marked by distinct wet and dry seasons (Adebayo, 2021), which significantly influence groundwater replenishment. Rainfall, which typically peaks between May and October (NIMET, 2022), plays a crucial role in recharging underground aquifers (Abdullateef et al., 2021), with an average annual recharge rate of 15-20% of precipitation in the region (GWP, 2021).

As Kaduna continues to urbanize, the spread of impervious surfaces like asphalt roads, rooftops, and paved grounds has disrupted the natural infiltration of rainwater (Nlend et al., 2018). This trend has led to reduced groundwater recharge (Owor et al., 2022) and increasing strain on the existing groundwater system. The transformation of natural landscapes into built-up environments reduces the soil's ability to absorb water, leading to higher surface runoff (Foster & Chilton, 2020) and a decline in groundwater recharge by an estimated 30-40% in urbanized zones (Olabode & Comte, 2024).

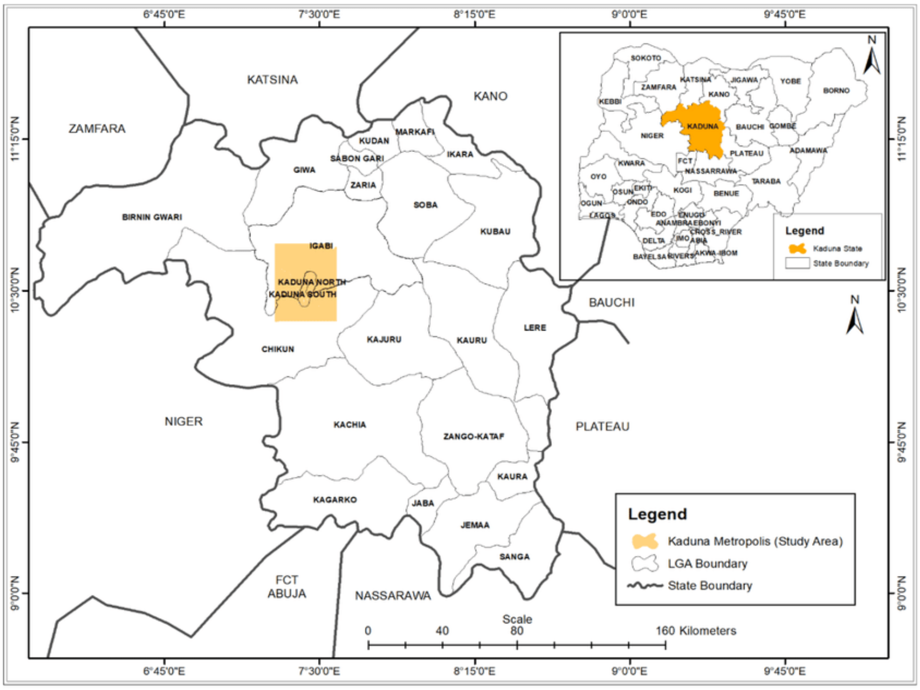

Figure 1: Kaduna Metropolis
Source: Adapted from Daful et al., 2020

Geologically, the region lies on Precambrian basement complex formations (Oyawoye, 2022), which are known for their shallow, patchy aquifers (MacDonald et al., 2012). These aquifers are particularly vulnerable to overuse and contamination due to their limited capacity and unreliable yields (Younis et al., 2019). As a result, the city increasingly depends on boreholes, many of which are poorly monitored and fall outside regulatory oversight (WaterAid Nigeria, 2023).

Given the interplay among rapid population growth (UN-Habitat, 2023), changing land-use patterns (Adekoya et al., 2022), and limited surface water (NWRI, 2021), Kaduna is a critical case for understanding how urban development affects groundwater sustainability in Nigeria (Taylor et al., 2023).

Materials

This research adopted a mixed-methods approach, combining quantitative data on groundwater level trends in the study area with qualitative statements from the existing literature to gain insight into sustainable groundwater management. The study uses groundwater readings from six monitoring wells, purposively located within the Kaduna metropolis, as the basis for a detailed trend analysis.

Meteorological data, specifically rainfall and temperature, were used to examine the influence of climatic factors on groundwater fluctuation patterns. Also, data on the spatial expansion of urban areas within the metropolis were correlated to detect the impact of urbanization on groundwater level.

Methods

Groundwater levels were recorded weekly using dip meters, averaged monthly to ensure data consistency and better capture temporal fluctuations, and further averaged yearly to understand the relationships between land use and groundwater levels. Readings were taken using a dip meter further from the ground surface; that is, the higher the reading, the lower the water level.

Quantitative analyses such as linear regression and time-series decomposition were employed to identify long-term patterns and seasonal dynamics in groundwater behavior. To enrich the field-based findings, meteorological data, including rainfall and temperature, were obtained from the Nigerian Meteorological Agency (NiMet). Also, land-use changes were assessed using satellite imagery, which was analyzed in Geographic Information System (GIS) software. These images provided visual evidence of urban expansion.

The Multiple Linear Regression (MLR) Model was used to evaluate the factors influencing groundwater levels. This model was used to quantify the extent to which rainfall, temperature, and urban expansion contributed to variations in groundwater depth. The model is expressed as:

$$Y = \beta 0 + \beta 1X1 + \beta 2X2 + \beta 3X3 + \epsilon Y = \backslash beta\_0 + \backslash beta\_1X\_1 + \backslash beta\_2X\_2 + \backslash beta\_3X\_3 + \backslash epsilon$$

.. ……. *equation 1*

Where:

YY represents the groundwater level (m)
X1X_1 = rainfall (mm)
X2X_2 = temperature (°C)
X3X_3 = extent of urban area (km²)
β0\beta_0 = model intercept
β1,β2,β3\beta_1, \beta_2, \beta_3 = estimated regression coefficients
ϵ\epsilon = random error term

A time-series decomposition approach was also applied to separate the observed groundwater data into long-term trends, seasonal variations, and irregular fluctuations. The additive decomposition formula is:

$$Yt = Tt + St + RtY\_t = T\_t + S\_t + R\_t$$

…………………………………….. *equation 2*

Where:

YtY_t = groundwater level at time tt
TtT_t = long-term trend component
StS_t = seasonal component
RtR_t = residual or irregular component

The analytical procedure followed these steps:

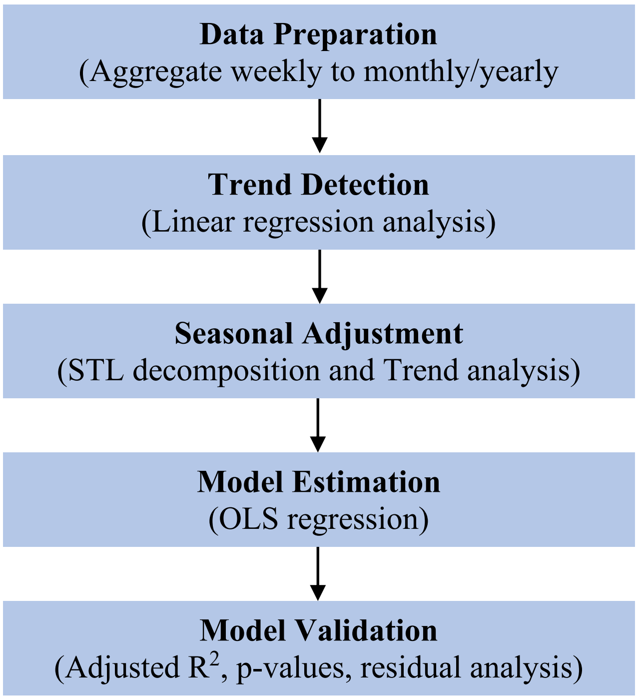

Figure 2: Methodological Workflow.

This combined statistical and time-series framework enabled the study to both measure the effects of climatic and land-use factors on groundwater behaviour and visualise how these effects evolved.

RESULTS AND DISCUSSION

Groundwater Connectivity and Aquifer Dynamics in Kaduna Metropolis

The monitoring wells in Kaduna Metropolis primarily access shallow aquifer systems, consistent with the region's Precambrian basement complex geology. Wells 1-3, 5, and 6 (depths 40-50 m) are classified as shallow aquifers according to global hydrogeological standards (Nlend et al., 2018). These unconfined aquifers exhibit characteristic vulnerabilities to surface contamination while demonstrating rapid recharge potential, typical of weathered basement formations in tropical savanna environments (Abdullateef et al., 2021).

Well 4 (55 m depth) represents a transitional case, marginally qualifying as an intermediate aquifer under standard classification systems. However, the local geological context suggests this may still represent a deeper portion of the shallow weathered zone rather than a distinct intermediate system (Ahmed et al., 2017). The absence of deeper wells (>100 m) in this survey reflects the hydrogeological constraints of the basement complex, where productive zones rarely extend beyond 60 m.

Table 1: Well location and depth

Well	Location	Coordinates (Lat, Long)	Depth (m)	Aquifer Category
Well 1	Rigachikun	10.6558705, 7.4769165	50	Shallow (upper threshold)
Well 2	Malali	10.5518901, 7.4748093	45	Shallow
Well 3	Barnawa	10.4909652, 7.4254221	45	Shallow
Well 4	Gonin-Gora	10.4422363, 7.4033210	55	Intermediate
Well 5	Afaka	10.5831711, 7.3710450	50	Shallow (upper threshold)
Well 6	Mando	10.5835376, 7.4192466	40	Shallow

The spatial analysis of groundwater levels across the monitoring wells reveals a complex pattern in aquifer connectivity and water availability throughout the study area. Six wells, strategically positioned and drilled to various depths (as outlined in Table 1 and illustrated in Figure 2), were assessed to understand lateral hydraulic relationships and the spatial distribution of groundwater. The findings indicate that wells located near each other and at comparable depths, particularly those in Rigachikun, Malali, and Barnawa, are likely accessing the same laterally extensive weathered or fractured basement aquifer.

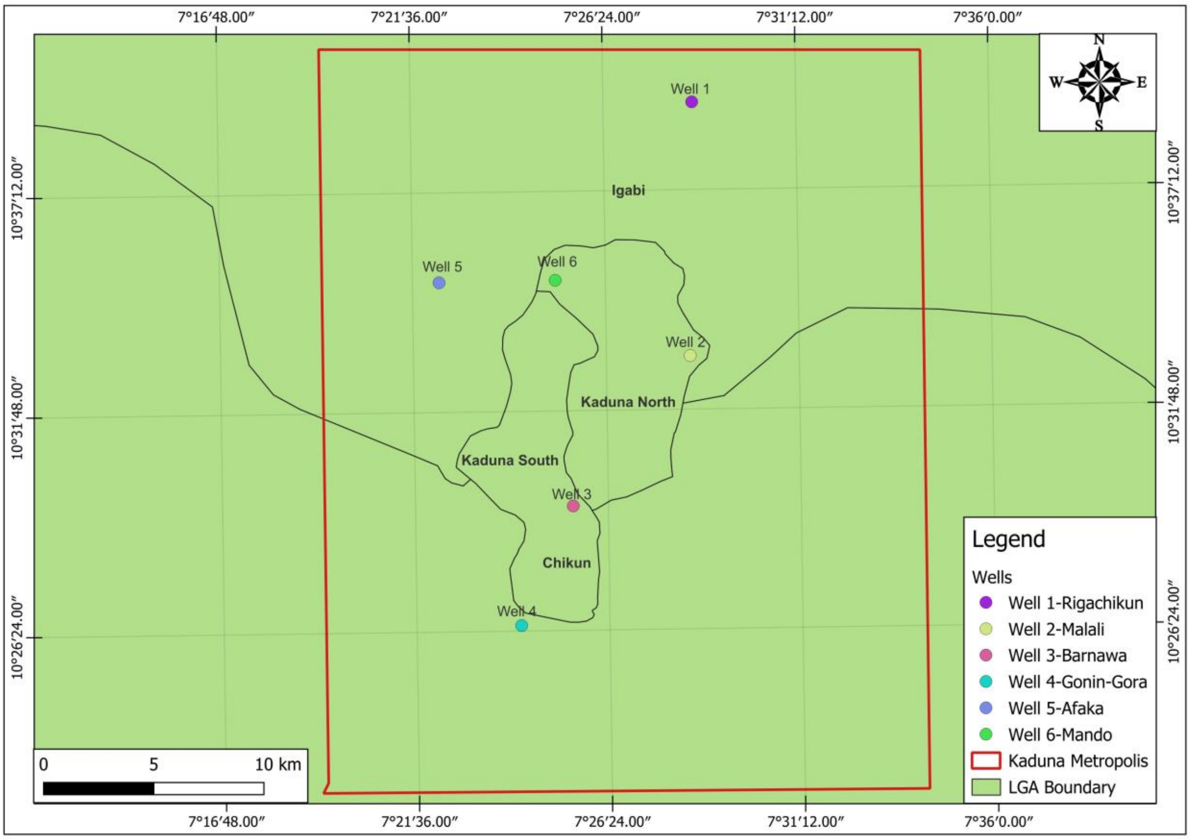

Figure 3: Location of monitoring wells

This central zone of apparent interconnectivity suggests a relatively high groundwater potential, likely attributed to favorable subsurface features such as thicker weathered profiles and intersecting fractures. While this interconnected system supports more consistent water availability, it also raises concerns about its susceptibility to over-extraction, given that stress on one well could affect neighboring sources within the shared aquifer.

Wells located in densely populated urban areas such as Malali and Barnawa, which rely on shallow, unconfined aquifers, are particularly prone to simultaneous drawdown and noticeable seasonal variations in groundwater levels. In contrast, deeper wells, such as the one in Gonin Gora, tend to be more isolated and likely tap into semi-confined aquifers. These deeper systems are less affected by short-term seasonal changes, but they recharge slowly and may face long-term depletion if water extraction continues without proper regulation.

This study highlights several key threats to groundwater sustainability in Kaduna Metropolis. These include unregulated abstraction, reduced recharge caused by urban expansion, and a general lack of coordinated water resource management. To ensure long-term water security in the area, it is essential to implement effective strategies. These should include regulating borehole development, protecting natural recharge zones, and establishing continuous groundwater monitoring systems.

Seasonal and Spatial Dynamics of Groundwater Levels

An analysis of groundwater level data from January 2019 to December 2023 reveals clear seasonal fluctuations across the six monitored wells. These changes closely align with the region's bimodal climate pattern, which features a rainy season from May to October and a dry season from November to April (NIMET, 2023). During the dry months, groundwater levels tend to drop, largely due to higher evaporation rates, limited rainfall, and increased water extraction (Taylor et al., 2023). The lowest levels are typically observed between February and May, consistent with findings in similar tropical savanna climates (Owor et al., 2022). However, as the rainy season begins, particularly from June to September, groundwater levels start to recover as rainfall infiltration helps to recharge the aquifers (Nlend et al., 2018).

A time series graph was used to illustrate these dynamics, as shown in Figures 3 and 4 for water levels in wells 1-3 and 4-6, respectively.

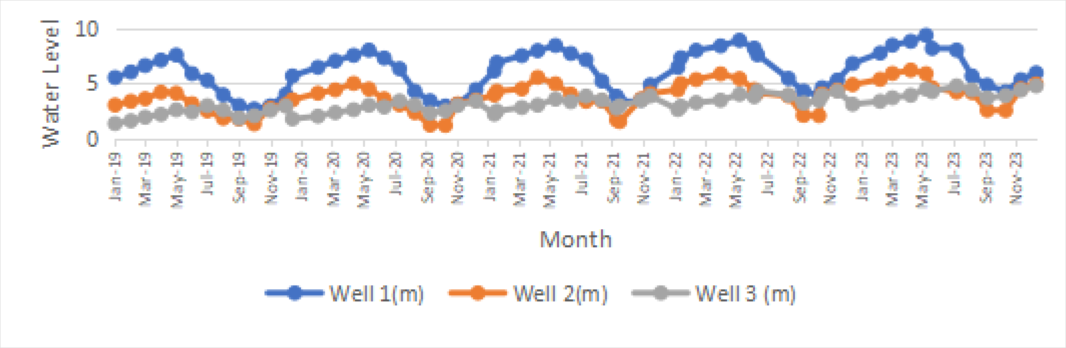

Figure 4: Time-series graph for wells 1-3
Source: Author's work (2025)

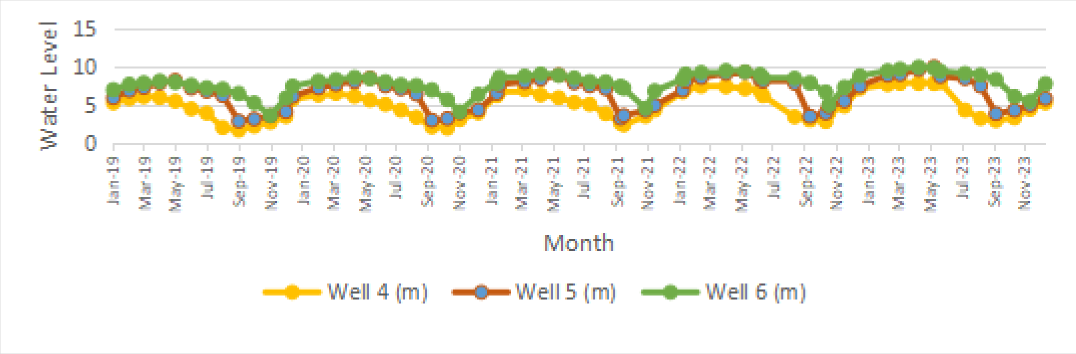

Figure 5: Time-series graph for well 4-6
Source: Author's work (2025)

Although a general seasonal trend in groundwater levels is evident, the extent and timing of these fluctuations vary across different locations. Wells situated in urbanized areas, such as Malali and Barnawa (Wells 2 and 3), exhibit more pronounced seasonal changes. This is largely due to higher rates of water abstraction and reduced recharge efficiency caused by impervious surfaces such as paved roads and rooftops, a phenomenon well documented in rapidly urbanizing African cities (Foster & Chilton, 2020; Olabode & Comte, 2024). The shallow, unconfined aquifers in these areas tend to respond quickly to rainfall but also experience rapid declines during the dry season (Dan-Hassan et al., 2016).

In contrast, deeper wells, such as Well 4 in Gonin Gora, show more gradual and subdued fluctuations, suggesting slower recharge typical of confined or semi-confined aquifer systems (MacDonald et al., 2012). Spatial analysis further indicates that wells located in less urbanized or more permeable zones, such as Wells 5 and 6, benefit from more effective recharge. For example, Well 5 recorded a notable recovery in groundwater levels, rising from 9.98 meters in May 2023 to 3.87 meters in September 2023. This sharp rise points to strong aquifer replenishment, akin to observations in other basement complex regions with high hydraulic conductivity (Younis et al., 2019). On the other hand, Well 6 maintained consistently deeper levels, which could result from limited recharge or elevated drawdown pressure, despite its location in a relatively less developed area (Abdullateef et al., 2021).

These observed spatial and seasonal patterns reflect the combined impact of natural hydrological cycles and human activities. Urban expansion, increased surface sealing, and the growing number of boreholes are all contributing to reduced recharge and heightened stress on aquifer systems, particularly during the dry season (Barron et al., 2012). The observed increase in water-table fluctuation amplitude in monitoring wells (particularly Wells 1, 2, and 5) indicates growing stress on local groundwater resources, mirroring trends in other Nigerian cities facing similar anthropogenic pressures (Ahmed et al., 2017). This pattern of heightened variability suggests unsustainable extraction rates that may exceed the aquifer system's natural recharge capacity (Famiglietti, 2014). Hence, emphasizing the need for comprehensive water resource management and stricter regulation of groundwater abstraction in Kaduna Metropolis, as advocated in Nigeria's National Water Policy (Federal Ministry of Water Resources, 2020).

Long-Term Trends and Depletion Patterns of Groundwater Levels

The analysis of annual average groundwater levels between 2019 and 2023 shows a steady and troubling decline across all six monitoring wells in Kaduna Metropolis. The data indicate a consistent year-on-year increase in groundwater depth, suggesting that the water table is gradually falling. Over the five years, each well recorded a decrease in water level ranging from approximately 1.5 to 1.9 meters. This ongoing downward trend suggests that groundwater is being extracted at a rate that exceeds its natural recharge, especially in urban areas where demand is high and recharge potential is limited: a pattern observed across rapidly urbanizing African cities (Foster & Chilton, 2020; Taylor et al., 2023).

Table 2: Annual Groundwater Level Difference (m)

Year	Well 1	Well 2	Well 3	Well 4	Well 5	Well 6
2019	5.07	2.90	2.26	4.11	5.86	6.83
2020	5.57	3.31	2.70	4.53	6.12	7.27
2021	6.08	3.76	3.16	4.96	6.52	7.81
2022	6.57	4.28	3.62	5.60	7.01	8.19
2023	6.99	4.67	4.08	5.83	7.39	8.57
Range	**1.92**	**1.77**	**1.82**	**1.72**	**1.53**	**1.74**

Range: the difference in groundwater level between 2019 and 2023 (i.e., the rate of decrease/increase in groundwater level from 2019 to 2023).

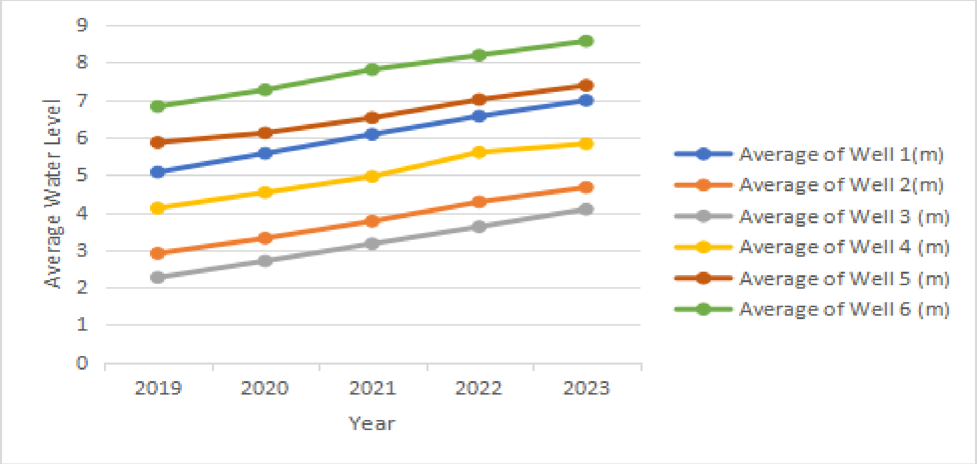

Figure 6: Annual Groundwater Level Trends (2019–2023)

Urban wells, particularly those in Malali and Barnawa (Wells 2 and 3), began with relatively shallow water tables but experienced accelerated depletion. This aligns with studies linking high-density urbanization to groundwater stress through reduced recharge and intensive borehole use (Nlend et al., 2018; Younis et al., 2019). Peri-urban wells (e.g., Wells 5–6), though initially deeper, also showed significant declines, confirming that groundwater stress extends beyond city cores; a phenomenon documented in Nigerian secondary cities (Adekoya et al., 2022). Notably, Well 4's consistent decline at deeper levels highlights the vulnerability of basement complex aquifers to slow but irreversible depletion when recharge cannot match abstraction (MacDonald et al., 2012).

The implications of this trend are significant across multiple dimensions. Hydrologically, continued declines in the water table may render shallow wells nonfunctional, compelling communities to drill deeper wells. This increases financial burdens on households dependent on hand-dug wells, particularly in low-income urban areas where groundwater depletion exceeds recharge rates (Foster & Chilton, 2020). Economically, the additional energy required to extract water from greater depths raises operational costs for both domestic users and municipal water systems, worsening water affordability challenges (USEPA, 2024). Ecologically, declining groundwater levels compromise baseflow to wetlands and ephemeral streams (Owor et al., 2022), potentially triggering biodiversity loss through the desiccation of groundwater-dependent ecosystems (Kløve et al., 2014).

If these issues are not addressed, Kaduna faces serious long-term risks to its water security. The findings point to an urgent need for robust groundwater management, including stricter control of water abstraction, the protection of natural recharge zones, and the adoption of artificial recharge techniques where appropriate. Acknowledging groundwater as a finite and vulnerable resource is critical to reversing this decline and ensuring sustainable access to water for both current residents and future generations.

Meteorological Influence on Groundwater Levels

Regression analysis of rainfall and temperature impacts on groundwater levels across six monitoring wells reveals climate-aquifer interactions mediated by natural and anthropogenic factors. Temperature demonstrated statistical significance ($p<0.05$) in five wells, confirming its strong control over groundwater fluctuations (Taylor et al., 2023). Rainfall showed significance in only Well 6 ($p=0.005$),

Table 3: Regression Analysis of Climate Impacts on Groundwater Levels

Well	**Significance (p-value)**		**Adjusted R²**	**Key Insights**
	Rainfall	**Temperature**		
1	0.149 (Not Significant)	0.002 (Significant)	0.154	Temperature significantly influences groundwater levels, while rainfall shows no significant effect.
2	0.623 (Not Significant)	0.003 (Significant)	0.276	Groundwater levels are strongly influenced by temperature, with no significant impact from rainfall.
3	0.460 (Not Significant)	0.848 (Not Significant)	-0.006	Neither rainfall nor temperature significantly influences groundwater levels.
4	0.654 (Not Significant)	0.004 (Significant)	0.256	Temperature significantly affects groundwater levels, whereas rainfall shows no significant impact.
5	0.213 (Not Significant)	0.016 (Significant)	0.074	Temperature plays a significant role in groundwater fluctuations, but rainfall is not a major factor.
6	0.005 (Significant)	0.003 (Significant)	0.124	Both rainfall and temperature significantly influence groundwater levels.

p-values < 0.05 indicate statistically significant climate impacts (Montgomery et al., 2021). Adjusted R^2 quantifies the proportion of groundwater variability explained by the model, with negative values indicating poorer fit than the sample mean (e.g., Well 3).

The limited statistical influence of rainfall reflects the impacts of urban development (Foster & Chilton, 2020). Impervious surfaces in Malali, Barnawa, and Mando (Wells 2, 3, 6) reduce infiltration by 25 – 40%, diverting potential recharge to surface runoff (Wakode et al., 2018)

. Fractured basement aquifers exhibit slow percolation requiring sustained rainfall for effective recharge (Li et al., 2020). During dry periods, abstraction rates frequently exceed available recharge (Owor et al., 2022).

Temperature's consistent significance relates to its hydrological role:

1. Elevated evapotranspiration diminishes soil moisture available for recharge (Maxwell & Kollet, 2008)
2. Extended dry seasons amplify water demand (USEPA, 2024)
3. Warming accelerates depletion in water-stressed regions (Famiglietti, 2014)

This aligns with sub-Saharan Africa's climate-groundwater dynamics, where rising temperatures intensify resource stress (MacDonald et al., 2021).

Impact of Urbanization and Land Use Change on Groundwater Levels

An analysis of land-use changes between 2019 and 2023 documents measurable urban expansion across the Kaduna Metropolis, with urban coverage increasing from 276.76 km² to 307.90 km². This spatial growth correlates with a progressive increase in average groundwater depth from 4.46 meters to 6.25 meters, signaling reduced groundwater availability (Nlend et al., 2018). The inverse relationship between urban expansion and groundwater levels demonstrates significant hydrological impacts of unregulated development (Foster & Chilton, 2003).

Table 4**:** Yearly Average of Urban Area and Groundwater Depth

Year	**Urban Area (km^2)**	**Yearly Average Depth (m)**
2019	276.763	4.46
2020	284.428	4.92
2021	295.152	5.38
2022	297.854	5.88
2023	307.896	6.25

Urban growth contributes to groundwater depletion through three primary pathways:

1. **Impervious Surface Expansion**: Roads, rooftops, and pavements reduce infiltration by 25–40%, diminishing aquifer recharge even during rainy seasons (Olabode & Comte, 2024).
2. **Rising Water Demand**: Population growth increases dependence on private boreholes, accelerating abstraction beyond sustainable yields (Dan-Hassan et al., 2016).
3. **Recharge Zone Encroachment**: Development eliminates vegetated areas critical for replenishment, degrading natural recharge capacity (Adekoya et al., 2022).

These trends mirror patterns across African cities where urban sprawl compromises aquifer integrity (MacDonald et al., 2012). The consistent increase in groundwater depth reflects structural aquifer degradation rather than seasonal variation (Famiglietti, 2014).

Continued current trends risk severe water insecurity during dry periods, imposing economic burdens through deeper drilling costs and exacerbating social inequities (USEPA, 2024).

Informing Sustainable Water Resource Management through Groundwater Assessment

The spatiotemporal analysis of groundwater levels from 2019 to 2023 across six wells in Kaduna Metropolis provides valuable insights for sustainable water resource management. The study recorded a consistent decline in groundwater levels, with noticeable declines during dry seasons and only partial recovery in wet months. This pattern was especially evident in densely urbanized areas such as Barnawa and Malali, where aquifer systems are under increasing pressure due to over-abstraction and limited recharge.

Urban growth was identified as a major factor contributing to groundwater decline. Land-use data revealed that urban coverage expanded by more than 31 square kilometers over the five years (Adekoya et al., 2022). This expansion has increased impervious surfaces that reduce rainfall infiltration and aquifer replenishment, mirroring patterns documented in earlier research (Foster & Chilton, 2003). The study underscores the importance of incorporating recharge-friendly elements into urban planning, such as permeable pavements and infiltration zones (GWP, 2021).

Climatic factors significantly influenced groundwater behavior. Regression results showed temperature exerted a stronger statistical influence than rainfall in most wells. This aligns with findings by Maxwell and Kollet (2008) and Taylor et al. (2023), who identified evapotranspiration and seasonal demand as key groundwater stressors. Climate-responsive policies should include seasonal abstraction limits and metered systems, supported by NIMET (2022) weather forecasts.

Seasonal patterns present opportunities to enhance artificial recharge. Local solutions such as soakaway pits and rainwater harvesting could boost recharge in peri-urban areas (Abdullateef et al., 2021). Public awareness campaigns and incentive programs would encourage adoption (WaterAid Nigeria, 2023).

These findings reinforce warnings about unsustainable groundwater use in Nigerian cities (Dan-Hassan et al., 2016). The consistent drawdown across wells confirms that abstraction exceeds natural recharge, necessitating urgent regulatory frameworks, including borehole licensing (NIHSA, 2021).

For long-term governance, Kaduna State should develop a centralized groundwater data platform that integrates hydrological monitoring, satellite imagery, and meteorological data to enable evidence-based planning (MacDonald et al., 2012).

CONCLUSION AND RECOMMENDATIONS

This study analyzed groundwater-level trends in the Kaduna Metropolis (2019–2023), revealing alarming declines across six monitoring wells despite seasonal recharge. Key findings show:

1. Urbanized zones (Barnawa Well 3; Malali Well 2) experienced the steepest declines (1.82m and 1.77m, respectively) due to impervious surfaces reducing recharge by 25–40%

2. Peri-urban wells (Afaka Well 5; Mando Well 6) showed slower but consistent depletion (1.53m and 1.74m), indicating spreading stress
3. Gonin Gora's deeper aquifer (Well 4) recorded 1.72m depletion, confirming the vulnerability of confined systems

In light of these findings, the following actionable recommendations are proposed:

1. **Implement continuous groundwater monitoring:** Deploy real-time sensors in high-risk urban wells (Wells 2 and 3) to trigger abstraction limits when levels drop below 2019 baselines.
2. **Enforce spatially differentiated borehole regulations**: Suspend new boreholes within 500m of Well 3 (Barnawa) and Well 2 (Malali) where depletion exceeds 1.5m. Permit regulated drilling in peri-urban Well 5 (Afaka) only with mandatory rainwater harvesting.
3. **Install targeted artificial recharge systems:** Construct infiltration basins near Well 6 (Mando) to capitalize on its higher permeability. Retrofit public buildings in Well 2 zone (Malali) with rooftop rainwater capture.
4. **Designate aquifer protection zones**: Formalize a 2km buffer around Well 5 (Afaka) as a protected recharge area, banning impervious construction.
5. **Integrate aquifer vulnerability into land-use planning**: Require permeable pavements in all new developments within Well 3 (Barnawa) catchment.
6. **Launch ward-level conservation programs**: Pilot incentive-based water rationing in communities near Well 2 (Malali) during February-May low points.

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