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Research paper

ASSOCIATION BETWEEN GROUNDWATER SOURCE CONFIGURATION AND ^{222}Rn OCCURRENCE: IMPLICATIONS FOR RADON SURVEILLANCE IN OYE EKITI, SOUTHWESTERN NIGERIA

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ABSTRACT

Groundwater ^{222}Rn occurrence is influenced by geological and hydrogeological conditions, and the configuration through which groundwater is accessed may contribute to the concentration encountered at the point of use. This study examined the association between groundwater source configuration and ^{222}Rn activity concentration in Oye Ekiti, southwestern Nigeria, and evaluated its relevance to radon surveillance. Forty groundwater sources, comprising 20 open wells and 20 borehole or pumped sources, were sampled during the dry season and analysed using a calibrated electronic radon detector. The median ^{222}Rn activity concentration was 17.50 Bq L^{-1} in borehole or pumped sources and 2.99 Bq L^{-1} in open wells, with a significant difference between distributions (Mann Whitney U = 287.0, p = 0.019) and a moderate distributional effect (Cliff's delta = 0.435). Concentrations exceeding 11.1 Bq L^{-1} occurred in 60% of borehole or pumped sources compared with 5% of open wells, demonstrating a pronounced source related difference in elevated ^{222}Rn occurrence. The distributional contrast remained evident when the highest concentration of 120.40 Bq L^{-1} was excluded (Mann Whitney U = 267.0, p = 0.032; Cliff's delta = 0.405), indicating that the observed pattern was not dependent on the extreme observation. The findings demonstrate that groundwater source configuration is associated with systematic variation in ^{222}Rn occurrence within the Oye Ekiti crystalline basement setting and may provide a useful basis for stratifying radon surveillance. Nevertheless, variability within both source categories indicates that source configuration should complement rather than replace direct measurement of individual groundwater supplies.

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1. Introduction

Radon-222 (^{222}Rn) is a naturally occurring radioactive noble gas produced in the ^{238}U decay series through the decay of ^{226}Ra in rocks and soils [26,27,30]. Due to its mobility and 3.82-day half-life, ^{222}Rn can migrate from mineral surfaces and pore spaces into groundwater, particularly where aquifers interact with uranium- and radium-bearing geological materials. Human exposure to radon occurs predominantly through inhalation of radon and its short lived progeny, with residential radon exposure associated with increased lung cancer risk [15]. Radon dissolved in drinking water can also contribute to exposure through ingestion and through transfer to indoor air during domestic water use [1–5,20,22,33].

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Groundwater ^{222}Rn concentrations vary considerably among locations, reflecting differences in geological and hydrogeological conditions that can influence radon occurrence and retention in groundwater [6–10]. Exposure of groundwater to the atmosphere can influence measured ^{222}Rn concentrations because dissolved radon can transfer from water to air during degassing [6–10]. Consequently, differences in source configuration and exposure conditions may contribute to variation in ^{222}Rn concentration measured at the point of collection. Differences between groundwater source configurations therefore warrant direct investigation rather than assuming that measurements from wells and borehole or pumped sources have comparable ^{222}Rn concentration distributions.

Studies from different geological settings have reported substantial variability in groundwater ^{222}Rn concentrations [7,8,10,12,18]. Investigations in Nigeria have likewise demonstrated spatial and source related variation in groundwater ^{222}Rn, including studies conducted in crystalline basement environments [2,3]. Although source related differences in groundwater ^{222}Rn have been reported in Nigeria, their magnitude, distributional consistency and statistical robustness within a common crystalline basement setting remain insufficiently quantified.

Oye Ekiti, southwestern Nigeria, is situated within the Precambrian Basement Complex, where groundwater is obtained from hand dug wells and boreholes. A previous study used the same 40 groundwater measurements to estimate age specific radiation dose and excess lifetime cancer risk associated with ^{222}Rn using a Monte Carlo simulation framework [21]. The present study therefore reanalyses these groundwater ^{222}Rn measurements to determine whether source configuration is associated with systematic differences in activity concentration. Unlike the previous study, which focused on age specific radiation dose and excess lifetime cancer risk, the present analysis evaluates source related differences in the concentration distribution, quantifies their magnitude and uncertainty, and examines the robustness of the observed association. Specifically, the study compares the concentration distributions of open wells and borehole or pumped sources, quantifies the magnitude and uncertainty of the source association using distribution free effect measures and bootstrap inference, evaluates differences in the occurrence of concentrations above a predefined comparative value, and tests the robustness of the association to the highest observed concentration.

2. Materials and Methods

2.1 Study area

The study was conducted in Oye Ekiti, Ekiti State, southwestern Nigeria, within the Precambrian Basement Complex. The sampling locations extend from 7.76445° to 7.89788° N and from 5.32277° to 5.33656° E (Figure 1). The area has a tropical climate characterised by distinct wet and dry seasons, with rainfall occurring predominantly from April to November and a comparatively dry period from December to March. Annual rainfall is approximately 1200 to 1400 mm, and the mean annual temperature is about 27 °C [34]. This seasonal rainfall regime provides the principal climatic context for groundwater recharge in the area.

Oye Ekiti is underlain by crystalline rocks of the Precambrian Basement Complex, with lithologies including migmatite gneiss, granite gneiss, banded gneiss, granite and charnockite [35]. Because crystalline basement rocks generally have limited primary porosity, groundwater occurrence is associated mainly with weathered zones and secondary structures such as joints and fractures. Geophysical investigations in Oye Ekiti have demonstrated spatial variation in weathered layer thickness, basement relief and subsurface fracturing, with corresponding variation in groundwater potential [10,34]. Recent hydrochemical and stable isotope investigations further characterise groundwater in Oye Ekiti as part of a crystalline basement aquifer system in which recharge and water rock interaction contribute to groundwater composition [35].

Groundwater is an important source of domestic water supply in Oye Ekiti and is obtained principally from hand dug wells and boreholes [10,35]. This hydrogeological setting is relevant to groundwater ^{222}Rn occurrence because radon emanation and its concentration in groundwater can be influenced by the mineralogical characteristics of aquifer materials, fracture systems, water rock interaction and groundwater residence conditions [23,25,32]. For the present analysis, groundwater sources were categorized as construction and abstraction configuration and do not imply hydrogeological aquifer confinement. Open wells comprised hand dug wells in which the water surface was directly exposed to the atmosphere during abstraction, whereas borehole or pumped sources comprised groundwater abstracted mechanically and conveyed through enclosed pipework before collection.

2.2 Sample collection, radon preservation and measurement

Groundwater sampling was conducted during the dry season from December 2023 to January 2024. A total of 40 groundwater sources were randomly selected, comprising 20 open wells and 20 borehole or pumped sources. The sampling points were distributed across the University main campus and surrounding areas of Oye Ekiti, including Irona, Idofin and Irare, the School Road environment and Falex, as documented in the published sampling framework. Geographic coordinates were recorded for each sampling location. The 40

observations corresponded to the same 40 groundwater sampling points previously reported in Olowomofe et al. [21], comprising 20 open wells and 20 borehole or pumped sources. The present analysis does not assume hydrogeological independence among these sources. Source depth, distance between neighbouring sources, screened interval, aquifer connectivity and other detailed hydrogeological characteristics were not recorded during the original sampling campaign and were therefore not incorporated into the analysis. The two source categories were defined according to their observable construction and abstraction configuration, with open sources comprising hand dug wells and borehole or pumped sources comprising mechanically abstracted groundwater supplied through enclosed delivery systems. The classification was used to examine the association between source configuration and measured ^{222}Rn activity concentration and was not intended to constitute a detailed hydrogeological classification of aquifer conditions. The determination of ^{222}Rn activity concentration followed ISO 13164 3:2013 for radon measurement in water by emanometry [13]. The RAD H_2O measurement procedure was applied using established procedures previously used for groundwater radon determination in Ekiti State [3].

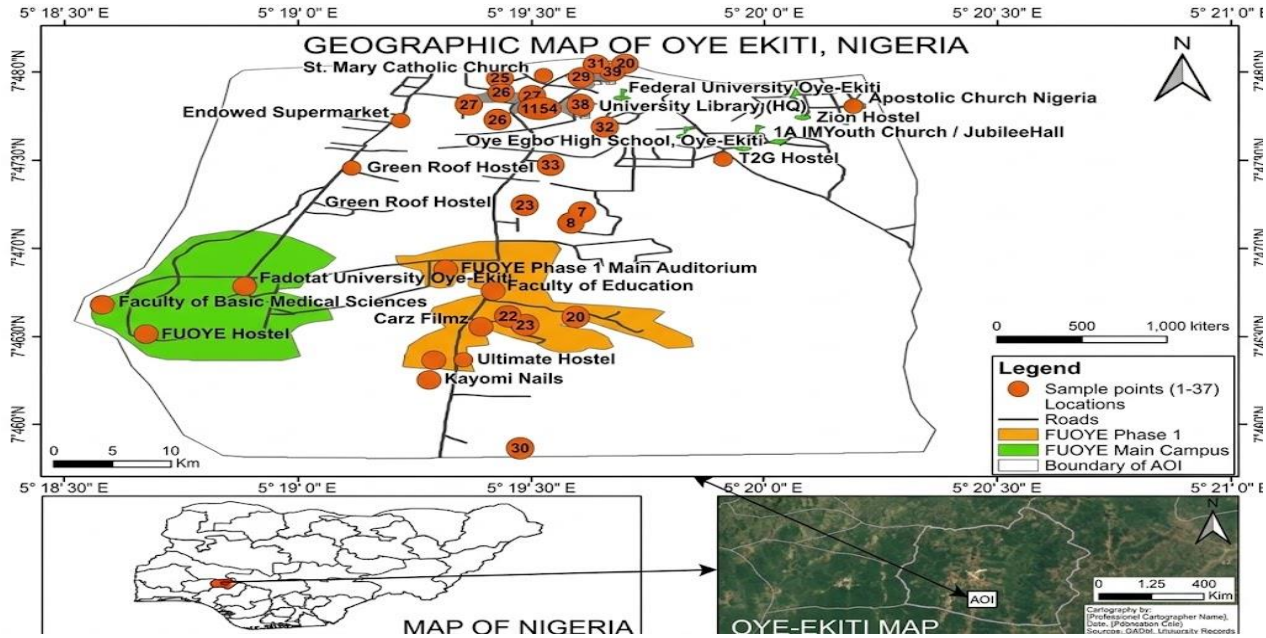


Figure 1. Spatial distribution of open and borehole or pumped groundwater sampling locations in Oye Ekiti, southwestern Nigeria.

Sampling procedures were adapted to the source configuration while maintaining precautions to minimise radon loss before analysis. For borehole or pumped sources, water was allowed to discharge before collection to displace stagnant water within the delivery line. Open well samples were collected carefully to minimise disturbance of the water column. Samples were transferred directly into 250 mL glass vials compatible with the RAD H_2O system. Water was introduced gently into each vial and allowed to overflow slowly, avoiding vigorous agitation, splashing and bubble formation. The vials were completely filled and sealed immediately with PTFE lined closures, leaving no visible headspace. These precautions were adopted because dissolved ^{222}Rn can readily transfer from water to air, and agitation or the presence of headspace can therefore promote radon loss before measurement [4,13].

The sealed samples were transported to the Radioanalytical Research Laboratory, Department of Physics, Ekiti State University, and remained unopened until measurement. Analyses were completed within 1 to 24 h of collection to minimise changes in activity associated with radioactive decay and sample handling. The physical half life of ^{222}Rn is approximately 3.82 days. Samples were therefore analysed within 1 to 24 h of collection to minimise activity loss due to radioactive decay before measurement [3,8,13].

^{222}Rn activity concentration was determined using a calibrated RAD7 electronic radon detector coupled to the RAD H_2O accessory. For each 250 mL sample, the water vial was incorporated into a closed air loop connected to the RAD7. The system aerated the sample to transfer dissolved radon from the aqueous phase into the recirculating air stream, followed by an equilibration period and four consecutive counting cycles. The RAD7 calculated the ^{222}Rn activity concentration in the original water sample from the radon concentration measured in the closed air loop using the fixed air to water volume relationship of the RAD H_2O configuration [8]. The measurement procedure was consistent with established RAD H_2O methods for groundwater radon determination [3,13]. The measurement arrangement and operating procedure were consistent with the established RAD H_2O method used for groundwater radon determination [3,8,13]. Humidity was controlled

during measurement because elevated relative humidity can reduce the electrostatic collection efficiency of positively charged ^{218}Po ions within the RAD7 detection chamber [8]. The detector and desiccant assembly were dried before analysis, and the internal relative humidity was maintained within the operating range recommended for RAD H_2O measurements [8].

Instrument performance was maintained through calibration against a NIST traceable ^{226}Ra reference source. Analytical quality assurance included duplicate measurement of 10% of the samples, blank measurements to assess detector background, and recovery measurements to verify analytical performance. Instrument performance was maintained through calibration against a NIST traceable ^{226}Ra reference source. Analytical quality assurance included duplicate measurement of 10% of the samples, blank measurements to assess detector background, and recovery measurements to verify analytical performance. Relative deviations for duplicate measurements were below 5%, detector background was below 1 pCi L^{-1}, and recoveries ranged from 95% to 105%. These procedures provided checks on measurement repeatability, background stability, and analytical recovery and were consistent with established RAD H_2O measurement procedures [3,8,13]. All 40 groundwater measurements satisfied the predefined quality control criteria and were retained for statistical analysis; no measurement was excluded. All 40 groundwater measurements satisfied the predefined quality control criteria and were retained for statistical analysis; no measurement was excluded. The sampling design was therefore intended to establish whether the observed groundwater source configuration was associated with differences in ^{222}Rn activity concentration across the study area. Accordingly, variables such as source depth, distance between neighbouring sources, borehole construction characteristics, screened interval, aquifer connectivity and detailed hydrochemical properties were not incorporated into the sampling design or statistical analysis. The resulting comparison should therefore be interpreted as an association between source configuration and measured ^{222}Rn activity concentration rather than as evidence of a causal hydrogeological effect. The measurement arrangement used for the RAD7 and RAD H_2O system is shown in Figure 2.

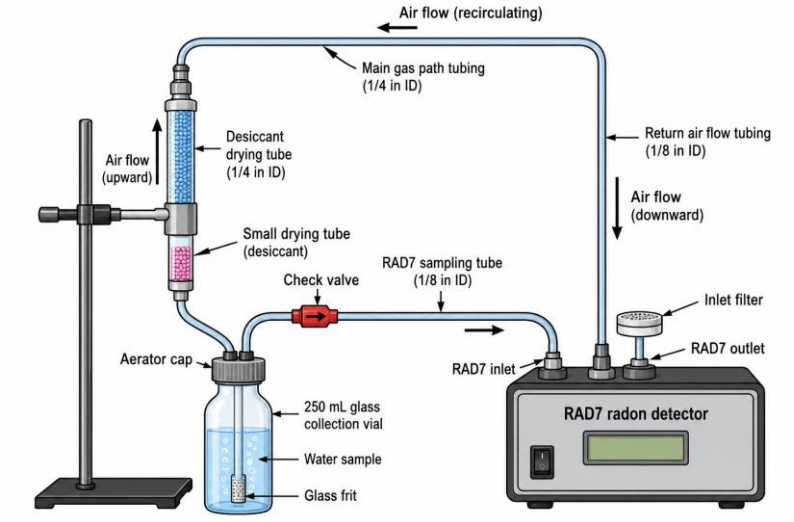


Figure 2. Schematic representation of the closed loop RAD7 RAD H_2O system used for measuring ^{222}Rn in groundwater samples.

2.3 Statistical analysis

The primary analysis examined whether the distribution of measured ^{222}Rn activity concentrations differed between groundwater source categories. The analytical dataset comprised 40 observations, including 20 open wells and 20 borehole or pumped sources. Because the study involved reanalysis of a fixed existing dataset, no prospective sample size calculation was performed. The primary outcome was ^{222}Rn activity concentration, expressed in Bq L^{-1}.

Concentration distributions were examined graphically and summarised using the median and interquartile range as the principal measures of central tendency and dispersion because the data were markedly right skewed. Arithmetic mean, standard deviation, geometric mean and observed range were additionally reported to facilitate comparison with published groundwater radon studies. Empirical cumulative distribution functions were used to visualise the complete concentration distributions without imposing distributional assumptions or arbitrary histogram intervals.

Differences between source categories were evaluated using a two-sided Mann Whitney U test [17]. The magnitude of distributional separation was quantified using Cliff's delta [6], with positive values indicating a greater tendency for ^{222}Rn concentrations to be higher in borehole or pumped sources. Relative differences between source categories were further expressed as borehole or pumped to open well ratios of the median

and geometric mean. Uncertainty in the median and geometric mean ratios was estimated using 20,000 nonparametric bootstrap resamples with bias corrected and accelerated (BCa) 95% confidence intervals [36]. The BCa procedure was used to accommodate potential bias and asymmetry in the sampling distributions of the ratio estimators arising from the strongly right skewed concentration data. A fixed random seed was used to ensure computational reproducibility.

A complementary exceedance analysis was performed using 11.1 Bq L^{-1}, equivalent to 300 pCi L^{-1}, corresponding to the U.S. EPA proposed maximum contaminant level for radon in drinking water [28]. This concentration was used solely as a comparative reference and was not interpreted as a universal threshold of radiological safety. The number and proportion of measurements above 11.1 Bq L^{-1} were determined separately for each source category. Source specific proportions were reported with 95% Wilson confidence intervals. Because of the small cell frequencies, the association between source category and exceedance status was assessed using Fisher's exact test. The magnitude of this association was further described using the odds ratio, relative risk and absolute difference in proportions, each accompanied by a 95% confidence interval.

A concentration of 11.1 Bq L^{-1} was therefore used as a predefined comparative value for the exceedance analysis. The number and proportion of measurements exceeding this value were compared between source categories, and sensitivity analysis was subsequently used to evaluate the robustness of the primary distributional comparison to the highest observed concentration.

All statistical tests were two sided, and statistical significance was evaluated at $p < 0.05$. Statistical analyses were performed using Python 3.13.5, with SciPy used for inferential procedures. Data organisation, numerical processing and tabulation were performed using pandas and NumPy, while graphical outputs were generated using Matplotlib. The same analytical dataset and computational procedures were used throughout to maintain consistency between numerical results, tables and figures.

3. Results

3.1 Distribution of ^{222}Rn activity concentration

The ^{222}Rn activity concentrations showed substantial variability among the 40 groundwater sources, ranging from 0.42 to 120.40 Bq L^{-1}. The distribution was right skewed, particularly among the borehole or pumped sources, and was therefore characterised using both conventional and robust descriptive statistics (Table 1). Borehole or pumped sources had a mean concentration of 18.71 ± 25.71 Bq L^{-1} and a median of 17.50 Bq L^{-1} (IQR: 3.92 to 21.65 Bq L^{-1}), whereas open wells had a mean of 5.01 ± 6.93 Bq L^{-1} and a median of 2.99 Bq L^{-1} (IQR: 2.32 to 4.83 Bq L^{-1}). The corresponding geometric means were 8.88 and 3.51 Bq L^{-1}, respectively.

Table 1. Distribution of ^{222}Rn activity concentrations according to groundwater source category

Source category	n	Mean ± SD (Bq L^{-1})	Median (IQR) (Bq L^{-1})	Geometric mean (Bq L^{-1})	Range (Bq L^{-1})	>11.1 Bq L^{-1}, n (%)
Borehole or pumped	20	18.71 ± 25.71	17.50 (3.92 to 21.65)	8.88	0.42 to 120.40	12 (60%)
Open well	20	5.01 ± 6.93	2.99 (2.32 to 4.83)	3.51	1.02 to 33.40	1 (5%)

Mann Whitney $U = 287.0$, $p = 0.019$; Cliff's delta = 0.435. Borehole or pumped to open well median ratio = 5.85 (BCa 95% CI: 1.49 to 7.91); geometric mean ratio = 2.53 (BCa 95% CI: 1.18 to 4.72).

The concentration distribution was shifted towards higher values among borehole or pumped sources (Figure 3). The difference was supported by the Mann Whitney test ($U = 287.0$, $p = 0.019$) and a moderate Cliff's delta of 0.435. The median concentration was 5.85 times that of open wells (BCa 95% CI: 1.49 to 7.91), while the geometric mean ratio was 2.53 (BCa 95% CI: 1.18 to 4.72). The broad range within the borehole or pumped group nevertheless demonstrates substantial within category heterogeneity, indicating that source configuration alone does not account for the observed variability.

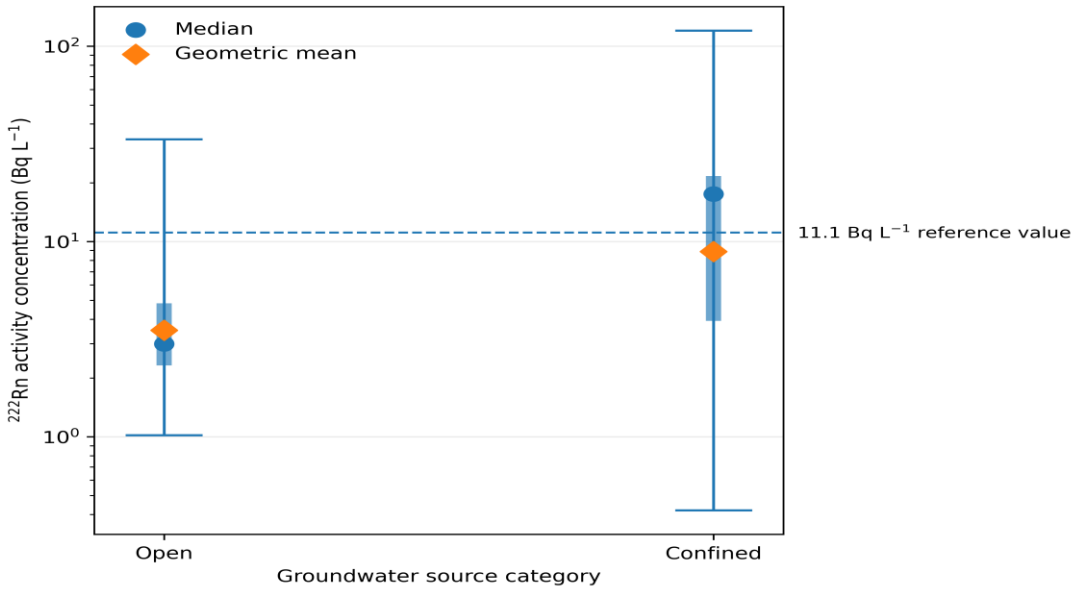


Figure 3. Distribution of ^{222}Rn activity concentrations in open and borehole or pumped groundwater sources. Vertical lines indicate the observed range, thick segments represent the interquartile range, circles indicate the median, and diamonds indicate the geometric mean. The horizontal dashed line denotes the 11.1 Bq L^{-1} comparative reference value. Concentrations are presented on a logarithmic scale because of the right skewed distribution.

3.2 Strength and robustness of the source association

The difference between source categories extended across the concentration distributions rather than being restricted to their measures of central tendency. The empirical cumulative distribution functions showed a consistent rightward displacement of the borehole or pumped source distribution, indicating that the source difference extended across a substantial portion of the observed concentration range rather than being confined to the arithmetic mean or upper tail (Figure 4). This distributional pattern is consistent with the Mann Whitney test and the moderate Cliff's delta reported above.

Bootstrap analysis further quantified the magnitude and uncertainty of the source related difference. Based on 20,000 resamples, the borehole or pumped to open well median ratio was 5.85 (BCa 95% CI: 1.49 to 7.91), while the geometric mean ratio was 2.53 (BCa 95% CI: 1.18 to 4.72) (Figure 5). The asymmetric confidence intervals reflect the right skewed concentration distributions and uncertainty associated with ratio estimation. Importantly, both intervals remained above the null ratio of 1, supporting a systematic upward shift in ^{222}Rn concentration among borehole or pumped sources rather than an apparent difference generated solely by the arithmetic mean or the highest observation

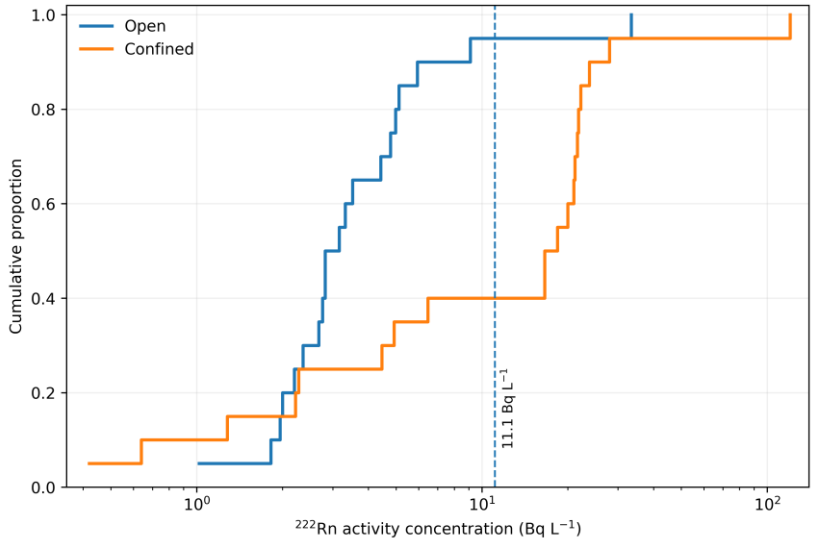


Figure 4. Empirical cumulative distributions of ^{222}Rn activity concentration in open and borehole or pumped groundwater sources. Concentrations are displayed on a logarithmic scale to

accommodate the right skewed distribution. The vertical dashed line represents the 11.1 Bq L^{-1} comparative value.

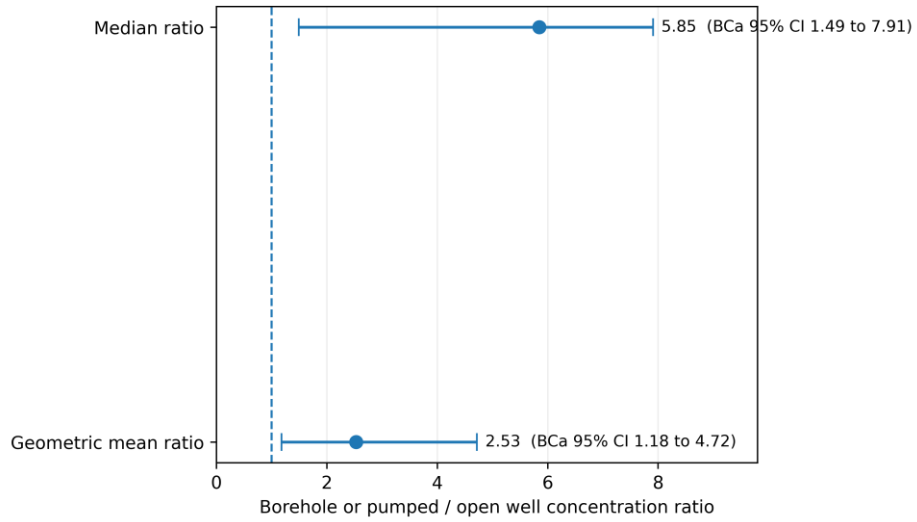


Figure 5. Relative difference in ^{222}Rn activity concentration between borehole or pumped sources and open wells. Points represent the observed ratios of the median and geometric mean, and horizontal intervals represent bias corrected and accelerated (BCa) 95% confidence intervals obtained from 20,000 bootstrap resamples. The vertical reference line at 1 represents no difference between source categories.

The distributional difference was also reflected in exceedance frequency: 12 of 20 borehole or pumped sources (60.0%; 95% CI: 38.7 to 78.1%) exceeded the predefined comparative value of 11.1 Bq L^{-1}, compared with 1 of 20 open wells (5.0%; 95% CI: 0.9 to 23.6%). Fisher's exact test indicated a strong association between source category and exceedance status (p = 0.00043), with an odds ratio of 28.5 (95% CI: 3.16 to 257.44). The absolute difference in exceedance proportions was 0.55 (95% CI: 0.27 to 0.74). The wide odds ratio interval reflects the modest sample size and sparse open well exceedances; the magnitude should therefore be interpreted primarily in terms of the direction and strength of the observed association rather than the precision of the point estimate. The exceedance frequencies and corresponding measures of association are summarised in Table 2

Table 2. Statistical strength and robustness of the association between groundwater source category and occurrence above the 11.1 Bq L^{-1} comparative value

Statistical measure	Estimate
Borehole or pumped sources >11.1 Bq L^{-1}	12/20 (60.0%)
95% Wilson CI	38.7 to 78.1%
Open wells >11.1 Bq L^{-1}	1/20 (5.0%)
95% Wilson CI	0.9 to 23.6%
Fisher's exact test	p = 0.00043
Odds ratio	28.5
95% CI	3.16 to 257.44
Relative risk	12.0
95% CI	1.72 to 83.80
Absolute difference in proportions	0.55
95% CI	0.27 to 0.74

Statistical measure	Estimate
Mann Whitney U test, complete dataset	U = 287.0, p = 0.019
Cliff's delta, complete dataset	0.435
Mann Whitney U test, OEI83 excluded	U = 267.0, p = 0.032
Cliff's delta, OEI83 excluded	0.405

4. Discussion

4.1 Source related variation in groundwater ^{222}Rn

The observed difference between groundwater source categories is environmentally relevant because source configuration was associated not only with the central tendency of ^{222}Rn activity concentration but also with the broader concentration distribution and the occurrence of elevated measurements. Borehole or pumped sources showed a clear shift towards higher concentrations relative to open wells. This pattern is consistent with observations from other Nigerian groundwater studies. Isinkaye et al. [9] reported ^{222}Rn concentrations in groundwater sources within a university campus in southwestern Nigeria, while Kolo et al. [14] specifically reported higher ^{222}Rn concentrations in borehole water than in hand dug wells in Bosso Community, North Central Nigeria. Regional investigations across southwestern Nigeria have likewise demonstrated substantial variability in groundwater ^{222}Rn occurrence across different geological and hydrogeological settings [1–3, 16]. Okeyode et al. [19] likewise reported higher mean ^{222}Rn concentrations in borehole water than in well and surface water. These findings indicate that groundwater source characteristics may provide useful information on systematic variation in measured ^{222}Rn, although the magnitude and direction of such differences remain dependent on local environmental conditions.

The comparison presented in Table 3 places the Oye Ekiti measurements within the range of ^{222}Rn concentrations reported from Nigerian groundwater and other relevant settings [24,25,31]. Absolute ^{222}Rn concentrations vary considerably among studies, reflecting differences in geological and hydrogeological conditions, including ^{226}Ra availability, water rock interaction and groundwater residence conditions [23,25]. Differences in source construction, abstraction conditions, sampling period and sample handling may introduce additional variability [4,12]. Consequently, differences in absolute concentration between study areas should not be interpreted solely as geographical differences in radiological conditions. Comparable evidence of elevated radon in groundwater has also been reported in a Greek village, where enhanced radon in water was investigated in relation to its transfer from water to indoor air and associated exposure pathways [22].

More important to the present research question is the consistency in the source related difference observed within the Oye Ekiti dataset. Borehole or pumped sources showed a higher concentration distribution than open wells, with a moderate distributional effect (Cliff's delta = 0.435). The bootstrap analysis further indicated a median concentration ratio of 5.85 and a geometric mean ratio of 2.53 for borehole or pumped sources relative to open wells. The occurrence of concentrations above 11.1 Bq L^{-1} was also markedly different, with 60% of borehole or pumped sources compared with 5% of open wells exceeding this comparative value (Fisher's exact test, p = 0.00043). The distributional difference remained evident after exclusion of the highest concentration of 120.40 Bq L^{-1}, indicating that the observed source related pattern was not dependent solely on the extreme observation.

However, because the present study re-analyses the 40 groundwater measurements previously used to assess age specific radiation dose and excess lifetime cancer risk [21], its contribution lies in characterizing the source related concentration pattern rather than generating a new measurement dataset. The present analysis demonstrates that the source related difference is evident across the concentration distribution, is quantifiable in terms of effect magnitude and relative concentration, and remains detectable after exclusion of the highest observation. This provides a distinct analytical basis for considering groundwater source configuration in radon surveillance.

4.2 Environmental and radiation protection significance

The findings from Oye Ekiti demonstrate that groundwater source configuration has practical relevance to the occurrence of elevated ^{222}Rn in the sampled groundwater system. Borehole or pumped sources had substantially higher ^{222}Rn concentrations than open wells, and 60% of these sources exceeded 11.1 Bq L^{-1} compared with only 5% of open wells. This source related pattern, together with the moderate distributional effect observed in the dataset, indicates that source configuration can provide useful information for identifying

groundwater supplies with a greater likelihood of elevated ^{222}Rn occurrence. The finding is consistent with evidence from Nigerian groundwater studies showing considerable variation in ^{222}Rn concentrations among wells and boreholes [1–3,11,14,19]. However, the Oye Ekiti results also show that the association is not absolute. The presence of 33.40 Bq L^{-1} in an open well and concentrations below 11.1 Bq L^{-1} in several borehole or pumped sources demonstrates that elevated ^{222}Rn is not restricted to a particular source category.

Within the Oye Ekiti setting, source configuration therefore provides a useful basis for stratifying groundwater radon surveillance, rather than replacing direct measurement. Borehole or pumped sources may warrant greater attention in routine screening because elevated concentrations occurred more frequently in this category. At the same time, open wells should not be excluded from surveillance because individual sources can also contain appreciable ^{222}Rn concentrations. This source specific approach is particularly relevant where monitoring resources are limited, as it can assist in allocating sampling effort while retaining direct measurement as the basis for radiological assessment.

The radiation protection relevance arises from the potential contribution of radon bearing groundwater to human exposure through ingestion and through transfer of dissolved ^{222}Rn from water to indoor air, where it may contribute to inhalation exposure [12,32]. The higher occurrence of elevated concentrations among borehole or pumped sources therefore identifies a group of groundwater supplies that may merit closer radiological characterization. The finding does not, however, establish that users of one source category necessarily receive greater radiation dose, because actual exposure depends on water consumption, household water use, radon transfer to indoor air and other exposure conditions. The present results are consequently most appropriately interpreted as evidence for source related variation in groundwater ^{222}Rn occurrence, rather than as a direct estimate of population radiation risk.

The observed variation also indicates that the relationship between source configuration and groundwater ^{222}Rn is embedded within a more complex environmental system. Groundwater ^{222}Rn occurrence is influenced by geological and hydrogeological conditions, including ^{226}Ra availability, radon emanation and transport, water rock interaction and groundwater residence conditions [23,25]. These processes were not directly characterized in the present study. The analysis was based on a single dry season sampling campaign, and information on source depth, detailed construction characteristics, aquifer mineralogy, ^{226}Ra activity, groundwater residence time and hydrochemistry was unavailable. The observed source related association should therefore not be interpreted as evidence of a specific hydrogeological mechanism. Repeated measurements across contrasting seasons, together with source specific hydrogeological and geochemical characterization, would provide the basis for determining the mechanisms responsible for the observed variation.

Overall, the Oye Ekiti findings support the use of groundwater source configuration as a practical surveillance stratifier for ^{222}Rn, while retaining individual source measurement as the essential basis for exposure assessment and radiation protection decisions. Where elevated groundwater radon is identified, subsequent management may include consideration of appropriate drinking water treatment or alternative water supply options, although treatment selection was beyond the scope of the present study [29].

Table 3. Comparison of groundwater ^{222}Rn concentrations reported in Oye Ekiti and selected previous studies

Study area	Groundwater source or setting	n	^{222}Rn concentration (Bq L^{-1})	Range (Bq L^{-1})	Relevance	Reference
Oye Ekiti	**Open wells**	**20**	**5.01 ± 6.93; median 2.99**	**1.02–33.40**	**Lower distribution**	**Present study**
Oye Ekiti	**Borehole or pumped sources**	**20**	**18.71 ± 25.71; median 17.50**	**0.42–120.40**	**Higher distribution and more concentrations >11.1 Bq L^{-1}**	**Present study**
Ekiti State University campus	Hand dug wells	8	9.81 ± 1.85	2.46–22.40	Lower mean than	[9]

Study area	Groundwater source or setting	n	^{222}Rn concentration (Bq L^{-1})	Range (Bq L^{-1})	Relevance	Reference
					borehole sources	
Bosso Community	Boreholes	10	24.78 ± 2.48	–33.30	8.48 Higher mean than hand dug wells	[14]
Southwestern Nigeria	Groundwater, six states	145	35.9 ± 38.4	271	1.6– Regional variability	[2]
Ekiti State	Groundwater	24	81.7 ± 61.3	271	9.5– Within state variability	[2]
Ibadan granitic terrain	Groundwater	52	34.03 ± 15.69	–76.90	7.60 Substantial variability	[1]
Morocco	Groundwater	51	14.4	–49.3	0.42 Variability	[25]

5. Conclusion

This study demonstrates that groundwater source configuration provides a useful basis for understanding and stratifying ^{222}Rn occurrence in Oye Ekiti, southwestern Nigeria. Borehole or pumped sources exhibited a substantially higher ^{222}Rn concentration distribution than open wells, with a median concentration ratio of 5.85 (BCa 95% CI: 1.49 to 7.91) and a moderate distributional effect. Concentrations above 11.1 Bq L^{-1} also occurred considerably more frequently among borehole or pumped sources, while sensitivity analysis confirmed that the observed pattern was not driven solely by the highest measured concentration.

The principal contribution of the study is the demonstration that source configuration is associated with systematic variation across the groundwater ^{222}Rn concentration distribution and can therefore serve as a practical stratification characteristic for radon surveillance. The combined use of distributional statistics, effect size estimation, BCa bootstrap inference, exceedance analysis and sensitivity testing provides a quantitative basis for characterizing the magnitude and robustness of this source related pattern beyond comparison of concentration means.

Source configuration can consequently inform surveillance prioritization, particularly where monitoring resources are limited, but the variability observed within both source categories means that it cannot substitute for direct measurement of individual groundwater supplies. The findings provide a basis for incorporating source configuration into groundwater radon surveillance in crystalline basement environments, with future investigations benefiting from seasonal measurements and integration of hydrogeological and geochemical characteristics to further resolve the processes underlying the observed variation.

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Conflict of Interest

Not Applicable

Data Availability Statement

Some of the research data associated with this article are included within the article. However, additional analytical outputs generated during the current study are available from the corresponding author upon reasonable request.

Author Contribution Statement

O.G.O. conceived the study, performed the reanalysis, curated the dataset, conducted the statistical analysis, interpreted the results, and prepared, reviewed, and approved the final manuscript.

Ethics Approval

Ethical approval was not required because the study did not involve human participants or experimental animals.

Informed Consent

This article does not contain any studies involving human subjects.

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