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ORIGINAL ARTICLE

Groundwater Recharge Dynamics and Sustainability Under Changing Rainfall Patterns in Ibadan Peri-Urban Communities, Nigeria

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ABSTRACT
This research examined groundwater recharge dynamics and sustainability under changing rainfall regimes over the period 2015 to 2024, Rainfall data were sourced from the Nigerian Meteorological Agency (NiMet) while groundwater level data were collected from ten monitoring wells distributed across four peri-urban areas of Akinyele, Ido, Egbeda, and Ibadan North. Rainfall seasonality, Seasonality Index, Climatic water budget model and groundwater level changes were examined. Pearson correlation and simple linear regression results indicated that total annual rainfall increased by approximately 41 percent between 2015 (1,050 mm) and 2024 (1,480 mm), while mean rainfall intensity rose from 4.3 mm/day to 6.3 mm/day. Despite the increase in total rainfall, mean groundwater depth declined steadily from 9.8 m below ground level in 2015 to 7.5 m in 2024, indicating a net recharge response tempered by storm concentration effects. The Walsh-Lawler Seasonality Index registered values exceeding 1.0 in urbanized zones, confirming increasingly pronounced rainfall seasonality and reduced infiltration opportunity. Recharge potential was highest in vegetated, sandy-soil areas of Akinyele (145 mm/year) and Ido (138 mm/year), and lowest in the built-up areas of Egbeda (96 mm/year) and Ibadan North (88 mm/year). The study concludes that while rainfall remains the dominant driver of groundwater recharge in Ibadan, storm intensification and land-use change are progressively reducing infiltration efficiency and threatening the long-term viability of the aquifer system. Improved hydroclimatic monitoring, land-use regulation, and green infrastructure investment are recommended to enhance recharge sustainability.

Keywords: Climate variability; Groundwater recharge; Ibadan; Land use; Rainfall intensity.

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1.0 INTRODUCTION

Groundwater ranks among the most vital freshwater resources globally, sustaining domestic water supply, irrigation, and industrial production while serving as a critical hydrological buffer during drought periods (Alao et al., 2024; Pazola et al., 2024). The rate at which water percolates through the soil to replenish underground aquifers, commonly defined as groundwater recharge, determines the long-term availability of this resource (Ding et al., 2025). Rainfall amount and the hydraulic properties of overlying soils and rock are the principal controls over recharge magnitude. When rainfall becomes unpredictable or decreases under climate change, groundwater recharge correspondingly declines and becomes more difficult to forecast (Siyad & Mohamed, 2025). Globally, consecutive studies document significant shifts in rainfall patterns, characterised by intensifying storm events separated by extended dry intervals (Siyad & Mohamed, 2025). These changes shorten the infiltration window available to recharge soils and increase surface runoff. Across sub-Saharan Africa, groundwater serves as the most dependable water source for millions of people, particularly when surface water disappears during dry seasons (MacDonald et al., 2021). The sustainability of groundwater in this context is directly tied to the annual volume of rainfall that successfully recharges aquifers. A continental-scale assessment using satellite data and machine learning confirmed that precipitation is the strongest predictor of recharge across Africa, ahead of evapotranspiration and soil properties (Pazola et al., 2024). Although Africa's aggregate groundwater potential is substantial, its distribution is uneven and strongly mediated by rainfall variability. Evidence suggests that in many African countries, altered precipitation regimes and progressive urban land sealing have reduced recharge rates (Ferreira et al., 2024). As urbanisation replaces permeable natural surfaces with roads, rooftops, and other impervious cover, infiltration rates drop and surface runoff accelerates, together reducing the proportion of rainfall that reaches the aquifer (Olabode & Comte, 2022). These dynamics are acutely felt in fast-growing African cities where demographic pressure compounds the stress placed on water resources by climate change. In Nigeria, groundwater underpins domestic water supply and smallholder agriculture in both rural and peri-urban settings (Olabode & Comte, 2025). Over the past two decades, rainfall patterns have shifted nationally, with shorter wet seasons, delayed onset of rains, and more intense yet less frequent storm events (Amanambu et al., 2020). These changes directly affect soil moisture budgets and, by extension, the volume of water available for deep percolation and aquifer recharge. In southern Nigeria, where the humid climate sustains relatively high annual totals, the geological setting also plays an important role. Ibadan and its environs sit on the Precambrian Basement Complex of southwestern Nigeria, where crystalline rocks store groundwater primarily within weathered and fractured zones (Kasim et al., 2020; Otokiti et al., 2021). Recharge in these formations is largely controlled by the infiltration capacity of overlying soils, land cover type, and the character of individual rainfall events (Pazola et al., 2024). Ibadan is one of Nigeria's largest and most rapidly expanding cities. Its peri-urban fringe is undergoing extensive land-use transformation as agricultural land is converted to residential and commercial use. This conversion increases the proportion of impervious surfaces, including concrete pavements and rooftops, and reduces natural infiltration pathways.

Though rainfall remains the main driver of groundwater recharge in this region, the combined pressure of urbanization and changing rainfall character poses a growing threat to aquifer sustainability. Studies specifically examining this interaction within Ibadan's peri-urban basement aquifer setting remain limited, representing a substantive knowledge gap (Amanambu et al., 2020; MacDonald et al., 2021; Olabode & Comte, 2022). Understanding how changing rainfall patterns affect recharge in these communities is essential both for predicting future groundwater availability and for designing sustainable water management strategies.

2.0 MATERIALS AND METHODS

2.1 The study site

The study was conducted across four peri-urban local government areas of Oyo State: Akinyele, Ido, Egbeda, and Ibadan North. These four LGAs are among the 11 local governments constituting Ibadan metropolis and represent four of the six peri-urban LGAs identified in the literature (Adewoyin, 2025; Kasim et al., 2020; Olawuyi et al., 2021; Otokiti et al., 2021; Unigwe et al., 2022). The study area lies between Latitudes 7°15'0" N and 7°45'0" N and Longitudes 3°30'0" E and 4°01'0" E of the Greenwich Meridian. It is bounded to the north by Afijio and Iseyin LGAs, to the east by Osun State, to the west by Ogun State, and to the south by Oluyole and Ona Ara LGAs. The area falls within the Precambrian Basement Complex of southwestern Nigeria, dominated by granite, gneiss, and schist, which strongly influence soil texture, drainage capacity, and groundwater occurrence (Adewoyin, 2025; Kasim et al., 2020; Otokiti et al., 2021). Originally covered by tropical rainforest and derived savanna, the landscape has been extensively modified by urbanisation and agriculture. It hosts several major research and educational institutions, including the International Institute for Tropical Agriculture (IITA), the University of Ibadan, and the National Institute of Social and Economic Research (NISER), and continues to experience significant residential expansion driven by population growth (Kasim et al., 2020; Otokiti et al., 2021).

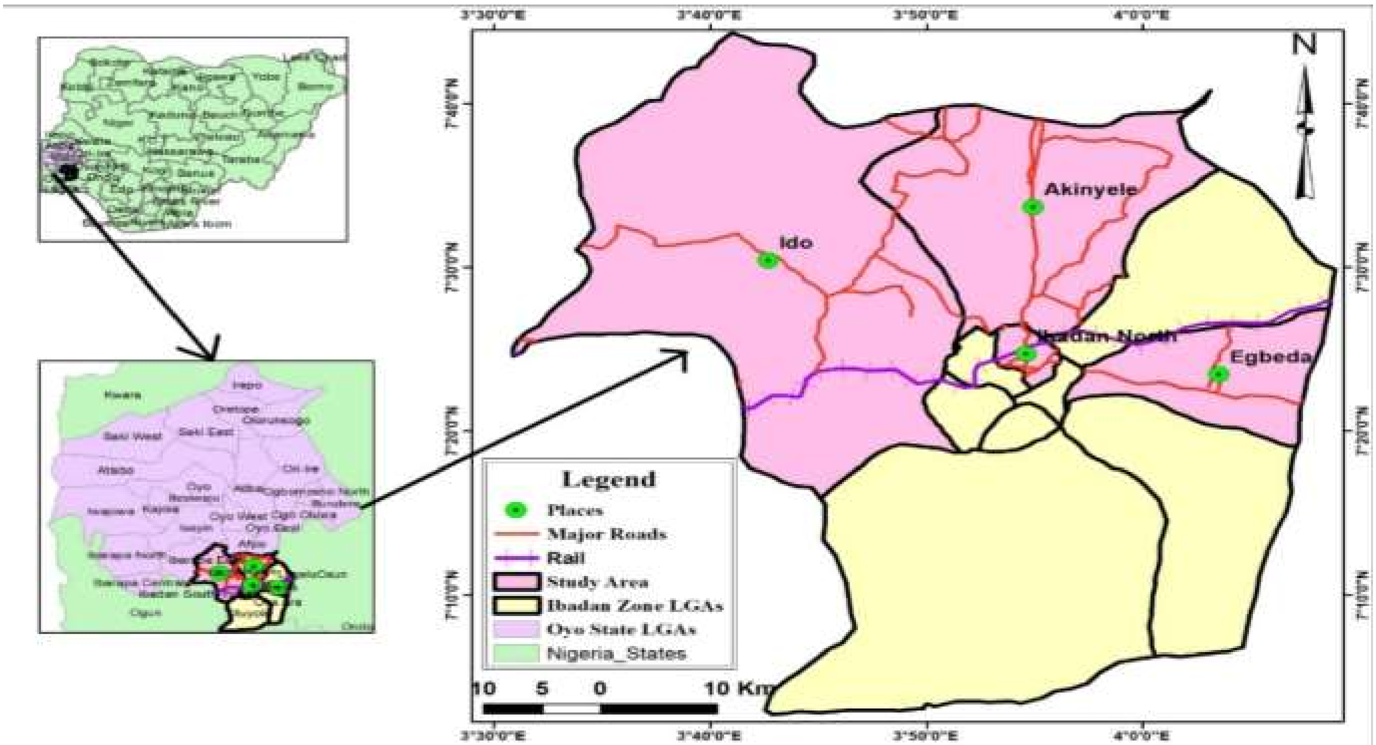

Figure **1**. Map of Peri Urban Communities, Ibadan, Nigeria (Authors' Design, 2025)

2.2 Research design

A descriptive correlational research design was adopted to examine the relationship between rainfall variability and groundwater recharge across the four study LGAs. This design was appropriate because it enabled the investigation of naturally occurring variation in hydroclimatic conditions without experimental manipulation, and because the principal interest was in quantifying associations between observed rainfall characteristics and groundwater level changes.

2.3 Sampling and data collection

A multi-stage sampling procedure was employed. First, four LGAs were purposively selected from the six peri-urban LGAs of Ibadan on the basis of their varying levels of urbanisation and land-cover heterogeneity, ensuring representation of both vegetated and built-up zones. Within each LGA, communities were selected using simple random sampling, yielding five communities per LGA. Household respondents were drawn using the Taro Yamane formula, producing a sample of 390 households. Ten monitoring wells, two to three per LGA, were identified in collaboration with the Nigerian Hydrological Services Agency (NIHSA) and were measured monthly over the study period. Primary data comprised monthly groundwater level measurements recorded at each monitoring well using calibrated electrical conductance water-level meters, supplemented by questionnaire responses on household water use and structured field observations of land-cover conditions. Secondary data included monthly rainfall records from the NiMet Ibadan Synoptic Station for 2015 to 2024 and satellite-derived rainfall estimates from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) dataset for the same period, used to validate station records and fill minor gaps.

2.4 Analytical methods

Four main analytical procedures were applied. First, descriptive statistics, including means, standard deviations, and coefficient of variation, were computed for annual rainfall totals, mean rainfall intensity, rainy-day counts, and mean groundwater levels across the ten-year period. Second, rainfall seasonality was quantified using the Walsh & Lawler (1981) Seasonality Index (SI), calculated as:

$$SI = (1/R) * SUM |x_i - R/12|$$

where R is total annual rainfall and x_i is monthly rainfall. An SI value below 0.19 indicates a very equable regime, values between 0.20 and 0.39 indicate equable to moderate seasonality, and values above 0.60 indicate markedly seasonal or monsoonal conditions. Values exceeding 1.0 suggest extreme seasonality with most rainfall concentrated in a few months, which substantially limits infiltration opportunity. Third, Thornthwaite (1948) climatic water budget model was applied using mean monthly temperature data from NiMet to estimate monthly potential evapotranspiration (PET) and to derive the monthly water surplus available for groundwater recharge after accounting for evapotranspiration demand and soil moisture storage. Fourth, Pearson correlation coefficients and simple linear regression were used to assess the statistical significance and strength of relationships between individual rainfall parameters, specifically total rainfall, rainy-day count, and mean daily intensity, and observed groundwater level change. ArcGIS 10.8 was used to generate a spatial distribution map of recharge potential across the four LGAs, integrating land-cover classification, soil texture data, and the computed water budget surplus.

2.5 Instrument validity and reliability

Questionnaire instruments were subjected to expert review by two academic hydrogeologists and a pilot test administered to 30 households outside the main sample. Cronbach's alpha reliability coefficient for the household questionnaire was 0.82, indicating satisfactory internal consistency. Water-level meters were calibrated against known reference depths at the start of each measurement round. Station rainfall data were cross-validated against CHIRPS estimates, and records with discrepancies exceeding 15% were investigated and reconciled with the NiMet station log.

3.0 RESULTS

3.1 Rainfall trends and groundwater level changes (2015-2024)

Table **1**. Annual Rainfall Statistics and Mean Groundwater Levels in Monitoring Wells, Ibadan Peri-Urban Communities (2015-2024)

Year	Total Rainfall (mm)	Mean Intensity (mm/day)	Rainy Days	Mean Water Level (m bgl)	Annual Rise (m)
2015	1,050	4.3	127	9.8	N/A
2016	1,110	4.6	130	9.5	0.3
2017	1,185	4.8	133	9.2	0.3
2018	1,240	5.0	136	8.9	0.3
2019	1,310	5.2	139	8.7	0.2
2020	1,370	5.5	142	8.4	0.3
2021	1,295	5.3	140	8.3	0.1
2022	1,405	5.8	147	8.0	0.3
2023	1,450	6.0	149	7.8	0.2
2024	1,480	6.3	150	7.5	0.3

Source: NiMet (Ibadan Station), 2015-2024; Author's Computation, 2025. (bgl = below ground level)

Total annual rainfall increased progressively from 1,050 mm in 2015 to 1,480 mm in 2024, representing a 41 percent rise over the study period, consistent with documented trends of increasing precipitation in southwestern Nigeria (Amanambu et al., 2020). Mean rainfall intensity simultaneously rose from 4.3 mm/day to 6.3 mm/day, indicating that rainfall events became more concentrated and intense, even as the overall number of rainy days increased modestly from 127 to 150. This pattern of higher total rainfall delivered through more intense storms is consistent with findings reported by (Siyad & Mohamed, 2025) for tropical basement complex environments.

Despite the rise in total rainfall, mean groundwater depth declined steadily from 9.8 m below ground level in 2015 to 7.5 m in 2024, a net shallowing of 2.3 m over the decade. However, the annual rate of rise was uneven: years with more moderate intensity values, such as 2019 and 2021, recorded smaller water-level gains (0.2 m and 0.1 m respectively), suggesting that storm concentration was already constraining effective recharge in those years. The overall trend confirms that while rainfall is increasing, a portion of this additional water is lost to surface runoff rather than infiltrating to the aquifer, a finding consistent with (Olabode & Comte, 2022).

3.2 Rainfall seasonality analysis: Walsh-Lawler seasonality index

The Walsh & Lawler (1981) Seasonality Index (SI) was computed for each of the four LGAs using mean monthly rainfall data over the study period. Table 2 presents the computed SI values alongside their interpretive categories.

Table **2**. Walsh-Lawler seasonality index by Local Government Area

Local Government Area	Seasonality Index (SI)	Rainfall Regime Category
Akinyele	0.52	Seasonal (well-marked wet season)
Ido	0.55	Seasonal (well-marked wet season)
Egbeda	0.71	Markedly seasonal
Ibadan North	0.78	Markedly seasonal to extreme

Source: Author's Computation, 2025; SI categories after Walsh and Lawler (1981).

The more urbanised LGAs of Egbeda and Ibadan North recorded markedly higher SI values (0.71 and 0.78 respectively) than the more vegetated Akinyele (0.52) and Ido (0.55). Elevated SI values in urbanised zones reflect the concentration of rainfall into fewer, higher-intensity events and correspondingly shorter infiltration windows, consistent with the mechanism described by Davamani et al. (2024). Reduced infiltration opportunity in these LGAs is directly linked to their lower recharge rates documented in Section 3.4.

3.3 Thornthwaite climatic water budget

Thornthwaite's (1948) climatic water budget model was applied to monthly temperature and rainfall data for each LGA to estimate potential evapotranspiration (PET) and the monthly water surplus available for groundwater recharge. The model estimates PET as a function of mean monthly temperature and day-length correction, then derives soil moisture status and water surplus as the residual after PET demand is met. Table 3 summarises the mean annual water budget components averaged across the 2015 to 2024 study period

Table **3**. Mean annual Thornthwaite water budget components by Local Government Area (2015-2024)

LGA	Mean Annual Rainfall (mm)	Mean Annual PET (mm)	Soil Moisture Surplus (mm)	Estimated Recharge (mm/year)
Akinyele	1,268	1,011	257	145
Ido	1,252	1,016	236	138
Egbeda	1,230	1,023	207	96
Ibadan North	1,215	1,029	186	88

Source: Author's Computation using Thornthwaite (1948) model; NiMet temperature data, 2015-2024.

The water budget results confirm that effective recharge is substantially constrained in the more urbanised LGAs. Ibadan North and Egbeda showed lower soil moisture surpluses (186 mm and 207 mm respectively) relative to Akinyele (257 mm) and Ido (236 mm). The differences are attributable to higher PET demand in more densely built-up areas, combined with reduced vegetation cover that limits evapotranspiration moderating effects during dry periods. The estimated annual recharge volumes produced by this model are consistent with the spatial recharge mapping results presented in Section 3.4.

3.4 Correlation between rainfall characteristics and groundwater level changes

Table **4**. Pearson Correlation between Rainfall Characteristics and Groundwater Level Changes (n = 10)

Variable	Correlation (r)	Significance (p)
Total Rainfall (mm)	0.81	0.001
Rainy Days	0.76	0.004
Rainfall Intensity (mm/day)	-0.43	0.045

Source: Author's Computation (SPSS, 2025).

Total rainfall volume showed a strong positive correlation with groundwater level rise ($r = 0.81$, $p = 0.001$), confirming that annual precipitation volume is the primary driver of recharge in the study area. The number of rainy days was also positively correlated ($r = 0.76$, $p = 0.004$), indicating that distributed, lower-intensity rainfall spread over more days promotes greater infiltration. In contrast, mean rainfall intensity showed a statistically significant negative correlation ($r = -0.43$, $p = 0.045$), consistent with the theory that brief, high-intensity storms exceed the infiltration capacity of soils and generate more surface runoff than they contribute to recharge (Davamani et al., 2024; Siyad & Mohamed, 2025). These findings collectively demonstrate that the shift toward more intense, concentrated rainfall events observed over the study period partially offsets the recharge benefit expected from increased total rai

The spatial recharge map confirmed marked heterogeneity across the four LGAs. Akinyele and Ido recorded the highest recharge potential (145 mm/year and 138 mm/year respectively), a pattern attributable to their predominance of sandy loam soils with higher infiltration rates, greater vegetation cover reducing surface runoff, and lower densities of impervious surfaces. In contrast, Egbeda and Ibadan North recorded the lowest recharge values (96 mm/year and 88 mm/year respectively), reflecting the progressive replacement of permeable soils by concrete, asphalt, and other impervious materials associated with dense residential and commercial development. These spatial contrasts mirror the findings of MacDonald et al. (2021) and Ferreira et al. (2024) on recharge heterogeneity in sub-Saharan African settings, and reinforce the evidence from Olabode & Comte (2022) that urban expansion is a primary suppressant of diffuse recharge even when total rainfall is adequate.

4.0 DISCUSSION

The results of this study demonstrate that groundwater recharge in the peri-urban communities of Ibadan is governed by the combined influence of rainfall characteristics and land-use conditions, with neither factor operating independently of the other. While total annual rainfall increased by 41 percent over the study period, the corresponding improvement in groundwater levels was attenuated by the simultaneous rise in mean rainfall intensity and the progressive reduction of permeable land surfaces in the more urbanised LGAs. This finding is theoretically consistent with both the Water Balance Theory and the Hydro-Climatic Interaction Theory applied in this study: the former predicts that recharge increases with rainfall surplus, while the latter explains why this relationship is moderated by storm concentration, infiltration lags, and altered surface conditions.

The application of the Walsh and Lawler (1981) Seasonality Index provides a novel quantitative dimension to understanding recharge variability in this setting. The markedly higher SI values recorded in Egbeda and Ibadan North indicate that rainfall in these urbanised LGAs is increasingly concentrated into shorter, more intense seasonal episodes, reducing the duration of low-intensity rainfall that most effectively promotes soil infiltration. This mechanistic explanation aligns with the negative correlation between rainfall intensity and groundwater level rise observed in the correlation analysis and corroborates the global review evidence assembled by Siyad & Mohamed (2025).The Thornthwaite (1948) water budget analysis further strengthens these conclusions by providing an independent estimate of recharge surplus based on the energy balance between precipitation and evapotranspiration. The consistently lower water surpluses estimated for the more urbanised LGAs, despite similar total rainfall, confirm that the recharge deficit in these areas is a function of reduced infiltration opportunity rather than reduced rainfall supply. This is consistent with Olabode & Comte (2022), whose WetSpass-M modelling of urban Lagos demonstrated that impervious cover reduces diffuse recharge substantially even without changes in rainfall. Spatially, the inverse relationship between urbanisation intensity and recharge potential is one of the most important applied findings of this study. The contrast between Akinyele (145 mm/year) and Ibadan North (88 mm/year) represents a 40 percent difference in estimated annual recharge, entirely attributable to land-cover differences rather than rainfall volume. This pattern has direct implications for land-use planning in Ibadan: the protection of high-infiltration zones in Akinyele and Ido from further impervious development is essential to maintaining the recharge function of the basement aquifer system that serves the wider peri-urban population. Taken together, the results of this study indicate that rainfall remains the primary driver of groundwater recharge in the Ibadan peri-urban setting, but that the recharge response to rainfall is being progressively suppressed by storm intensification, increasing rainfall seasonality, and land-use change. Effective management of groundwater in this context requires an integrated response that combines enhanced hydroclimatic monitoring, land-use controls that protect natural recharge zones, and green infrastructure interventions to restore infiltration capacity in already urbanised areas.

5.0 Conclusion

This study examined groundwater recharge dynamics and sustainability under changing rainfall patterns in four peri-urban local government areas of Ibadan, Nigeria, over the period 2015 to 2024. Using the Walsh-Lawler Seasonality Index, Thornthwaite's climatic water budget model, Pearson correlation analysis, and ArcGIS spatial mapping, the study demonstrated that increasing total rainfall has been accompanied by rising storm intensity and worsening rainfall seasonality, particularly in the more urbanised LGAs. While mean annual rainfall rose by 41 percent over the study period and groundwater levels showed a net rise of 2.3 m, the rate of recharge improvement was constrained by intensifying events and expanding impervious cover. Estimated annual recharge ranged from 145 mm/year in the less urbanised Akinyele LGA to 88 mm/year in the more densely built-up Ibadan North LGA, a difference of 40 percent driven by land-cover rather than rainfall volume. The study concludes that rainfall remains the primary driver of groundwater recharge in Ibadan's peri-urban basement aquifer system, but that long-term aquifer sustainability is threatened by the combined effect of storm concentration, increasing seasonality, and progressive land conversion. Sustained and integrated management action is necessary to prevent recharge rates from declining further.

Recommendations

First, government agencies including NiMet and the Nigerian Hydrological Services Agency (NIHSA) should expand and upgrade the existing rainfall and groundwater monitoring network in the Ibadan peri-urban area. Real-time hydroclimatic data are essential for early detection of recharge deficits and for calibrating future water budget models. Monthly groundwater measurement campaigns should be institutionalised across all ten monitoring wells identified in this study. Second, urban development policies in Ibadan should incorporate zoning provisions that protect areas of demonstrated high recharge potential, particularly in Akinyele and Ido LGAs where sandy loam soils and vegetated cover sustain recharge rates of 138-145 mm/year. Environmental impact assessments for new residential and commercial developments in these LGAs should include mandatory groundwater recharge evaluations. Third, urban planners and development authorities should mainstream green infrastructure into physical development plans for all four LGAs. Specific interventions recommended include the construction of permeable pavements in new residential estates, the designation of green buffer zones around existing groundwater monitoring wells, and the installation of rooftop rainwater harvesting and infiltration systems in high-density residential areas of Egbeda and Ibadan North. These measures would partially compensate for the loss of natural recharge pathways associated with impervious surface expansion.

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Conflict of interest

The authors declare no conflict of interest regarding the publication of this manuscript

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