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Short Communication

ASSESSING GROUNDWATER DEPLETION AND SUSTAINABLE WATER MANAGEMENT IN MINNA METROPOLIS, NIGERIA: IMPLICATIONS FOR SUSTAINABLE DEVELOPMENT GOAL 6

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Abstract: Groundwater depletion has become a major environmental challenge in Minna Metropolis, Nigeria, due to rapid urbanization, population growth, and inadequate municipal water supply. Consequently, residents increasingly depend on groundwater abstraction through boreholes and hand-dug wells, placing pressure on the underlying basement aquifer system. This study assessed groundwater sustainability by integrating hydrogeological mapping, household water-demand estimation, and rainfall-based recharge analysis. A total of 385 households were surveyed using structured questionnaires, while ten years (2013-2023) of rainfall data were analysed to estimate groundwater recharge using a simplified water balance approach. Results indicate that groundwater occurs mainly within weathered and fractured basement formations, with groundwater flow predominantly oriented in the NE-SW direction. Household survey results revealed an operational per capita water requirement of 62.5 L/day/person, corresponding to an estimated total urban water demand of approximately 15.5 million L/day. In contrast, estimated groundwater recharge from rainfall infiltration was approximately 408,940 L/day. The large disparity between groundwater demand and recharge indicates unsustainable abstraction conditions and increasing vulnerability of the aquifer system to depletion. The study identified major recharge and discharge zones and highlights the need for integrated groundwater management strategies including recharge-zone protection, artificial recharge enhancement, rainwater harvesting, and regulation of borehole development. These findings provide important insights for sustainable urban groundwater governance and contribute to the achievement of Sustainable Development Goal 6.

Introduction

Sustainable water management has become a major challenge in rapidly urbanizing cities, particularly in developing countries where population growth frequently exceeds the expansion of water infrastructure. Groundwater constitutes an important source of domestic water supply because of its relative accessibility, reliability during dry seasons, and lower treatment requirements compared with surface water sources (Mukherjee & Singh, 2020). In many Nigerian cities, inadequate municipal water supply has increased dependence on groundwater abstraction through boreholes and hand-dug wells (Wada & Bierkens, 2014). Minna Metropolis, located within the Nigerian Basement Complex terrain, depends largely on groundwater resources for domestic water supply. Groundwater occurrence in basement terrains is commonly associated with weathered and fractured zones characterized by limited storage capacity and spatially variable recharge conditions. Rapid urban expansion, increasing population, and uncontrolled groundwater abstraction have intensified pressure on these aquifer systems, raising concerns regarding long-term sustainability.

Previous studies in Minna and similar urban centres in Nigeria have focused mainly on groundwater occurrence, hydrogeological characteristics, and water quality conditions (Idris-Nda *et al.*, 2013). Other global studies have emphasized the increasing vulnerability of urban groundwater systems to depletion resulting from over-abstraction and reduced recharge associated with urbanization (Salihu & Jimada, 2016). The urbanization reduces infiltration through the expansion of impervious surfaces, while increasing water demand intensifies stress on aquifer systems. In basement complex environments, recharge is often localized and structurally controlled, making groundwater systems, particularly sensitive to excessive abstraction. Despite increasing groundwater dependence in Minna Metropolis, limited studies have integrated household water demand, recharge estimation, and hydrogeological controls within a unified framework for evaluating groundwater sustainability. Most existing

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investigations have treated groundwater occurrence, quality, and exploitation independently without quantitatively comparing abstraction demand with recharge capacity. Consequently, there is still insufficient information to determine whether current groundwater utilization in Minna is sustainable relative to natural recharge conditions. This study therefore integrates household water-use surveys, hydrogeological mapping, groundwater inventory analysis, and rainfall-based recharge estimation to evaluate groundwater sustainability in Minna Metropolis. The study specifically estimates urban groundwater demand, evaluates recharge potential, and compares both components to assess sustainability conditions. The findings provide useful information for groundwater management and contribute to Sustainable Development Goal 6, which seeks to ensure the availability and sustainable management of water resources for all.

Study Area

Minna Metropolis (Fig. 1) is located in north-central Nigeria within the Basement Complex terrain and serves as the capital of Niger State. The area lies between latitudes 9°31′N and 9°40′N and longitudes 6°27′E and 6°37′E. The climate is characterized by wet and dry seasons, with annual rainfall averaging approximately 1,418 mm. Geology of the area consists predominantly of crystalline basement rocks including granites, gneisses, and schists. Groundwater occurrence is mainly associated with weathered overburden and fractured bedrock zones.

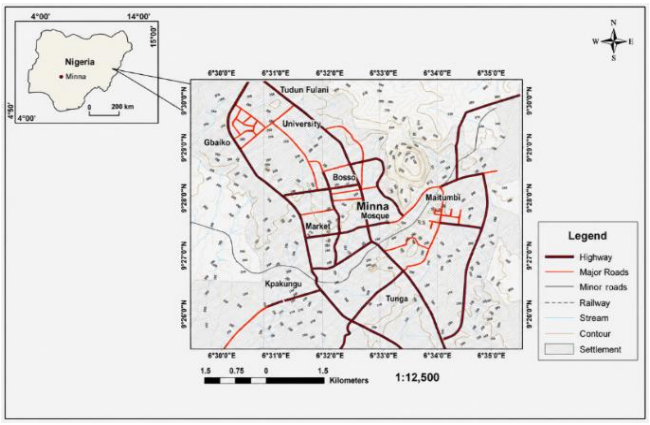

Fig. 1 Location map of the study area.

Materials and Methods

Field investigations involving borehole and hand-dug well inventory surveys were conducted across the study area to evaluate groundwater occurrence and abstraction patterns. Geographic coordinates of wells and boreholes were recorded using a handheld Global Positioning System (GPS) device and integrated into a Geographic Information System (GIS) environment for spatial analysis. Groundwater contour maps, abstraction distribution maps, and land-use classifications were generated using ArcGIS 10.x software. Spatial analysis was used to identify groundwater flow directions as well as probable recharge and discharge zones within the metropolis.

Household Survey and Sampling

A total of 385 households were surveyed using structured questionnaires to obtain information on household characteristics, water sources, and daily water-use patterns within Minna Metropolis. The sample size was determined using the standard sampling formula for large population at a 95% confidence level and 5% margin of error following Nelson & Ward (1981). A stratified grid-based sampling approach was adopted to ensure adequate spatial representation across the study area. Households were randomly selected within each grid to minimize sampling bias and improve coverage of different residential zones. The questionnaire survey collected information on household size, household composition, primary and secondary water sources, estimated daily water consumption, and dominant domestic water-use activities. The survey also provided the basis for estimating household water demand and evaluating groundwater dependence within the metropolis.

Water Demand Estimation

Per capita water requirement was estimated from household survey responses. The operational average household water requirement obtained from the survey was 62.5 L/day/person. Total daily water demand for the study area was estimated using the projected population of approximately 248,000 inhabitants.

The total daily water demand was calculated using:

$$D = P \times q$$

where D represents total daily water demand (L/day), P is the projected population, and q is the per capita water requirement (L/day/person). Using the estimated per capita requirement and projected population, the total daily water demand for the study area was estimated at approximately 15.5 million L/day.

Rainfall Data and Recharge Estimation

Ten years of rainfall data (2013–2023) were obtained from the Nigerian Meteorological Agency (NiMet) and used to estimate groundwater recharge within the study area. Mean annual rainfall was calculated and converted to rainfall volume over the study area using:

$$V_r = R \times A$$

where V_r is rainfall volume (m^3/year), R is mean annual rainfall (m/year), and A is the study area (m^2). Surface runoff was estimated using the Rational Method:

$$Q = C \times V_r$$

where Q represents runoff volume (m^3/year), C is the runoff coefficient, and V_r is rainfall volume (m^3/year). Runoff

coefficients were assigned according to land-use characteristics after Baiamonte (2020). Weighted runoff volume for the study area was estimated at approximately 289,520 m³/year. Groundwater recharge was estimated using a simplified water balance relationship:

$$I = V_r - Q$$

where I is the infiltration volume available for groundwater recharge (m³/year). The estimated infiltration volume was converted to daily recharge values, resulting in an estimated groundwater recharge of approximately 408,940 L/day.

Software and Analytical Tools

Data processing and statistical analysis were conducted using Microsoft Excel and SPSS. Spatial analysis, groundwater contour mapping, and land-use classification were performed using ArcGIS 10.x.

Results and Discussion

A total of 385 households were surveyed across Minna Metropolis to evaluate groundwater dependence, household water demand, and groundwater sustainability within the study area. The dominant residential structure identified was two-bedroom apartments, accounting for approximately 43% of the surveyed households, followed by single-bedroom apartments representing 39% (Table 1). Households comprising 4–6 persons constituted the largest household-size category, accounting for approximately 50% of respondents. The survey further revealed heavy dependence on groundwater-derived and informal water supply systems. Water vendors constituted the dominant domestic water source, accounting for approximately 48% of respondents, while hand-dug wells and boreholes accounted for 26% and 16%, respectively. Only about 10% of households depended primarily on municipal water board supply. Domestic water use within the study area was dominated by bathing and laundry activities, accounting for approximately 49% and 37% of total household water use, respectively. Cooking and dishwashing represented relatively lower proportions of household water consumption.

The estimated operational per capita water requirement obtained from the household survey was approximately 62.5 L/day/person (Fig. 2). Using the projected population of approximately 248,000 inhabitants, the total daily water demand for Minna Metropolis was estimated at approximately 15.5 million L/day. This estimate reflects the substantial dependence of the growing urban population on groundwater resources due to inadequacy of the municipal water supply system.

Analysis of rainfall data for the period 2013–2023 indicates a mean annual rainfall of approximately 1,418 mm/year. The total annual rainfall volume over the study area was estimated at approximately 438,669 m³/year. Surface runoff estimated using the Rational Method yielded a runoff volume of approximately 289,520m³/year. The difference between rainfall volume and runoff produced an estimated infiltration volume of approximately 149,149 m³/year, available for groundwater recharge. This corresponds to an estimated groundwater recharge of approximately 408,940 L/day. Comparison between groundwater demand and recharge indicates that total daily water demand (15.5 million L/day) substantially exceeds estimated groundwater recharge (408,940 L/day), resulting in a deficit of approximately 15.1 million L/day. Spatial analysis further revealed clustering of boreholes and hand-dug wells within densely populated residential areas of the metropolis (Fig. 3). Groundwater flow within the study area generally trends in the NE–SW direction, while Tudun Fulani and Maitunbi constitute probable recharge zones. Kpakungu and adjoining lowland areas appear to function as discharge zones.

Table 1. Summary of questionnaire results.

Parameter Question	Response	Frequency	Percentage (%)
Household type (Bedroom)	Single bedroom	150	39
	Two bedrooms	167	43
	Three bedrooms	50	13
	Four bedrooms	18	5
Household size (Person)	1 person	38	10
	2–4 people	77	20
	4–6 people	193	50
	6–8 people	58	15
	Above 8 people	19	5
Household composition	Single	96	25
	One-parent family	15	4
	Married with children	273	71
Water source for domestic use	Borehole	61	16
	Water board	39	10
	Well water	100	26
	Water vendor (Mai Ruwa)	185	48
Domestic water use	Cooking	15	4
	Dish washing	39	10
	Laundry	142	37
	Bathing	185	49
Daily water requirement (Litres)	50 litres	58	15
	50–200 litres	193	50
	200–400 litres	96	25
	Above 400 litres	38	10

The results indicate strong dependence on groundwater resources within Minna Metropolis due to inadequate and unreliable municipal water supply infrastructure. The dominance of water vendors, boreholes, and hand-dug wells as primary domestic water sources demonstrates the increasing pressure placed on groundwater resources by rapid urbanization and population growth. Similar groundwater dependence has been reported in several rapidly growing

Nigerian urban centres where public water supply systems remain insufficient to meet increasing demand.

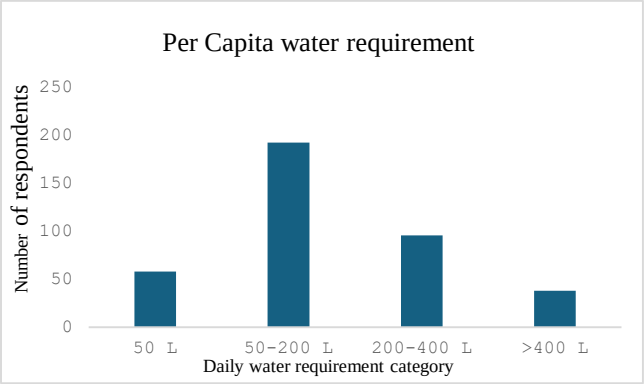

Fig. 2 Distribution of household daily water requirement categories in the study area.

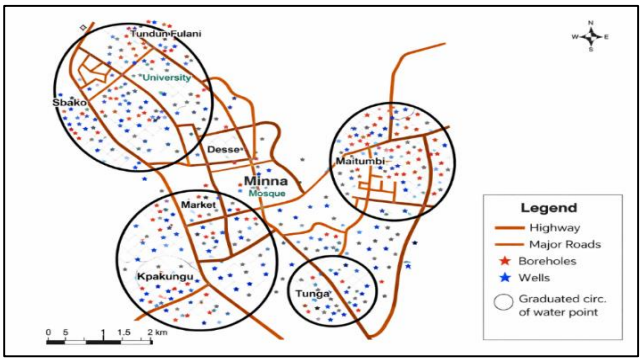

Fig. 3 Spatial distribution of boreholes and hand-dug wells showing zones of intensified groundwater abstraction within Minna Metropolis.

The estimated per capita water requirement of 62.5 L/day/person falls within the minimum domestic water requirement recommended by the World Health Organization for basic household needs. However, although individual household water consumption may not be excessive, the cumulative effect of increasing urban population results in substantial overall groundwater demand within the metropolis. The recharge estimation results reveal that groundwater replenishment within the study area is relatively limited compared with abstraction demand. In basement complex terrains, groundwater occurrence is commonly restricted to weathered and fractured zones characterized by low storage capacity and localized recharge conditions.

The relatively low recharge estimate obtained in this study, therefore reflects both geological controls and the increasing influence of urbanization, which reduces infiltration through the expansion of impervious surfaces such as roads, buildings, and paved environments. The substantial imbalance between groundwater demand and recharge indicates unsustainable groundwater abstraction conditions within Minna Metropolis. Continuous abstraction under such conditions may result in progressive groundwater depletion, declining water tables, reduced well yields, and increased drilling depths. Concentrated abstraction within densely populated residential areas further increases the possibility of localized aquifer stress and groundwater-level decline. The identified recharge zones within Tudun Fulani and Maitunbi are hydrologically important for sustaining aquifer replenishment within the metropolis.

Protection of these areas from uncontrolled urban development, waste disposal, and land-use alteration is therefore essential for long-term groundwater sustainability. Similarly, the identified discharge zones may represent areas vulnerable to groundwater contamination and localized drawdown under intensified abstraction conditions. The findings of this study have important implications for Sustainable Development Goal 6 (SDG 6), particularly targets 6.4, which emphasizes sustainable freshwater withdrawals and efficient management of water resources. The observed demand–recharge imbalance suggests that current groundwater utilization patterns within the metropolis may not be sustainable without appropriate management interventions. Consequently, sustainable groundwater management strategies including recharge-zone protection, managed aquifer recharge, rainwater harvesting, regulation of borehole development, and expansion of municipal water supply infrastructure are recommended to reduce pressure on groundwater resources and improve long-term urban water security within Minna Metropolis.

Conclusion

Groundwater remains the primary source of domestic water supply in Minna Metropolis due to inadequate municipal water infrastructure. The study estimated a per capita water demand of 62.5 L/day/person, resulting in a total urban water demand of approximately 15.5 million L/day. In contrast, groundwater recharge derived from rainfall-runoff analysis was estimated at only 408,940 L/day, indicating a substantial deficit and unsustainable groundwater abstraction. Recharge zones were identified around Tudun Fulani and Maitunbi, while Kpakungu and surrounding lowland areas function as probable discharge zones.

The observed imbalance between groundwater demand and natural recharge highlights the increasing risk of groundwater depletion in the metropolis. To ensure long-term groundwater sustainability and support Sustainable Development Goal 6, measures such as recharge-zone protection, managed aquifer recharge, rainwater harvesting, regulation of borehole development, and improvement of municipal water supply infrastructure are strongly recommended.

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