INDONESIAN JOURNAL OF INNOVATION AND APPLIED SCIENCES (IJIAS)
Journal Homepage: https://ojs.literacyinstitute.org/index.php/ijias
ISSN: 2775-4162 (Online)
Research Article

Volume 5	Issue 2	June (2025)	DOI: 10.47540/ijias.v5i2.1997	Page: 193 – 202

Investigation of Erosion-Induced Groundwater Pollution in Selected Wells Around Kwarin Awaja, Birnin Kudu, Nigeria

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ARTICLE INFO

Keywords: Erosion, Groundwater Pollution, Rainfall Events, Shallow Wells, Water Quality.

Received : 04 May 2025
Revised : 29 June 2025
Accepted : 30 June 2025

ABSTRACT

Soil erosion in semi-arid regions contributes significantly to groundwater contamination, particularly through sediment-laden runoff entering shallow aquifers. The intensification of rainfall events has accelerated surface erosion, leading to increased transport of sediments and contaminants into shallow wells, which serve as the primary water source for many households. This study investigated the extent and mechanisms of groundwater contamination in twelve selected wells around Kwarin Awaja, focusing on changes in water quality before and after major rainfall events. Water samples were analyzed for turbidity, electrical conductivity (EC), pH, coliform bacteria, nitrates, and heavy metals (cadmium and chromium). Results showed significant increases in turbidity, nitrates, total dissolved solids, chloride, sulphate, and electrical conductivity after rainfall, indicating erosion-induced pollutant infiltration. Paired sample t-tests revealed significant post-rainfall increases in turbidity (up to 12.1 NTU) and EC (up to 675 µS/cm), with values exceeding national standards such as Nigeria Standards for Drinking Water Quality (NSDWQ) in wells closest to active erosion sites. Pearson correlation analysis showed strong associations between proximity to erosion features and elevated pollution indicators. Microbial contamination, absent before rainfall, was detected in several wells after rainfall events. The findings highlight the vulnerability of shallow groundwater to erosion-driven pollution and underscore the need for targeted interventions to protect water quality in erosion-prone rural environments.

INTRODUCTION

Soil erosion is a major global environmental challenge, particularly prevalent in arid and semi-arid regions. In Nigeria, especially in the northern region, erosion has resulted in land degradation, loss of soil fertility, and pollution of water resources (Isukuru et al., 2024; Odoh et al., 2024). Communities relying on groundwater for domestic use have reported deteriorating water quality, often marked by discoloration, foul odors, and outbreaks of waterborne diseases after heavy rains (Aladejana et al., 2020; Odewade et al., 2025; Tanko et al., 2024). Furthermore, these challenges are consistent with broader patterns observed across northern Nigeria, where climate change has amplified the frequency and intensity of extreme weather events.

Groundwater, traditionally considered a safe source of drinking water, is increasingly at risk due to surface runoff carrying sediments, organic matter, and contaminants into inadequately protected wells (Abanyie et al., 2023; Li et al., 2021). The authors submitted further that, absence of standard well linings and the close proximity of open wells to actively eroded land surfaces have compounded the risk in many rural areas. During the rainy season, minor rills and gullies can evolve into expansive erosional features, bypassing natural filtration processes and accelerating the transport of pollutants into aquifers. Similar patterns have been documented in erosion-prone areas of West Africa, where groundwater quality significantly declines following seasonal rainfall events (Schroeter et al., 2025).

Existing studies on groundwater pollution in Nigeria have predominantly focused on urban contamination from industrial and agricultural sources, while rural erosion-induced pollution remains comparatively underexplored (Amin Kodiya et al., 2025; Ojo et al., 2024; Sadeeq et al., 2024; Tanko et al., 2024). According to the previous authors submission, most research emphasizes chemical parameters such as nitrate and heavy metal concentrations without adequately linking observed pollution trends to dynamic geomorphological processes like rainfall-triggered erosion. Addressing this gap is crucial for improving water security in vulnerable rural communities.

This study investigates erosion-induced groundwater contamination in selected wells around Kwarin Awaja, a rural community in Birnin Kudu Local Government Area of Jigawa State, Nigeria, characterized by highly erodible soils and reliance on shallow wells. The objective of this study is to assess the extent and mechanisms of groundwater pollution following rainy season erosion events. The findings aim to contribute to scientific understanding and support community resilience by informing sustainable groundwater management strategies in northern Nigeria's semi-arid regions.

METHODS

Study Area

Kwarin Awaja is located in Birnin Kudu Local Government Area of Jigawa State, Nigeria. Geographically, the area lies between latitudes 11°25'N and 11°32'N and longitudes 9°15'E and 9°22'E (Figure 1). It has a semi-arid climate characterized by high temperatures, low annual rainfall (ranging between 600 mm and 800 mm), and prolonged dry seasons. The landscape is generally flat to gently undulating, with sparse vegetation dominated by shrubs and grasses. The underlying geology consists mainly of sedimentary formations, particularly sandstones and clays, which are susceptible to weathering and erosion. The area has several gully erosion sites caused by intense rainfall and anthropogenic activities such as farming on steep slopes and poor waste management (Garba et al., 2023).

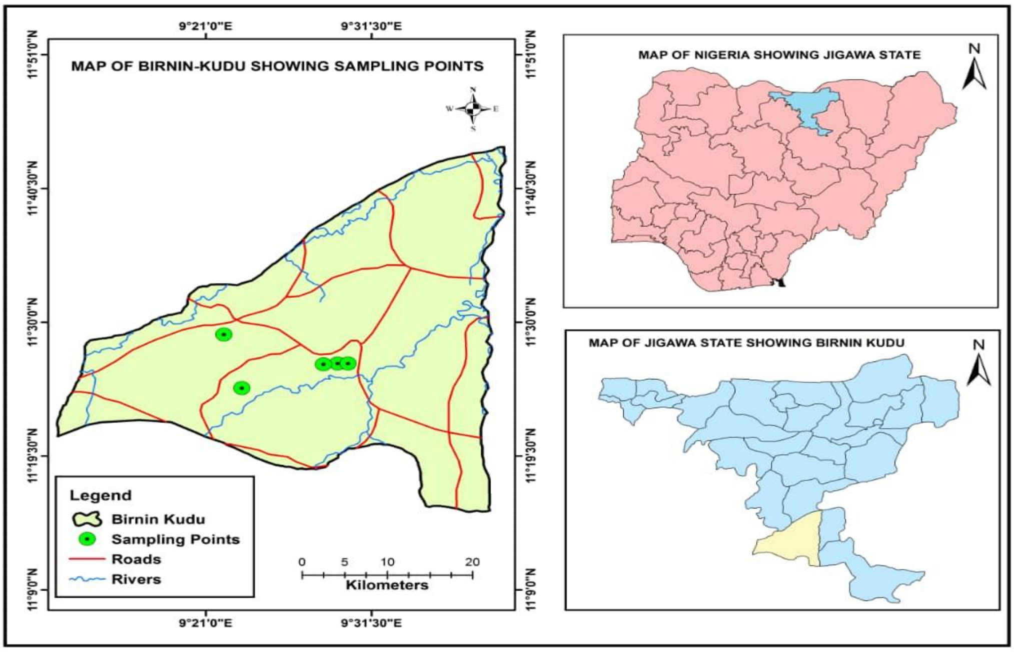

Figure 1. Study area showing sampling points
Source: Author's fieldwork (2024)

Sampling Design and Collection

A purposive sampling strategy was employed to select twelve wells across Kwarin Awaja communities, focusing on those located near active erosion features and known to exhibit past signs of water quality deterioration. This targeted approach followed risk-based site selection principles outlined by Palinkas et al. (2015). Water samples were collected twice from each well, first at the onset of the rainy season to establish baseline conditions and again within 48 hours after significant rainfall events exceeding 20 mm/day, to capture erosion-related changes in groundwater quality, following the methodology of Ogbozige et al. (2018). To evaluate the influence of proximity on contamination risk, the distances from each well to the nearest active erosion site were measured using straight-line ground methods, adapted from Uchendu et al. (2021). The wells were categorized based on proximity: SW_1 to SW_4 were situated within 50 meters of erosion sites, SW_5 to SW_8 were located beyond 100 meters, while SW_9 to SW_{12} were approximately 200 meters away. All sampling, handling, and preservation procedures were conducted in accordance with standard methods outlined in APHA (2017), ensuring the accuracy, integrity, and comparability of the data collected across different wells and time periods.

Water Quality Analysis

Water samples were collected from all selected hand-dug wells during two critical periods to effectively assess the impact of erosion on groundwater quality in 2024. The first sampling took place during the early rainy season in July 2024 to establish baseline water quality conditions, while the second sampling was conducted within 48 hours following major rainfall events. These post-rainfall samplings were intended to capture the immediate effects of surface runoff and erosion, in line with the procedure documented by Kabiru (2023). The collected samples were analyzed for key water quality parameters known to reflect erosion-induced contamination. These included turbidity, electrical conductivity (EC), pH, coliform bacteria, nitrate, chloride, sulphate concentrations, and selected heavy metals such as cadmium and chromium. The analytical procedures adhered strictly to the Standard Methods for the Examination of Water and Wastewater as outlined by the American Public Health Association (APHA), following methodologies previously reported by Hassan (2020). Turbidity, an indicator of sediment influx, was measured using a turbidimeter, while TSS was determined by the gravimetric method. These parameters directly reflect the level of particulate matter introduced by erosion. The pH and electrical conductivity were measured using calibrated meters to detect chemical changes associated with runoff infiltration. Coliform bacteria, serving as microbial indicators of fecal contamination from surface input, were quantified through membrane filtration, following the guidelines provided by Aram et al. (2021). Nitrate and sulphate concentrations were determined using the colorimetric method to assess nutrient enrichment, which is often linked to agricultural activities during erosion episodes. Finally, concentrations of cadmium and chromium, representing potential pollutants from both geogenic and anthropogenic sources, were analyzed using an Atomic Absorption Spectrophotometer (AAS), in accordance with protocols established by Mohammad et al. (2024).

Statistical Analysis

Paired sample t-tests were used to compare the water quality parameters before and after rainfall. Pearson correlation coefficients were calculated to analyze the relationship between proximity to erosion features and the selected pollution indicators. SPSS version 26 was used for all analyses, and statistical significance was determined at $p < 0.05$. Normality tests were conducted to validate the data distribution.

RESULTS AND DISCUSSION

Physicochemical Parameters of Water Samples

The water samples collected from twelve selected hand-dug wells in the study area were analyzed for various physicochemical, heavy metals, and microbial parameters, both before the onset of rainfall (baseline) and after rainfall (post-rainfall). The results indicate significant variations in water quality during the two periods. Table 1 and 2 compares the values of the measured parameters at different sampling points with Nigerian drinking water standards of NSDWQ.

Table 1. Physicochemical Parameters of Water Samples in Kwarin Awaja before the onset of rainfall (baseline)

Parameter	NSDWQ	SW_1	SW_2	SW_3	SW_4	SW_5	SW_6	SW_7	SW_8	SW_9	SW_{10}	SW_{11}	SW_{12}
pH	6.5-8.5	7.1	7.2	7.15	7.3	7.25	7	7.35	7.05	7.25	7.1	7.2	7.3
Turbidity (NTU)	5	6.3	8	7.2	6.9	9.1	7.55	8.3	6.7	7.6	7	8.1	6.8
EC (µs/cm)	1000	580	620	595	610	605	600	625	585	615	590	605	595
Nitrate (mg/L)	50	0.1	0.22	0.18	0.2	0.15	0.25	0.19	0.17	0.16	0.21	0.18	0.23
Chloride (mg/L)	250	35.6	37.2	36.1	38.4	39.2	38.6	39.2	38	34.1	38.2	39	37.8
Sulphate (mg/L)	100	186	180	210	220	202	200	198	200	180	240	220	210
Cadmium (mg/L)	0.003	0.002	0.002	0.002	0.001	0.002	0.003	0.002	0.002	0.001	0.002	0.003	0.002
Chromium (mg/L)	0.005	0.058	0.062	0.065	0.055	0.059	0.06	0.063	0.064	0.056	0.061	0.067	0.06
Coliform Bacteria (MPN)	ABSENT	0	0	0	0	0	0	0	0	0	0	0	0

Source: Author's analysis (2024)

The analysis of physicochemical parameters in the water samples from the study area revealed notable variations between baseline and post-rainfall conditions. The pH levels ranged from 7.1 to 7.35 before rainfall and slightly increased to between 7.2 and 7.4 afterward (Table 1 and Table 2), indicating neutral to slightly alkaline conditions. Spatial analysis revealed that wells closer to erosion sites (SW_1–SW_4) exhibited slightly lower pH values compared to those farther away. This trend may be attributed to the infiltration of organic acids and leachates from eroded soils, which can lower the pH of groundwater. This shift indicates a potential influence of rainfall on the alkalinity of the groundwater. Studies across Nigeria have shown similar trends, where rainwater tends to dilute acidic components, thereby raising pH levels. For instance, a study in Ibadan, Nigeria, identified erosion and flooding as significant contributors to groundwater contamination, affecting parameters like pH (Ayejoto & Egbueri, 2023). In the Sahel region of Africa, areas with recent groundwater recharge were found to be more vulnerable to surface contamination, potentially impacting pH levels (Wang et al., 2020).

Turbidity levels increased from an average of 7.2 NTU at baseline to 10.5 NTU post-rainfall (Table 1 and Table 2). Higher turbidity was observed in wells located within 50 meters of erosion sites, indicating that erosion significantly contributes to the suspension of particulate matter into groundwater. The elevated turbidity in these wells is likely due to runoff from disturbed soils during rainfall events, where finer particles bypass natural filtration layers. Wells situated farther from erosion sites exhibited lower turbidity levels, suggesting that distance provides a natural buffer against sediment infiltration. Similar findings were reported in studies conducted in Nigeria, where rainfall-induced runoff significantly elevated turbidity levels in groundwater sources (Lapworth et al., 2017). The turbidity values observed in Kwarin Awaja exceed the Nigerian Standard for Drinking Water Quality (NSDWQ) limit of 5 NTU, indicating a risk for water quality deterioration and potential health hazards related to waterborne diseases.

Electrical conductivity (EC) measurements showed a rise from an average of 600 µS/cm to 670 µS/cm after rainfall (Table 1 and Table 2), which is below the NSDWQ standard of 1000 µS/cm. This indicates moderate ionic content and suggests that the groundwater is within acceptable limits for household use. Slightly higher EC values were observed in wells nearer to erosion zones, possibly reflecting the leaching of dissolved ions from disturbed soils into the groundwater. Over time, continued erosion could increase EC through sustained input of weathered minerals, especially if erosion exposes saline or mineral-rich subsoils (Yin et al., 2016; Shokri et al., 2024). This increase suggests a higher concentration of dissolved salts and minerals, likely due to runoff carrying contaminants into the groundwater (Padhye et al., 2023). Research in various African contexts has demonstrated that rainfall can influence EC levels significantly, especially in areas susceptible to erosion and runoff (Li et al., 2021).

Nitrate levels in the sampled water increased from 0.15 to 0.32 mg/L after rainfall (Table 1 and Table 2). These concentrations are still below the NSDWQ limit of 50 mg/L; however, slightly higher nitrate levels were observed in wells closer to erosion sites, which may indicate early-stage leaching of organic matter or nearby domestic waste from eroded soil layers. Over time, continued erosion could enhance nitrate infiltration, especially in areas with agricultural runoff or poor waste management practices. Studies have shown that excessive nitrate levels in groundwater can lead to health issues, including methemoglobinemia, particularly in infants (Ayejoto & Egbueri, 2023; Chaudhary et al., 2025). In regions like East Africa, agricultural practices have similarly been linked to rising nitrate levels in groundwater, prompting calls for improved land management practices (Ligate et al., 2021; Prabagar et al., 2020).

Chloride concentrations remained relatively stable, with minor fluctuations before and after rainfall (Table 1 and Table 2). The chloride levels were consistently below the NSDWQ limit of 250 mg/L, indicating that salinity issues may not be a significant concern at this time. The comparison of the two tables indicates that rainfall and erosion contribute to a slight increase in chloride concentration in the groundwater. This increase is likely due to the leaching of chloride ions from the soil and their transport into groundwater sources via runoff. However, the chloride levels are still well below the permissible limit, indicating that this is not a major concern in the study area. Similar trends have been observed in other studies where chloride levels in groundwater tend to increase during the rainy season due to increased leaching (Faraji & Shahryari, 2024). Also, studies in Nigeria have reported that chloride levels in rural groundwater sources often remain low, unless influenced by industrial activities or saline intrusion (Amararu et al., 2023).

Sulphate levels in the well water increased significantly from 186 mg/L to 240 mg/L post-rainfall (Table 1 and Table 2). Sulphate levels are above the NSDWQ limit even before rainfall, and they increase further after rainfall, suggesting that erosion plays a role in mobilizing sulphate from the soil into the groundwater. This submission is in agreement with the study of Amararu et al. (2023). This rise is concerning, as elevated sulphate concentrations can indicate contamination from agricultural runoff or industrial activities (Balaram et al., 2023). Previous studies have shown that high sulfate levels can lead to gastrointestinal issues and other health concerns. In a comparative study in Ethiopia, sulfate levels exceeding 100 mg/L were linked to agricultural practices and erosion (Shferaw et al., 2024), mirroring the situation in Kwarin Awaja.

Table 2. Physicochemical Parameters of Water Samples in Kwarin Awaja after rainfall (post-rainfall)

Parameter	NSDWQ	SW_1	SW_2	SW_3	SW_4	SW_5	SW_6	SW_7	SW_8	SW_9	SW_{10}	SW_{11}	SW_{12}
pH	6.5-8.5	7.2	7.3	7.25	7.35	7.15	7.1	7.4	7.20	7.25	7.15	7.3	7.35
Turbidity (NTU)	5	9.8	10.5	11.2	8.6	10	9.4	12.1	10.7	11.4	9.2	10.8	9.6
EC (µs/cm)	1000	630	675	655	645	660	670	640	635	660	625	655	645
Nitrate (mg/L)	50	0.25	0.32	0.19	0.2	0.15	0.22	0.28	0.23	0.21	0.27	0.3	0.18
Chloride (mg/L)	250	47	46.5	46.2	48.3	45.9	49.35	48.2	48.4	50.2	48.1	47.6	48
Sulphate (mg/L)	100	240	248	250	262	238	250	260	244	238	202	260	270
Cadmium (mg/L)	0.003	0.003	0.003	0.002	0.004	0.003	0.002	0.003	0.003	0.003	0.003	0.004	0.003
Chromium (mg/L)	0.05	0.072	0.078	0.075	0.08	0.073	0.07	0.074	0.076	0.079	0.075	0.077	0.074
Coliform Bacteria (MPN)	ABSENT	1	1	1	1	0	1	1	1	1	0	1	1

Source: Author's analysis (2024)

Heavy Metals Concentration from Sampled Water

The analysis of heavy metals revealed that cadmium levels remained below the NSDWQ limit of 0.003 mg/L, showing no significant change between baseline and post-rainfall conditions (Table 1 and Table 2). The comparison of the two tables suggests that rainfall and erosion may contribute to a slight increase in cadmium contamination of the groundwater; this outcome is in tandem with the study from Kubier et al. (2019). This finding aligns with studies conducted in various parts of Nigeria, where cadmium concentrations in groundwater have generally been low, attributed to limited industrial activities in rural areas (Nnaemeka-Okeke & Okeke, 2024; Nlemolisa et al., 2025). However, even low levels of cadmium can accumulate over time and pose health risks, particularly in populations reliant on groundwater for drinking. Meanwhile, continuous monitoring is essential to ensure that these levels remain within safe limits, especially in light of potential future agricultural intensification (Hossain et al., 2025).

In contrast, chromium concentrations exceeded the NSDWQ limit of 0.05 mg/L in some samples, particularly post-rainfall (Table 1 and Table 2). Chromium levels are above the NSDWQ limit even before rainfall, and they increase further after rainfall, suggesting that erosion plays a significant role in its mobilization. This elevation is concerning, as chromium is a known toxicant that can have serious health implications, including cancer (Khatoon et al., 2025). The increase in chromium levels in Kwarin Awaja may be linked to runoff from nearby industrial activities or urban areas, as observed in various studies across Africa (Ayejoto et al., 2023; Agbasi et al., 2023). Similar findings have been reported in other studies that have investigated the impact of erosion on heavy metal contamination of water resources (Georgaki et al., 2023).

Bacteriological Parameters of Water Samples

The presence of coliform bacteria in the water samples post-rainfall, with values indicating contamination, underscores a significant public health concern (Table 2), with counts of 1 MPN (Most Probable Number) in 10 out of 12 samples. The absence of coliforms in baseline samples suggests that rainfall events significantly influence water quality. The result of this study is in agreement with the findings of Dey et al. (2022). The presence of coliform bacteria after rainfall at ten sample locations indicates that surface runoff during rainfall events introduces fecal contamination into the groundwater. The detection of coliforms suggests fecal contamination, which can lead to waterborne diseases. Similar findings have been reported in rural Nigerian (Odewade et al., 2025) and many countries where inadequate sanitation and runoff contribute to microbial contamination of drinking water sources (Banseka et al., 2024). This finding is consistent with numerous studies that have shown a strong correlation between rainfall and microbial contamination of groundwater, particularly in areas with inadequate sanitation and well protection (Li et al., 2021).

Influence of Erosion-Induced Runoff on Groundwater Quality in The Study Area

The findings from the data analysis reveal a significant influence of erosion-induced runoff on groundwater quality in the study area. Table 3 indicates that water quality parameters such as turbidity, nitrate, total dissolved solids (TDS), and electrical conductivity (EC) exhibited elevated mean values after the rainfall events compared to the pre-rainfall period. These increases are indicative of contamination likely caused by sediment-laden surface runoff entering the groundwater system.

Table 3. Water Quality Parameters Before and After Rainfall

Parameter	N	Mean (Before Rainfall)	Std. Dev. (Before)	Mean (After Rainfall)	Std. Dev. (After)
pH	30	6.45	0.27	6.38	0.31
Turbidity (NTU)	30	1.85	0.43	4.76	0.52
Nitrate (mg/L)	30	3.25	0.66	6.89	0.71
Electrical Conductivity (µS/cm)	30	480.50	32.10	610.75	36.40

Source: Author’s analysis (2024)

The paired sample t-tests presented in Table 4 confirm that the changes observed in key parameters were statistically significant ($p < 0.05$). Notably, turbidity and nitrate levels rose markedly after the rainfall, suggesting the infiltration of surface pollutants associated with soil erosion, agricultural activities, and domestic waste. The significant increase in EC and TDS also reflects the higher mineral and ionic loads introduced into the aquifer during runoff events. These findings are in line with previous studies that highlight the vulnerability of shallow groundwater systems to contamination from surface erosion processes (Akanbi et al., 2023; Azad et al., 2024).

Table 4. Paired Sample t-Test for Pre- and Post-rainfall Water Quality

Parameter	Mean Difference	Std. Dev.	t-value	df	Sig.
pH	-0.07	0.16	-1.96	29	0.059
Turbidity (NTU)	2.91	0.61	15.14	29	0.000
Nitrate (mg/L)	3.64	0.75	12.58	29	0.000
Electrical Conductivity (µS/cm)	130.25	27.41	19.63	29	0.000

Source: Author's analysis (2024)

Moreover, Pearson correlation coefficients in Table 5 show strong negative correlations between the proximity to erosion features and pollution indicators such as turbidity ($r = -0.712$), nitrate ($r = -0.648$), and EC ($r = -0.597$). These relationships indicate that groundwater sources located closer to erosion-prone areas tend to have higher pollutant concentrations. This supports the hypothesis that erosion gullies and bare surfaces serve as direct pathways for contaminants to reach subsurface water, particularly during high-intensity rainfall periods.

Table 5. Pearson Correlation Between Proximity to Erosion Features and Pollution Indicators

Parameter	Pearson Correlation (r)	Sig.
Turbidity *vs* Proximity	-0.712	0.000
Nitrate *vs* Proximity	-0.648	0.001
EC *vs* Proximity	-0.597	0.002
pH *vs* Proximity	0.118	0.527

Source: Author's analysis (2024)

Note: Negative correlation implies higher pollution concentrations closer to erosion features.

The normality tests conducted prior to the t-tests confirmed that the water quality data met the assumptions required for parametric analysis. This enhances the reliability of the statistical inferences drawn from the dataset.

Conclusion

This study demonstrates that erosion plays a significant role in degrading groundwater quality in Kwarin Awaja. Wells located near active erosion features showed higher concentrations of pollutants following rainfall, with marked increases in turbidity and electrical conductivity. The presence of coliform bacteria post-rainfall further indicates that surface runoff is introducing microbial contaminants into the aquifer system. Although pH and nitrate levels remained within acceptable limits, the detection of elevated chromium concentrations in some wells raises additional health concerns. These findings confirm that erosion is a major driver of groundwater pollution in the study area, particularly during the rainy season, and that shallow, unlined wells are especially vulnerable. Addressing this challenge is essential for safeguarding public health and ensuring sustainable access to safe drinking water in rural communities. To mitigate erosion-induced groundwater pollution in this and similar areas, community-based erosion control measures such as check dams and vegetative barriers are recommended near vulnerable wells. Wells should be properly lined and, where possible, relocated farther from erosion sites. Regular water quality monitoring after heavy rainfall and public education on safe water practices are also essential to protect groundwater and enhance community resilience.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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