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Integrated Hydrogeochemical and Microbial Risk Assessment of Sandstone Aquifers in Tropical Sedimentary Basins: Methods, Controls, and Public Health Implications

Esomchukwu Jennifer Onyeka[1], Charles Onyeka Nwamekwe[2*] and Ifeanyichukwu Benjamin Unigwe[3]
co.nwamekwe@unizik.edu.ng
[1]Nnamdi Azikiwe University, P.M.B. 5025 Awka, Anambra State - Nigeria.
[2]Nnamdi Azikiwe University, P.M.B. 5025 Awka, Anambra State - Nigeria.
[3]University of the West of England, Frenchay Campus, Coldharbour Lane, Bristol, BS16 1QY, United Kingdom.

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ABSTRACT

Sandstone aquifers in tropical sedimentary basins are major groundwater reservoirs, yet their public-health safety is often underestimated when assessment is restricted to physicochemical quality. This review addresses the persistent mismatch between chemically acceptable groundwater and microbiologically unsafe water, especially in shallow, permeable aquifers exposed to intense rainfall, pit latrines, septic systems, dumpsites, agricultural runoff, and weak wellhead protection. A structured narrative synthesis was conducted using peer-reviewed hydrogeological, hydrogeochemical, microbiological, vulnerability, and environmental health studies from Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. The review focused on tropical sandstone aquifer systems in Africa, Asia, and South America. It examined lithological controls, major-ion evolution, microbial indicators, contamination pathways, WHO-based classification, Water Quality Index applications, contamination indices, multivariate statistics, GIS-based vulnerability mapping, and integrated hydro-microbial risk scoring. The synthesis shows that groundwater chemistry is governed mainly by silicate weathering, carbonate dissolution, cation exchange, shale interbeds, residence time, and anthropogenic inputs. However, chemical compliance does not confirm potable safety. Reported evidence includes TDS below 500 mg/L in chemically acceptable Nigerian basin aquifers, while all 12 shallow wells in Abeokuta tested positive for total coliform and Escherichia coli. Microbial loads increased during wet seasons, with Calabar groundwater recording total coliform increases from 76 to 468 CFU/100 mL and Salmonella/Shigella reaching 1081 CFU/100 mL. DRASTIC mapping further classified 21% of the Dahomey Basin as highly vulnerable. The review therefore proposes an integrated framework linking hydrochemistry, microbial evidence, vulnerability, GIS, and health-risk interpretation for safer, adaptive, and evidence-based groundwater governance.

Keywords: *Sandstone aquifers; hydrogeochemistry; microbial contamination; groundwater vulnerability; public health risk.*

Introduction

Sandstone aquifers rank among the most significant groundwater reservoirs in tropical sedimentary basins. Their high porosity, permeability, and storage capacity make them reliable sources of water for domestic, agricultural, and industrial use (Kumar et al., 2025; Mallick et al., 2021). These aquifers occur widely within Cretaceous and Tertiary sedimentary terrains across Africa, Asia, and South

America (Fantong et al., 2023; Okolo et al., 2024; Wali et al., 2020). In tropical Nigeria, for example, sandstone formations within the Anambra and Cross River basins serve as primary water-bearing units for growing populations (Wali et al., 2020b, 2020a). Groundwater from sandstone aquifers in the Garoua region of northern Cameroon and the Lake Malawi basin supports communities where seasonal rainfall limits surface water availability (Banda et al., 2024; Fantong et al., 2023). The Guarani Aquifer System in Brazil, hosted in Cretaceous sandstones, supplies water across multiple states and remains a focus of recharge and quality studies (Batista et al., 2018; Lima et al., 2023). In Southeast Asia, sandstone and associated sedimentary formations in Malaysia and Indonesia form productive aquifers that sustain both rural and urban water demands (Rathinasamy et al., 2018; Zainol et al., 2021). Across these regions, dependence on groundwater from sandstone formations intensifies during dry seasons when surface water systems become unreliable (Banda et al., 2024; Emeka et al., 2025).

The hydrogeological behaviour of sandstone aquifers depends on lithological composition, grain size distribution, cementation, structural discontinuities, weathering intensity, and the presence of shale interbeds (Chibuzor et al., 2023; Okolo et al., 2024; Wali et al., 2020a). In southeastern Nigeria, the Ajali Sandstone is confined in places by overlying shale units, creating artesian conditions whose productivity varies with formation thickness (Wali et al., 2020a). Shale interbeds within sandstone sequences in the Benue Trough and Anambra Basin control permeability distribution and compartmentalize flow systems (Chibuzor et al., 2023; Eyankware et al., 2021). These factors govern recharge processes, groundwater residence time, ion mobility, and contaminant transport (Fantong et al., 2023; Wali et al., 2020b). Rock-water interactions, including silicate weathering, ion exchange, and mineral dissolution, shape the chemical evolution of groundwater along flow paths (Banda et al., 2024; Okolo et al., 2024). In tropical basins, shallow aquifer conditions, intense rainfall, and poor sanitary infrastructure compound the vulnerability of groundwater to both chemical and microbial contamination (Adejuwon, 2025; Oke, 2020; Zainol et al., 2021). Leachate from waste dumps, seepage from pit latrines, and agricultural runoff introduce nitrate, heavy metals, and pathogens into shallow sandstone aquifers with limited protective cover (Adejuwon, 2025; Odoh et al., 2024; Oke, 2020). These conditions demand integrated assessment approaches that address both the hydrogeochemical and microbial dimensions of groundwater quality in tropical sedimentary settings (Banda et al., 2024; Wali et al., 2020b).

Most groundwater quality studies in tropical sedimentary basins focus on physicochemical parameters such as pH, electrical conductivity, total dissolved solids, major ions, and nutrients like nitrate and sulphate (Adejuwon & Odusote, 2023; Nwamekwe et al., 2024; Wali et al., 2020). These parameters provide useful information on hydrochemical evolution, water type classification, and suitability for domestic or agricultural use (Fantong et al., 2023; Wali et al., 2020). Studies in the Cross River and Anambra basins of Nigeria, for example, reported groundwater of acceptable chemical quality based on WHO guidelines, with TDS below 500 mg/l and most cations and anions within permissible limits (Wali et al., 2020). Similar findings in coastal Akwa Ibom State showed physicochemical parameters within standard ranges for several locations (Nwamekwe et al., 2024). The problem is that chemically acceptable groundwater often still harbors pathogenic microorganisms. In Abeokuta, Nigeria, shallow wells met most physicochemical standards for potable water, yet all 12 samples tested positive for total coliform and E. coli above WHO permissible limits, with contamination traced to nearby pit latrines (Adejuwon, 2025). In Zanzibar, fecal coliform counts in shallow wells decreased with distance from pit latrines, confirming sanitary infrastructure as a contamination source independent of chemical quality). Groundwater near a municipal dumpsite in Calabar showed bacterial counts far exceeding permissible limits across seasons, with higher microbial contamination during the wet season (Ochelebe et al., 2022). These cases demonstrate that Water Quality Index scores or hydrochemical classifications alone fail to capture pathogen-related public health risks (Adejuwon, 2025; Wali et al., 2020). In permeable sandstone aquifers with shallow water tables, rapid contaminant migration from latrines, septic systems, animal waste, and surface runoff introduces microbial hazards that chemical analysis does not detect (Ochelebe et al., 2022; Oke, 2020).

Hydrochemical and microbial contamination processes in tropical aquifer systems share common controls and operate simultaneously, making integrated assessment a practical necessity (Nwamekwe et al., 2025; Nlend et al., 2021; Vucinic et al., 2022). Lithology governs both groundwater chemistry through mineral dissolution and ion exchange, and aquifer vulnerability through permeability and protective capacity of overlying materials (Ohwoghere-Asuma et al., 2018; Oke, 2020). In the Dahomey Basin, DRASTIC vulnerability mapping showed 21% of the area at high pollution risk due to shallow water tables, flat slopes, and frequent precipitation, conditions that favour both chemical and microbial contaminant transport (Oke, 2020). Climatic factors in tropical regions, including intense seasonal rainfall, drive recharge, runoff generation, and mobilization of both dissolved chemicals and fecal bacteria into aquifer systems (Nakhle et al., 2021; Nlend et al., 2021). In Lao PDR, E. coli concentrations in streams correlated with suspended sediment during the rainy season, illustrating how hydrological processes simultaneously transport chemical and biological contaminants (Nakhle et al., 2021). Anthropogenic pressures from waste disposal, agriculture, urbanization, and poor sanitation affect chemical and biological groundwater quality through the same pathways (Adejuwon, 2025; Nkwunonwo et al., 2024; Ochelebe et al., 2022). Leachate from dumpsites introduces heavy metals alongside microbial contaminants into shallow aquifers (Nkwunonwo et al., 2024; Ochelebe et al., 2022). An integrated hydrogeochemical-microbial framework combines chemical suitability assessment, fecal contamination indicators, aquifer vulnerability analysis, and spatial contamination patterns into a single analytical model (Nwamekwe et al., 2026; Vucinic et al., 2022). In western Cuba, researchers integrated hydrogeological, geochemical, and microbiological data to characterize a coastal carbonate aquifer, demonstrating how microbial community analysis complemented chemical and physical methods for understanding mixing processes and contamination pathways (Nwamekwe et al., 2025). Flow cytometry paired with fecal indicator bacteria analysis in karst aquifers showed how microbial fingerprinting strengthened contamination source identification beyond what chemical data alone provided (Vucinic et al., 2022). This type of integration supports stronger public health protection, contamination risk prioritization, and sustainable groundwater management in tropical sedimentary basins (Nwamekwe et al., 2025; Oke, 2020; Vucinic et al., 2022).

This review evaluates the methods, controlling factors, and public-health implications associated with integrated hydrogeochemical and microbial risk assessment in sandstone aquifers within tropical sedimentary basins. Specifically, the review examines:

1. hydrogeochemical evolution processes in sandstone aquifers;
2. microbial contamination indicators and transport pathways;
3. the influence of lithology, climate, and land use on groundwater vulnerability;
4. integrated assessment tools including WQI, contamination indices, multivariate statistics, and GIS mapping; and
5. future directions for groundwater risk management in tropical environments.

Research Method

The study adopts a structured narrative synthesis method to comprehensively synthesize and compare the results of multi-disciplinary research on the hydrogeological, hydrogeochemical and microbiological characteristics of sandstone aquifers in tropical sedimentary basins. Since the core research problem was split across a variety of different fields and study types (geochemistry, subsurface microbiology, geospatial vulnerability, and public health), a narrative synthesis approach was chosen over a traditional quantitative meta-analysis, in order to harmonize the very diverse data types. An extensive literature review was conducted using specific Boolean string queries and academic database searches in

Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar with the terms such as "sandstone aquifer," "hydrochemistry," "microbial indicators," and "vulnerability mapping. There were strict inclusion criteria applied to the articles, only peer-reviewed papers were included and all were oriented towards tropical sandstone networks in Africa, Asia, and South America under anthropogenic stress, such as poorly protected wells, agricultural runoff, and pit latrines. Extracted data were compiled to thematic streams of core elements relating to lithological controls, microbial contamination pathways and vulnerability to the overlay index. The analytical phase involved thematically synthesising the various data sets within and across studies, with a direct comparison of the physical-chemical compliance data with the seasonal microbial data. This combination of approaches methodically identifies monitoring gaps in the structure, and proposes a comprehensive framework for evidence informed groundwater governance that is adaptive.

This review adopted a structured narrative synthesis approach centred on groundwater quality studies conducted within tropical sandstone aquifer systems. The search drew from peer-reviewed articles, hydrogeological reports, environmental health studies, and groundwater vulnerability investigations indexed in Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar (Banda et al., 2024; Mallick et al., 2021; Zainol et al., 2021). Priority went to studies published within the last two decades, as this period reflects the most active phase of integrated groundwater research in tropical sedimentary basins (Oke, 2020; Wali et al., 2020b, 2020a). Foundational hydrogeological and sedimentological works were included where they provided necessary context on aquifer architecture, formation characteristics, or baseline hydrochemistry (Eyankware et al., 2021; Okolo et al., 2024). The search combined terms related to sandstone aquifers, tropical basins, hydrogeochemistry, microbial contamination, groundwater vulnerability, and public health risk (Adejuwon, 2025; Oke, 2020; Vucinic et al., 2022). Studies from West Africa, Central Africa, Southeast Asia, and South America received particular attention because these regions host extensive Cretaceous and Tertiary sandstone formations under tropical climatic conditions (Batista et al., 2018; Fantong et al., 2023; Wali et al., 2020b). The review also incorporated methodological studies on GIS-based spatial analysis, multivariate statistical techniques, and aquifer vulnerability mapping where these contributed to understanding contamination patterns in sedimentary aquifer systems (Ohwoghere-Asuma et al., 2018; Oke, 2020; Zainol et al., 2021).

The review targeted studies addressing sandstone aquifers in tropical sedimentary basins, hydrochemical groundwater evolution, microbial contamination and fecal indicators, groundwater vulnerability assessment, GIS and spatial contamination mapping, integrated groundwater risk assessment frameworks, and public health implications of groundwater contamination

(Adejuwon, 2025; Nwamekwe et al., 2020; Oke, 2020; Okolo et al., 2024; Wali et al., 2020b). Hydrochemical evolution studies were included when they characterized dominant geochemical processes such as silicate weathering, ion exchange, and mineral dissolution within sandstone aquifer systems (Banda et al., 2024; Eyankware et al., 2021; Okolo et al., 2024). Microbial contamination studies qualified for inclusion when they reported fecal indicator bacteria data from groundwater sources in tropical settings and linked contamination to sanitary infrastructure, land use, or seasonal hydrological conditions (Adejuwon, 2025; Nakhle et al., 2021; Ochelebe et al., 2022). Vulnerability assessments using DRASTIC or similar index-based methods were included where they addressed sedimentary basin aquifers and evaluated protective capacity of overlying formations (Ohwoghere-Asuma et al., 2018; Oke, 2020). Studies limited strictly to either hydrochemistry or microbiology without broader groundwater risk interpretation were evaluated only where they contributed to integrated understanding of contamination processes in tropical aquifer systems (Nwamekwe et al., 2024; Wali et al., 2020c).

The conceptual framework proposed in this review links aquifer lithology, hydrochemical evolution, microbial contamination pathways, anthropogenic pressure, climatic influence, groundwater vulnerability, and public health outcomes within one analytical structure. Lithological controls on groundwater chemistry, as documented in studies of the Anambra Basin and Benue Trough (Eyankware et al., 2021; Okolo et al., 2024; Wali et al., 2020a), form the foundation of the framework because mineral composition and grain size distribution govern both ion mobility and contaminant transport capacity. Hydrochemical evolution data from Piper diagrams, Gibbs plots, and ionic ratio analyses (Banda et al., 2024; Okolo et al., 2024) feed into water quality classification, while microbial indicator data from fecal coliform, E. coli, and total coliform analyses (Adejuwon, 2025; Ochelebe et al., 2022; Vucinic et al., 2022) provide the biological contamination dimension. The framework incorporates anthropogenic pressures including pit latrine seepage (Adejuwon, 2025), dumpsite leachate (Nkwunonwo et al., 2024; Odoh et al., 2024), and agricultural runoff (Lima et al., 2023; Nakhle et al., 2021) as contamination drivers operating through the same transport pathways. Climatic factors, particularly seasonal rainfall intensity and recharge variability, modulate both chemical and microbial contaminant mobilization (Nakhle et al., 2021; Nlend et al., 2021). Aquifer vulnerability mapping through DRASTIC and protective capacity assessments (Ohwoghere-Asuma et al., 2018; Oke, 2020) provides the spatial risk dimension. The integration of hydrogeological, geochemical, and microbiological data within a single framework, as demonstrated in carbonate aquifer studies in Cuba (Nwamekwe et al., 2024) and karst systems in Europe (Vucinic et al., 2022), serves as the methodological model adapted here for tropical sandstone settings. This structure supports contamination risk prioritization and public health protection strategies grounded in the physical, chemical, and biological realities of tropical sedimentary aquifer systems (Nwamekwe et al., 2025; Oke, 2020).

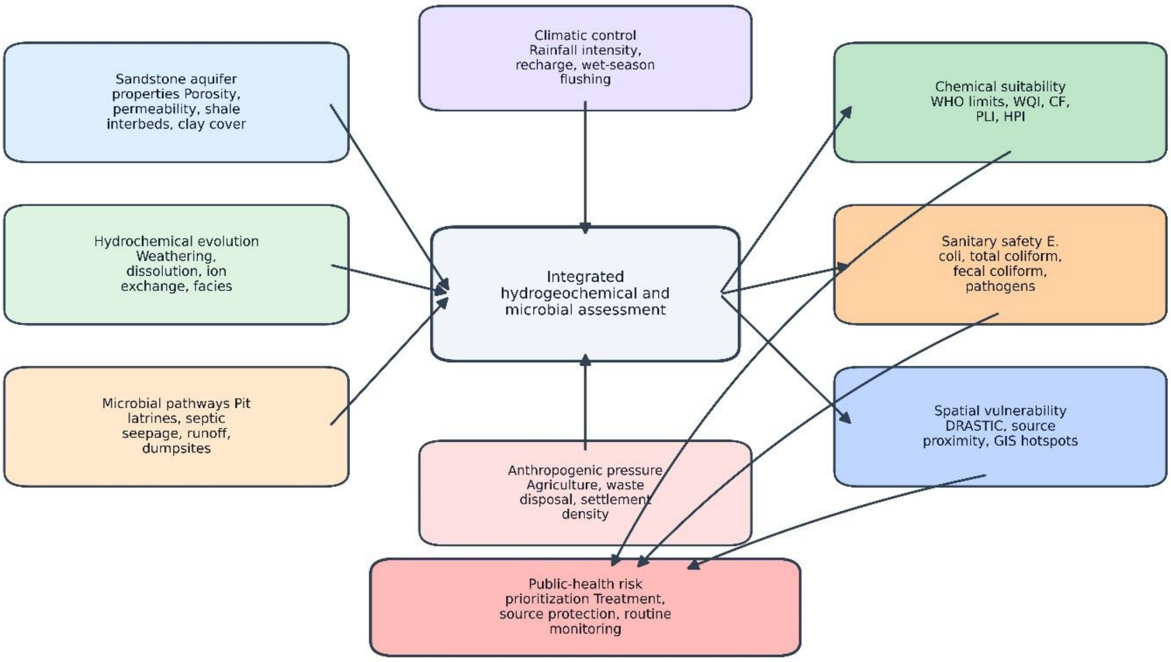


Figure 1: Conceptual framework linking sandstone aquifer properties, hydrochemical evolution, microbial contamination, vulnerability, and public-health risk.

Figure 1 is the framework that connects sandstone aquifer properties, hydrochemical evolution, microbial pathways, climate, land use, vulnerability mapping, and public-health outcomes into one integrated risk interpretation structure.

Results

3.1 Lithological Control

The chemical composition of groundwater in sandstone aquifers depends on the mineralogical makeup of the host rock and associated formations. Quartz-rich sandstones produce low-reactivity groundwater because quartz resists chemical weathering, as observed in the Wajid Sandstone of Saudi Arabia where clean sands consisting of 95% quartz grains yielded relatively low dissolved ion concentrations in the upper formation (Masoud & Aldosari, 2020). In contrast, feldspathic sandstones release sodium, calcium, magnesium, and bicarbonate through hydrolytic alteration of silicate minerals. In Cross River State, Nigeria, aquifer conduits rich in silicate minerals produced groundwater with significant amounts of Ca2+, Mg2+, and Na+ from calcite and silicate weathering processes (Vitalis et al., 2024). The Egbako aquifer in the Northern Bida Basin showed similar patterns, with silicate weathering and simple dissolution identified as dominant processes controlling ion release (Aweda et al., 2023). Shale interbeds exert strong control on groundwater chemistry by reducing permeability, modifying flow paths, and supplying clay-associated ions through cation exchange. In the Anambra Basin, the Imo Shale displayed permeability stability across much of the intermediate unit, while the Ajali Formation's confinement by overlying shale created artesian conditions with variable productivity (Wali et al., 2020). In the Benue Trough, groundwater within the Asu River Group and Eze Aku Group showed chemistry controlled by interactions between groundwater and surrounding host rocks, with shale-rich zones producing distinct hydrochemical signatures (Eyankware et al., 2021). The Wajid Sandstone further demonstrated this control, where the lower section with high shale content (greater than 10%) showed inferior groundwater quality compared to the upper clean sandstone section with effective porosity up to 25% (Masoud & Aldosari, 2020). Carbonate cement and limestone intercalations increase bicarbonate and hardness levels, as documented in the geological transition zones of northeastern Nigeria where carbonate dissolution contributed to Ca-Mg-HCO3 facies in basement terrains (Lawal et al., 2022).

3.2 Major Ion Chemistry and Water Types

Groundwater chemistry in sandstone aquifers reflects mixed hydrochemical facies shaped by recharge processes, mineral dissolution, ion exchange, and anthropogenic inputs. In the Onitsha area of southeastern Nigeria, Piper diagrams identified Ca2+-Mg2+-Cl-SO42- as the dominant facies with Ca2+ and Cl- as the dominant ions (Okolo et al., 2024). The Egbako aquifer in the Bida Basin displayed calcium-bicarbonate (Ca-HCO3), sodium-bicarbonate (Na-HCO3), and mixed calcium-sodium bicarbonate (Ca-Na-HCO3) water types, with the abundance of major cations following the order Ca2+ greater than K+ greater than Na+ greater than Mg2+ and anions following HCO3- greater than NO3- greater than Cl- greater than SO42- (Aweda et al., 2023). In the Lake Malawi Basin, five groundwater types were identified, with Ca-Mg-HCO3 as the prominent facies associated with fresh recharge inputs (Banda et al., 2024). The geological transition zones of northeastern Nigeria showed contrasting facies between basement and sedimentary terrains. Ca2+-Mg2+-HCO3- facies characterized recharge meteoric water in basement areas, while Na+-K+-HCO3- facies dominated the sedimentary zones due to cation exchange reactions (Lawal et al., 2022). In the Langat Basin of Malaysia, groundwater belonged to Na-Cl with saline water type and Na-HCO3 with mixed water type characteristics, where the saline signature derived from agricultural activities and the mixed types from water-rock interaction (Zainol et al., 2021). The Hadejia-Yobe Basin in semi-arid northeastern Nigeria held groundwater of low hardness and dissolved salts within WHO standards, with the Chad Formation serving as the most productive aquifer. These patterns confirm that Piper trilinear diagrams, Durov diagrams, and Gibbs plots remain effective tools for interpreting groundwater evolution and geochemical interaction across different sandstone aquifer settings (Aweda et al., 2023; Masoud & Aldosari, 2020; Okolo et al., 2024).

3.3 Geochemical Processes

Rock-water interaction represents the dominant hydrochemical control in sandstone aquifers across tropical basins. Gibbs diagrams from the Onitsha area showed samples plotting in the rock dominance zone, confirming water-rock interaction and dissolution of rock minerals as the primary controls on water chemistry (Okolo et al., 2024). In the Egbako aquifer, bivariate and scatter plots identified silicate weathering, simple dissolution, and ion exchange as the dominant processes, with saturation indices revealing undersaturation in evaporites and supersaturation in silicates such as quartz and kaolinite (Aweda et al., 2023). The Wajid Sandstone aquifer system in Saudi Arabia showed groundwater chemistry controlled by water-rock interaction through mineral dissolution and cation exchange, with longer residence times in deeper aquifers producing a trend evolving from freshwater to brackish water (Masoud & Aldosari, 2020).

In the Qingdong coalmine aquifer system, TDS content increased with aquifer depth, indicating greater degrees of water-rock interaction at depth, with weathering of silicate minerals and dissolution of evaporite minerals identified as the two principal sources of chemical variation (Chidiebube et al., 2025). Recharge dilution during wet seasons reduces ion concentration in shallow aquifers, while evaporation during dry conditions increases salinity and TDS (Chidiebube et al., 2025a; Masoud & Aldosari, 2020). Anthropogenic activities also shape hydrochemistry. In the Egbako aquifer, high nitrate concentrations in southwestern agricultural fields indicated fertilizer influence on groundwater chemistry (Aweda et al., 2023). In the Langat Basin, multivariate analysis confirmed that industrial, agricultural, and weathering activities all contributed to groundwater contamination (Zainol et al., 2021). Leachate infiltration from dumpsites in Agu-Awka, southeastern Nigeria, elevated pH, biological oxygen demand, chemical oxygen demand, mercury, chromium, and arsenic above WHO permissible limits for drinking water (Odoh et al., 2024).

3.4 Key Contaminants

Iron contamination is widespread in ferruginized sandstone environments across tropical basins. In the Anambra Basin, the Ajali Sandstone underlying Ekpoma is highly ferruginous, and groundwater from this formation requires treatment for excess iron content. Groundwater in coastal areas of Akwa Ibom State showed iron concentrations above potable water standard limits in multiple locations (Nwamekwe et al., 2024). In the Langat Basin, iron dominated the heavy metal sequence (Fe greater than Mn greater than Zn greater than As) in groundwater samples (Zainol et al., 2021). Nitrate contamination poses direct health risks including methemoglobinemia and is strongly associated with agriculture, septic systems, and waste disposal. In the Egbako aquifer, high nitrate concentrations in agricultural areas rendered groundwater unsuitable for human consumption in those zones (Aweda et al., 2023).

In the Lake Malawi Basin, measurable nitrate across the country highlighted widespread human impact on groundwater quality from extensive fertilizer use and increasing numbers of pit latrines and septic systems (Banda et al., 2024). The Guarani Aquifer outcrop area in Brazil showed nitrate concentrations in groundwater reaching surface water above regulatory levels, linked to expansion in sugarcane production (Lima et al., 2023). Sulphate and chloride serve as indicators of evaporative concentration, wastewater influence, or saline input. In the geological transition zones of northeastern Nigeria, chloride and sulphate concentrations varied between basement and sedimentary terrains, reflecting differences in lithological composition and anthropogenic pressure (Lawal et al., 2022). Elevated TDS reflects increasing mineralization and groundwater-rock interaction, as demonstrated in the Wajid Sandstone where TDS increased with aquifer depth (Masoud & Aldosari, 2020). In the Hadejia-Yobe Basin, all studied parameters remained within WHO standards, with TDS concentrations indicating water of acceptable quality. Heavy metals including mercury, chromium, arsenic, and lead present additional contamination concerns near dumpsites and industrial areas (Adejuwon & Odusote, 2023; Nkwunonwo et al., 2024; Odoh et al., 2024).

Table 1: Major hydrochemical indicators, sources, interpretation, and public-health relevance.

Indicator	**Primary sources or controls**	**Interpretation in sandstone aquifers**	**Public-health or management relevance**
pH	Carbonate buffering, acidic soils, waste leachate	Signals acidity, alkalinity, corrosion potential, and geochemical stability	Affects taste, pipe corrosion, metal solubility, and treatment needs
Electrical conductivity	Dissolved ions from weathering, evaporation, saline intrusion,	Rapid proxy for mineralization and salinity pressure	Supports screening of quality deterioration and spatial hotspots

	anthropogenic inputs		
Total dissolved solids	Water-rock interaction, evaporative concentration, residence time	Indicates total mineral load and depth-related chemical evolution	High TDS reduces acceptability and may signal contamination
Calcium and magnesium	Silicate weathering, carbonate dissolution, ion exchange	Defines hardness and Ca-Mg-HCO3 facies in recharge-influenced waters	Hardness affects scaling, taste, and domestic/industrial usability
Sodium and potassium	Feldspar weathering, cation exchange, saline inputs, wastewater	High sodium often reflects exchange reactions or anthropogenic influence	Important for drinking acceptability and irrigation suitability
Bicarbonate	Carbonate dissolution, CO2-driven weathering, recharge processes	Marks fresh recharge and carbonate/silicate weathering processes	Useful for hydrochemical facies interpretation
Chloride	Wastewater, septic seepage, saline inputs, evaporation	Conservative tracer of wastewater influence or salinity intrusion	High chloride suggests contamination and taste problems
Sulphate	Evaporite dissolution, industrial discharge, oxidation of sulphide minerals	Indicates geogenic or anthropogenic sulphate enrichment	High levels may produce laxative effects and scaling
Nitrate	Fertilizer, pit latrines, septic systems, animal waste	Strong marker of sanitary or agricultural contamination	High nitrate threatens infants through methemoglobinemia risk

Iron and manganese	Ferruginized sandstone, reducing conditions, lateritic cover	Common in tropical sandstone aquifers with iron-rich sediments	Causes staining, metallic taste, and treatment demand
Heavy metals	Dumpsite leachate, mining, industrial areas, geogenic sources	Local toxic contamination hotspots require targeted assessment	Supports HPI, health risk analysis, and remediation prioritization

Table 1 summarizes core chemical indicators, likely natural or anthropogenic sources, diagnostic interpretation, and public-health relevance for evaluating groundwater quality in tropical sandstone aquifers.

3.5. Microbial Contamination in Tropical Aquifer Systems

3.5.1 Sanitary Indicators

Total coliform, fecal coliform, and Escherichia coli remain the most widely used indicators of microbial contamination in groundwater systems across tropical regions (Adejuwon, 2025; Ochelebe et al., 2022; Vucinic et al., 2022). E. coli serves as the most specific indicator of recent fecal contamination because it originates from the intestinal tract of warm-blooded animals and humans (Adejuwon, 2025; Vucinic et al., 2022). In Abeokuta, Nigeria, all 12 shallow well samples tested positive for total coliform and E. coli above the zero-count permissible standard set by WHO, USEPA, and SON (Adejuwon, 2025). Near a municipal dumpsite in Calabar, southeastern Nigeria, total coliform bacteria averaged 76 CFU/100ml in the dry season and 468 CFU/100ml in the wet season, while total Salmonella/Shigella counts reached 1081 CFU/100ml during the wet season (Ochelebe et al., 2022). In Zanzibar, fecal coliform counts in shallow wells decreased by 42 CFU/100ml for every unit increase in distance from the nearest pit latrine. In northern Lao PDR, E. coli concentrations in streams showed strong seasonal patterns, with higher and extreme values occurring during the rainy season (Nakhle et al., 2021). Flow cytometry paired with fecal indicator bacteria analysis in karst aquifers demonstrated how microbial fingerprinting strengthened contamination source identification, distinguishing between diffuse agricultural inputs and point-source sewage contamination (Vucinic et al., 2022). These studies confirm that fecal indicator bacteria remain essential for assessing the sanitary safety of groundwater, particularly in tropical settings where multiple contamination sources operate simultaneously (Adejuwon, 2025; Nakhle et al., 2021; Ochelebe et al., 2022).

3.5.2 Contamination Pathways

Microbial contaminants enter sandstone aquifers through multiple pathways including infiltration from pit latrines, septic systems, agricultural wastes, animal grazing zones, poorly managed dumpsites, and contaminated surface water systems (Adejuwon, 2025; Nakhle et al., 2021; Ochelebe et al., 2022). In the Adatan community of Abeokuta, Nigeria, shallow wells located closer to pit latrines had greater total coliform and E. coli counts than those at greater distances, confirming direct seepage through permeable soil and subsurface materials (Adejuwon, 2025). In Zanzibar, the Ordinary Least Square regression model showed nitrate and chloride concentrations increasing as the distance between shallow wells and the nearest pit latrine decreased. Leachate from municipal dumpsites introduces both chemical and microbial contaminants into shallow aquifers. In Calabar, groundwater samples collected around a major dumpsite showed bacterial counts far exceeding permissible limits, with wet season contamination levels consistently higher than dry season values due to enhanced leachate mobilization by rainfall (Ochelebe et al., 2022).

In the Mekong basin of Lao PDR, E. coli concentrations correlated with total suspended sediment during the rainy season, indicating that surface runoff transports fecal bacteria attached to soil particles into water systems (Nakhle et al., 2021). Heavy rainfall and shallow groundwater conditions in tropical regions enhance vertical migration of contaminants through permeable sandstone units (Nlend et al., 2021; Oke, 2020). In the Dahomey Basin, areas with flat slopes, frequent precipitation, and shallow water tables showed the highest vulnerability to pollution from surface sources (Oke, 2020). Aquifer protective capacity assessments in the western Niger Delta revealed poor to good protection ratings, with areas of low hydraulic conductivity and thin clay cover showing the greatest susceptibility to contamination from both point and non-point sources (Ohwoghere-Asuma et al., 2018).

3.5.3 Influence of Land Use and Source Protection

Groundwater vulnerability increases where wells are shallow, poorly sealed, or located close to drainage channels and sanitation facilities (Adejuwon, 2025; Oke, 2020). Land use patterns directly affect the type and intensity of contamination reaching aquifer systems. In the Langat Basin of Malaysia, multivariate analysis confirmed that industrial, agricultural, and weathering activities all contributed to groundwater contamination, with saline water type characteristics derived from agricultural activities (Zainol et al., 2021). In the Mekong basin, the highest E. coli concentrations were measured in catchments dominated by unstocked forest areas and in Vientiane province where agricultural and settlement activities concentrate (Nakhle et al., 2021). In the Guarani Aquifer outcrop area of Brazil, expansion in sugarcane production increased nitrate concentrations in groundwater reaching surface streams above regulatory levels (Lima et al., 2023).

Runoff from agricultural lands and settlements introduces nutrients and microorganisms into recharge zones, as documented in the Egbako aquifer where high nitrate concentrations in southwestern agricultural fields indicated fertilizer influence on groundwater chemistry (Aweda et al., 2023). Poorly protected hand-dug wells and springs are especially vulnerable to contamination. In Zanzibar, shallow wells in squatter settlements located close to pit latrines showed elevated fecal coliform, nitrate, and chloride levels. The Landzun Stream in Bida, Nigeria, consumed in its untreated state, showed seasonal enrichment in magnesium, lead, potassium, and iron above WHO guidelines, with 72% to 83% of samples failing odor requirements across seasons (Emeka et al., 2025a). DRASTIC vulnerability mapping in the Dahomey Basin classified 21% of the area at high pollution risk, with high-vulnerability zones concentrated in regions closer to the coast with flat slopes and frequent precipitation (Oke, 2020).

3.5.4 Contradiction Between Chemical and Microbial Safety

One of the persistent challenges in groundwater assessment is that water classified as chemically acceptable often remains microbiologically unsafe (Adejuwon, 2025; Ochelebe et al., 2022; Wali et al., 2020). In the Cross River and Imo-Kwa-Ibo basins of Nigeria, hydrochemical analysis showed groundwater of excellent quality with TDS below 500 mg/l and most cations and anions within WHO guidelines, yet no broad microbial analysis accompanied these assessments (Wali et al., 2020). The Anambra Basin review similarly reported water of acceptable quality based on physical and chemical parameters but noted the absence of water quality index, heavy metals pollution index, and microbiological evaluation (Wali et al., 2020a). The Adatan community study in Abeokuta provided direct evidence of this contradiction. All physicochemical parameters except temperature, carbonate, dissolved oxygen, and biochemical oxygen demand fell within WHO and SON permissible limits, yet all 12 samples tested positive for total coliform and E. coli above zero-count permissible standards (Adejuwon, 2025).

Near the Calabar dumpsite, groundwater showed bacterial contamination levels far exceeding permissible limits across both seasons, a finding that chemical analysis alone would not capture (Ochelebe et al., 2022). Water Quality Index methods classify groundwater based on physicochemical parameters and assign suitability ratings without incorporating microbial data (Iqbal et al., 2023; Wali et al., 2020b). This approach creates a false sense of safety for communities relying on these assessments for drinking water decisions (Adejuwon, 2025; Wali et al., 2020a). The limitation is compounded in tropical sandstone aquifers where shallow permeable units facilitate rapid contaminant migration from sanitary sources (Oke, 2020). These findings demonstrate that integrated assessment combining hydrochemical and microbiological parameters is necessary to provide a complete picture of groundwater safety in tropical sedimentary basins (Adejuwon, 2025; Nwamekwe et al., 2025; Vucinic et al., 2022).

Table 2: Microbial indicators, contamination meaning, likely sources, and risk interpretation.

Indicator	**Contamination meaning**	**Likely sources or pathways**	**Risk interpretation**
Total coliform	General sanitary quality failure or intrusion of environmental/fecal bacteria	Poor well sealing, runoff entry, contaminated distribution systems	Triggers sanitary inspection and repeat microbiological testing
Fecal coliform	Evidence of fecal influence and warm-blooded animal or human waste input	Pit latrines, septic tanks, animal waste, surface runoff	Indicates unsafe water requiring treatment before consumption
Escherichia coli	Specific indicator of recent fecal contamination	Fresh sewage, latrine seepage, open defecation, livestock manure	Zero-count drinking-water standard means any detection is unacceptable
Salmonella/Shigella	Pathogen-specific evidence of enteric disease risk	Human fecal waste, dumpsite leachate, sewage-impacted recharge	Signals direct risk of typhoid, dysentery, and gastrointestinal infection
Vibrio cholerae	Pathogen-specific cholera transmission risk	Contaminated water systems, poor sanitation, wet-season mobilization	Requires urgent public-health response and disinfection

Heterotrophic bacteria	Broad microbial load and regrowth potential	Biofilms, stagnant wells, organic contamination, distribution systems	Supports treatment performance and regrowth assessment
Flow cytometry fingerprint	Microbial community pattern and source discrimination	Diffuse agricultural input, sewage point sources, aquifer biofilms	Improves source attribution beyond chemical data alone
Antibiotic-resistant bacteria	Emerging microbial health hazard	Hospitals, wastewater, livestock operations, urban runoff	Important for future pathogen-specific risk monitoring

Table 2 organizes microbial indicators by sanitary meaning, contamination source, detection importance, and risk implication, showing why microbiological evidence must complement hydrochemical assessment.

3.6. Integrated Risk Assessment Methods

3.6.1 WHO-Based Classification

Groundwater suitability for drinking is most commonly evaluated against World Health Organization (WHO) drinking water standards, which provide threshold limits for physicochemical parameters including pH, nitrate, sulphate, chloride, iron, total dissolved solids, and microbial indicators (Mallick et al., 2021; Wali, et al., 2020b, 2020a). In the Cross River and Imo-Kwa-Ibo basins of Nigeria, most examined cations and anions fell within WHO reference guidelines, with TDS concentrations below 500 mg/l and electrical conductivity below 500 µS/cm (Wali, et al., 2020b). The Anambra Basin similarly reported water of acceptable quality based on physical and chemical parameters compared against WHO standards (Wali, et al., 2020a). In the Hadejia-Yobe Basin, all studied parameters had concentrations within both WHO and Nigeria's standard for drinking water quality (Wali et al., 2024). In the Tarkwa mining area of Ghana, all groundwater samples fell within WHO drinking water standards for major ions (Seidu & Ewusi, 2020). WHO-based classification remains the primary reference framework for groundwater quality assessment across tropical regions (Davraz & Batur, 2021; Mallick et al., 2021).

In the Yalvaç-Gelendost basin of Turkey, analysis results were compared with WHO drinking water standards, and most parameters did not exceed permissible limits except for arsenic and fluoride in some samples (Davraz & Batur, 2021). The WHO framework also sets a zero-count standard for E. coli and total coliform in drinking water, a threshold that groundwater in many tropical settings fails to meet despite acceptable physicochemical quality (Adejuwon, 2025). In Abeokuta, Nigeria, all 12 shallow well samples exceeded the WHO zero-count permissible standard for total coliform and E. coli, even though most physicochemical parameters fell within acceptable limits (Adejuwon, 2025). This pattern confirms that WHO-based classification provides a necessary but incomplete assessment of groundwater safety when applied to physicochemical parameters alone (Adejuwon, 2025; Wali, et al., 2020b).

3.6.2 Water Quality Index and Limitations

The Water Quality Index (WQI) simplifies multiple hydrochemical parameters into a single numerical score that classifies groundwater suitability for drinking (Iqbal et al., 2023; Jolaosho et al., 2024; Wali, et al., 2020). In the Kaduna Basin of Nigeria, computed WQI values revealed groundwater of excellent quality across three sub-areas, with overall WQI scores of 13.46, 7.64, and 10.26 (Wali, et al., 2020). In Quetta, Pakistan, WQI demonstrated that groundwater sources were safe for human consumption, though values declined in northern parts due to urbanization over a six-year period (Iqbal et al., 2023). In southwestern Nigeria, WQI and water pollution index were applied alongside hydrogeochemical models to assess groundwater quality, with findings indicating that parameters generally adhered to international standard limits (Jolaosho et al., 2024). The Entropy-weighted Water Quality Index (EWQI) represents an improvement over traditional WQI by incorporating entropy to minimize human subjectivity in parameter weighting (Xiao et al., 2025).

The primary limitation of WQI is its reliance on physicochemical parameters without incorporating microbial indicators (Wali, et al., 2020b, 2020a). The Cross River and Imo-Kwa-Ibo basin review noted the absence of broad water quality analysis based on water quality indices and the lack of studies modelling pollution or land use impacts on groundwater quality (Wali, et al., 2020b). The Anambra Basin review identified similar gaps, noting that studies fell short of WQI analysis, heavy metals pollution index, and total hazard quotient evaluation (Wali, et al., 2020a). WQI scores classify groundwater as suitable for consumption based on chemical conditions, yet this classification does not account for fecal contamination that poses direct health risks (Adejuwon, 2025; Wali, et al., 2020). Communities relying on WQI-based assessments for drinking water decisions face a false sense of safety where microbial contamination pathways remain unevaluated (Adejuwon, 2025; Wali, et al., 2020a).

3.6.3 Contamination Factor and Pollution Load Index

Contamination Factor (CF) evaluates individual parameter exceedance relative to guideline standards, while Pollution Load Index (PLI) provides a cumulative contamination interpretation across multiple parameters (Jolaosho et al., 2024; Wali, et al., 2020). In southwestern Nigeria, single factor pollution assessment of nine heavy metals in groundwater showed varying degrees of contamination across borehole and hand-dug well samples (Jolaosho et al., 2024). The water pollution index applied in the same study complemented the groundwater quality index by identifying localized chemical stressors that WQI alone did not capture (Jolaosho et al., 2024). Heavy Metal Pollution Index (HPI) offers a similar approach for evaluating metallic contamination. The Anambra Basin review identified the absence of HPI analysis as a gap in existing studies, noting that increasing dependence on groundwater demands such evaluation (Wali, et al., 2020a). In the Kaduna Basin, groundwater quality was assessed using multiple indices including WQI and physicochemical classification, with calcium, magnesium, sodium, and TDS identified as the major elements influencing hydrochemistry through regression analysis (Wali, et al., 2020). In the Wajid Sandstone aquifer of Saudi Arabia, factorial analysis distinguished six main factors explaining over 60.8% of total groundwater quality variation, with TDS, total hardness, nitrate, turbidity, and ammonium showing strong positive loads in the first factor (Masoud & Aldosari, 2020). These indices help identify localized contamination hotspots and prioritize areas requiring intervention, but they share the same limitation as WQI in that they address chemical conditions without incorporating microbial contamination data (Jolaosho et al., 2024; Wali, et al., 2020a).

3.6.4 Hydrogeochemical and Statistical Tools

Piper diagrams, Gibbs plots, ionic ratios, Pearson correlation, and Principal Component Analysis (PCA) are widely applied to evaluate hydrochemical evolution, contamination sources, and groundwater processes in sandstone aquifer systems (Aweda et al., 2023; Jolaosho et al., 2024; Wali, et al., 2020; Wali et al., 2024). Piper trilinear diagrams classify groundwater into hydrochemical facies based on the relative proportions of major cations and anions. In the Egbako aquifer, Piper diagrams identified calcium-bicarbonate, sodium-bicarbonate, and mixed calcium-sodium bicarbonate water types (Aweda et al., 2023). In the Tarkwa mining area of Ghana, Piper and Chadha diagrams showed Ca-HCO3 and mixed Ca-Mg-Cl as the dominant water types (Seidu & Ewusi, 2020). Gibbs diagrams distinguish between precipitation dominance, rock-water interaction, and evaporation as the primary controls on groundwater chemistry. In the Onitsha area, Gibbs plots placed samples in the rock dominance zone (Okolo et al., 2024). In the Nakivale sub-catchment of Uganda, all groundwater samples fell within the rock-weathering dominance region of the Gibbs diagram (Igbokwe and Nwamekwe, 2025).

Pearson correlation analysis reveals relationships between hydrochemical elements and helps identify natural and anthropogenic influences on groundwater evolution. In the semiarid Sokoto Basin, Pearson correlation revealed strong relationships between hydrochemical elements suggesting both natural and anthropogenic influences, with results concurrent with PCA, hierarchical clustering analysis, and Piper and Gibbs models (Wali et al., 2024). PCA reduces large datasets to principal components that explain the greatest variance in groundwater chemistry. In the Qingdong coalmine, PCA identified weathering of silicate minerals and dissolution of evaporite minerals as the two principal sources of chemical variation, with their contribution ratios quantified by the Unmix model (Chidiebube et al., 2025b). Schoeller plots, Durov diagrams, and interionic molar ratios complement these tools by illustrating relative ion concentrations and identifying ion exchange processes (Okeagu et al., 2024; Jolaosho et al., 2024).

3.6.5 GIS-Based Vulnerability Mapping

GIS-based spatial analysis allows identification of contamination hotspots, vulnerable recharge zones, and groundwater risk corridors in tropical sedimentary basins (Iqbal et al., 2023; Jolaosho et al., 2024; Oke, 2020). The DRASTIC vulnerability methodology, which integrates seven parameters (depth to water, net recharge, aquifer media, soil media, topography, impact of vadose zone, and hydraulic conductivity), is the most widely applied index-based approach (Mallick et al., 2021; Oke, 2020). In the Dahomey Basin of Nigeria, DRASTIC mapping classified 21% of the area at high vulnerability and pollution risk, 61% at moderate vulnerability, and 18% at low vulnerability (Oke, 2020). Sensitivity analysis showed the greatest impact with removal of topography, soil media, and depth to groundwater, while the most important single parameter affecting the rating system was the impact of the vadose zone (Oke, 2020). In Ndokwa West, Delta State, Nigeria, proximity analyses with 5 to 10 km buffer zones around landfill sites showed that most topographic features were at risk of pollution due to leachate migration, with the groundwater vulnerability map classifying 21.5% of the area at high contamination risk (Nkwunonwo et al., 2024).

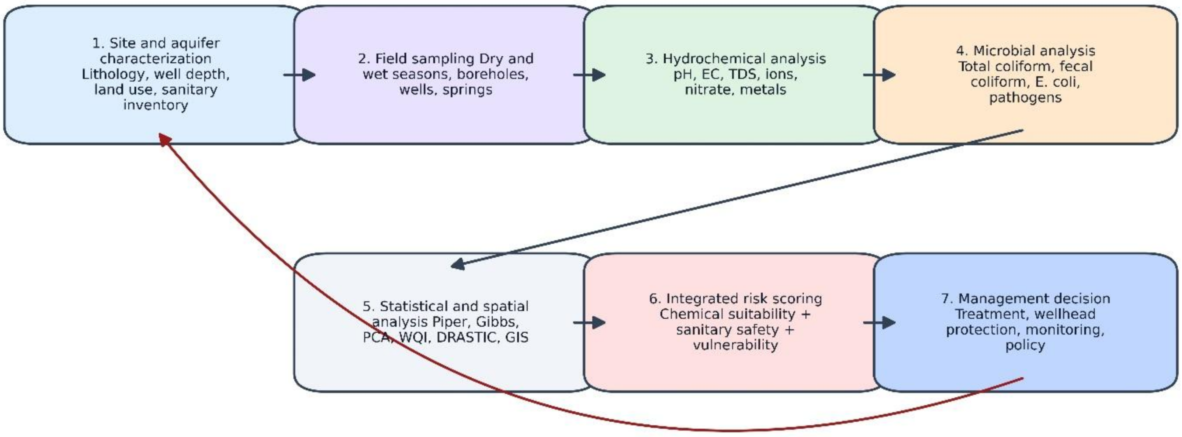
Spatial distribution maps prepared using GIS platforms display the geographical distribution patterns of individual parameters and heavy metals across sampling networks (Iqbal et al., 2023; Jolaosho et al., 2024). In Quetta, Pakistan, land use land cover (LULC) analysis on Google Earth Engine was combined with hydrogeochemical data to assess the spatial distribution of groundwater quality and its vulnerability to pollution, revealing that urbanization and agricultural expansion degraded groundwater quality over a six-year period (Iqbal et al., 2023). In southwestern Nigeria, spatial maps showed the geographical distribution patterns of heavy metals in groundwater from boreholes and hand-dug wells (Jolaosho et al., 2024). GIS-based overlay analysis integrates multiple data layers including aquifer properties, land use, contamination sources, and water quality parameters to produce composite risk maps that support groundwater management planning (Iqbal et al., 2023; Nkwunonwo et al., 2024; Oke, 2020).

3.6.6 Integrated Hydro-Microbial Risk Scoring

Integrated groundwater risk models combine hydrochemical quality, microbial contamination, aquifer vulnerability, land use, and source protection into one decision-support framework (Nwamekwe et al., 2025; Oke, 2020; Vucinic et al., 2022). In western Cuba, researchers tested an experimental modelling approach ranging from hydrogeology and geomorphology to microbiology to characterize both the hydraulic features and behaviour of a coastal carbonate aquifer (Nwamekwe et al., 2025). The interdisciplinary approach proved effective for understanding the hydraulic role of fault zones, the influence of discontinuous heterogeneities on groundwater flow, mixing processes between different water bodies, and the role of karst conduits in influencing the halocline within the mixing zone (Nwamekwe et al., 2024). Flow cytometry paired with fecal indicator bacteria analysis in karst aquifers demonstrated how microbial fingerprinting strengthened contamination source identification beyond what chemical data alone provided (Vucinic et al., 2022). Microbial pathogenic contamination of aquifers remains a globally important water quality problem, with polluted groundwater responsible for a disproportionate fraction of reported waterborne disease outbreaks, particularly in developing countries and rural regions (Vucinic et al., 2022).

The DRASTIC vulnerability framework provides the spatial risk dimension for integrated models (Oke, 2020). Combining DRASTIC outputs with hydrochemical classification and microbial indicator data creates a composite risk assessment that addresses both chemical suitability and sanitary safety (Nwamekwe et al., 2025; Oke, 2020). Health risk assessment models developed by the USEPA evaluate potential risks from contaminated groundwater through oral ingestion and dermal pathways for adults and children (Davraz & Batur, 2021; Seidu & Ewusi, 2020; Xiao et al., 2025). In the Tarkwa mining area, the hazard quotient for heavy metals suggested acceptable non-carcinogenic risk, but carcinogenic risk estimated for arsenic exceeded the acceptable threshold (Seidu & Ewusi, 2020). In the Yalvaç-Gelendost basin, potential non-carcinogenic effects through oral intake were identified for some water samples for adults, while carcinogenic risk of arsenic through oral intake posed health risks for children

(Davraz & Batur, 2021). These health risk models, when combined with microbial contamination data and aquifer vulnerability mapping, form a comprehensive integrated framework for groundwater risk assessment in tropical sandstone aquifer systems (Nwamekwe et al., 2025; Oke, 2020; Seidu & Ewusi, 2020; Vucinic et al., 2022).



Feedback loop: monitoring results update sampling priorities, vulnerability zones, and treatment decisions.

Figure 2: Workflow for integrated hydrogeochemical-microbial assessment.

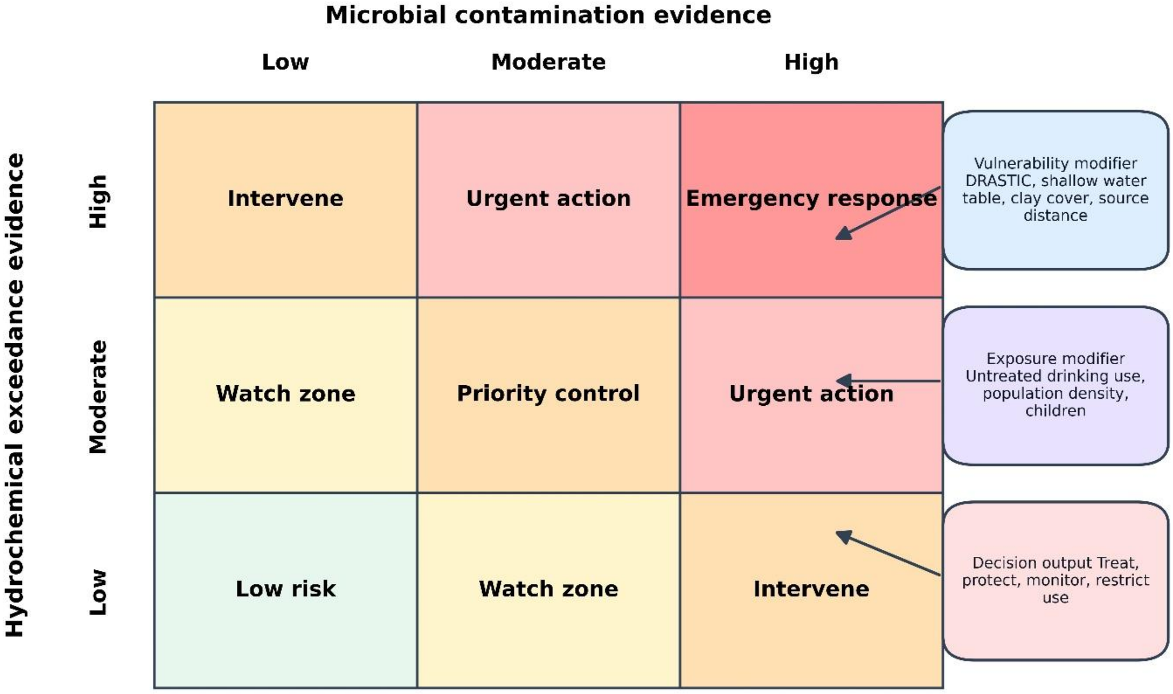
Figure 2 is the workflow that shows sequential field characterization, seasonal sampling, hydrochemical and microbial testing, statistical and GIS analysis, integrated scoring, and management feedback for groundwater protection.

3.7. Public Health and Water-Resource Management Implications

3.7.1 Public Health Risks

Fecal contamination of groundwater increases the risk of waterborne diseases including diarrhea, cholera, typhoid fever, dysentery, and gastrointestinal infections, particularly in tropical regions where communities depend on untreated groundwater for drinking (Bancessi et al., 2020; Martínez-Santos et al., 2017; Vucinic et al., 2022). In Guinea-Bissau, most microbiological parameters in all three water source types (piped water, tubewells, and shallow wells) fell outside acceptable ranges in both dry and wet seasons, consistent with the high number of diarrheal cases in the country (Bancessi et al., 2020). In Calabar, Nigeria, total Salmonella/Shigella counts reached 1081 CFU/100ml and Vibrio cholerae reached 433 CFU/100ml in groundwater near a municipal dumpsite during the wet season, posing direct disease transmission risks to consumers (Ochelebe et al., 2022).

In rural Mali, about 73% of domestic well samples rendered over 50 CFU/100ml thermotolerant coliforms, with population density and latrine proximity identified as statistically significant predictors of fecal pollution (Martínez-Santos et al., 2017). Microbial pathogenic contamination of aquifers remains a globally important water quality problem, with polluted groundwater responsible for a disproportionate fraction of reported waterborne disease outbreaks in developing countries and rural regions (Vucinic et al., 2022). At Walkerton, Ontario, Canada, rapid transport of pathogenic contaminants through a fractured aquifer system to water supply wells resulted in 2,300 illnesses and 7 deaths (Vucinic et al., 2022). Elevated nitrate concentrations pose additional health risks. In the Guarani Aquifer outcrop area, nitrate in groundwater reached surface water above regulatory levels due to sugarcane production expansion (Lima et al., 2023). Nitrate ingestion causes methemoglobinemia in infants and has been linked to other health effects in adults (Banda et al., 2024; Xiao et al., 2025). Iron contamination, common in ferruginized sandstone environments, produces metallic taste, staining, and consumer dissatisfaction, as documented in Port Harcourt where iron concentrations exceeded WHO limits due to leaching from laterized soil cover and iron-rich sediments (Okpala et al., 2024). In northern Australia, groundwater from sandstone aquifers with elevated iron harboured Burkholderia pseudomallei, the causative agent of melioidosis, alongside iron-cycling bacteria in biofilms within distribution systems (Okpala et al., 2024).



Hydrochemical exceedance evidence \ Microbial contamination evidence	Low	Moderate	High
High	Intervene	Urgent action	Emergency response
Moderate	Watch zone	Priority control	Urgent action
Low	Low risk	Watch zone	Intervene

Figure 3. Integrated groundwater risk scoring matrix for chemical, microbial, and vulnerability evidence

Figure 3 is the matrix that converts chemical exceedance, microbial contamination, vulnerability, and exposure evidence into risk categories that guide monitoring urgency, treatment priority, and source-protection decisions.

3.7.2 Treatment Priorities

Groundwater treatment strategies in tropical sandstone aquifer settings must address both chemical and microbial contamination to protect public health (Bancessi et al., 2020; Ezeanyim et al., 2025; Okpala et al., 2024). Disinfection through chlorination remains the most widely applied method for eliminating bacterial pathogens in groundwater supplies (Bancessi et al., 2020; Ezeanyim et al., 2025). Chlorine is effective against bacteria, viruses, and Giardia, and a residual level of chlorine in the distribution system prevents regrowth of microorganisms (Ezeanyim et al., 2025a). In Guinea-Bissau, residual chlorine never reached the minimum recommended level in any water source or season, suggesting a high risk of contamination throughout the supply chain (Bancessi et al., 2020). In rural Mali, nearly two-thirds of the population used bleach to purify drinking supplies, but domestic-scale treatment as implemented was far from effective (Martínez-Santos et al., 2017). Iron removal systems are a priority in ferruginized sandstone aquifer environments. In northern Australia, a curtain was installed in a ground-level water storage tank to encourage settling of iron prior to disinfection in a community supplied by sandstone aquifers with high iron levels (Nwamekwe and Igbokwe, 2024).

In Port Harcourt, Nigeria, water treatment involving demineralization and iron removal was recommended to improve groundwater quality from acidic, iron-rich aquifers. Nitrate reduction technologies are needed where agricultural activities and sanitary infrastructure contaminate shallow aquifers (Lima et al., 2023; Xiao et al., 2025). Turbidity control is important because suspended particles shield bacteria from chlorine disinfection and UV sterilization (Elendu, 2023; Okpala et al., 2025). Sanitary wellhead protection forms a critical first barrier against contamination. In Pakistan, well rehabilitation programs that added hand pumps and closed wellheads to prevent runoff entry reduced fecal contamination in domestic wells (Igbokwe et al., 2025). Proper well development reduces turbidity and sand content, increasing the success rate of subsequent disinfection (Okpala et al., 2025a).

3.7.3 Source Protection

Groundwater protection requires proper well construction, sanitary setback enforcement, drainage management, and control of waste disposal practices near recharge zones (Igbokwe et al., 2024; Martínez-Santos et al., 2017; Oke, 2020). In rural Mali, GIS-based analysis revealed that a large proportion of domestic wells fell within the influence area of pit latrines, with population density, well density, and latrine density all identified as statistically significant predictors of fecal pollution at different spatial scales (Martínez-Santos et al., 2017). In Zanzibar, fecal coliform counts decreased by 42 CFU/100ml for every unit increase in distance from pit latrines to shallow wells, confirming the importance of sanitary setback distances. In Pakistan, the post-flood well-cleaning campaign reduced fecal contamination from 85% to 20% within 7 to 30 days after cleaning, but contamination rates rose again to 62% in subsequent months and years due to lack of behavioural change and continued proximity to pit latrines (Igbokwe et al., 2025a). Better protection of the wellhead through installation of hand pumps and closure of well openings to prevent surface runoff entry was recommended as the most effective long-term action (Igbokwe et al., 2024a).

DRASTIC vulnerability mapping in the Dahomey Basin showed that high-vulnerability areas prone to pollution were regions closer to the coast with flat slopes and frequent precipitation, providing spatial guidance for siting activities that generate pollutants such as landfills, soakaways, and petrochemical industries (Oke, 2020). Aquifer protective capacity assessments using VLF-EM surveys in the western Niger Delta revealed that aquifers were poorly protected and susceptible to contamination from point and non-point sources where clay capping was absent (Ohwoghere-Asuma et al., 2018). In Guinea-Bissau, shallow wells in peri-urban areas lacked wellheads despite being protected from free access by animals, and piped water showed increasing fecal contamination levels from the source to the consumer tap, indicating degradation of the distribution network (Bancessi et al., 2020). These findings confirm that source protection measures must address wellhead integrity, sanitary setback distances, land use controls around recharge zones, and waste disposal management to reduce contamination risks in tropical sandstone aquifer systems (Martínez-Santos et al., 2017; Oke, 2020).

3.7.4 Monitoring Strategies

Routine hydrochemical and microbial monitoring should be integrated into groundwater management programs, particularly in rural and semi-urban communities that rely on untreated groundwater sources (Bancessi et al., 2020; Banda et al., 2024; Martínez-Santos et al., 2017). In the Lake Malawi Basin, measurable nitrate across the country highlighted an urgent need for detailed modelling to predict future trends of nitrate in groundwater with respect to extensive fertilizer use and increasing numbers of pit latrines arising from rapid population growth (Banda et al., 2024). In Zanzibar, the study recommended routine monitoring of shallow wells alongside application of low-cost technologies such as raised and lined pit latrines to minimize potential risk of groundwater pollution. Seasonal monitoring is essential because contamination levels fluctuate with rainfall patterns. In Calabar, Nigeria, microbial contamination levels near a municipal dumpsite were consistently higher in the wet season than the dry season (Ochelebe et al., 2022). In Lao PDR, E. coli concentrations showed strong seasonality with higher and extreme values during the rainy season, correlated with total suspended sediment concentrations (Nakhle et al., 2021).

In Guinea-Bissau, microbiological parameters tended to worsen in the wet season across all water source types (Bancessi et al., 2020). Monitoring programs should combine physicochemical parameters with fecal indicator bacteria analysis to capture both chemical and sanitary dimensions of groundwater quality (Adejuwon, 2025; Vucinic et al., 2022). Flow cytometry paired with fecal indicator bacteria analysis has demonstrated value for fingerprinting microbial pollution sources in aquifer systems (Vucinic et al., 2022). The semiarid Sokoto Basin study showed that seasonal and multivariate statistical analyses provide a user-friendly tool for monitoring shallow groundwater quality under different environmental conditions (Wali et al., 2024). In Pakistan, an assessment framework based on microbial quality grading and sanitary inspection risk scores was applied to prioritize remedial action for individual wells (Igbokwe et al., 2025b). These monitoring approaches, when applied consistently across tropical sandstone aquifer systems, support early detection of contamination trends, inform treatment decisions, and strengthen public health protection for groundwater-dependent communities (Banda et al., 2024; Vucinic et al., 2022; Wali et al., 2024).

3.8. Research Gaps and Future Directions

3.8.1 Limited Seasonal Datasets

Many groundwater studies in tropical sedimentary basins rely on single-season sampling, which limits understanding of seasonal contamination dynamics (Onyeka et al., 2024; ELSamadoni et al., 2025; Wali et al., 2024). In the semiarid Sokoto Basin, the Kruskal-Wallis test revealed that seasonality exerts a considerable influence on shallow groundwater through significant differences in temperature, electrical conductivity, dissolved oxygen, TDS, bicarbonate, chloride, ammonia, and phosphate between dry and wet seasons (Wali et al., 2024). In Calabar, Nigeria, microbial contamination levels near a municipal dumpsite were consistently higher in the wet season than the dry season, with total bacteria counts rising from 5155 CFU/100ml in the dry season to 10,356 CFU/100ml in the wet season (Ochelebe et al., 2022). In Guinea-Bissau, microbiological parameters tended to worsen in the wet season across all water source types (Bancessi et al., 2020).

In the Mocorito River Aquifer of northwestern Mexico, spatial and seasonal analyses showed heterogeneity among sites, with the greatest water quality deterioration in agricultural areas during periods of intensive irrigation and fertilization (Onyeka and Emeka, 2025). In Lao PDR, E. coli concentrations showed strong seasonality with higher and extreme values during the rainy season, correlated with total suspended sediment concentrations (Nakhle et al., 2021). The Chittagong University campus study in Bangladesh found differences in WQI classifications between summer and winter seasons, with 92% of samples rated excellent to good in summer compared to 84% in winter. These findings confirm that single-season datasets fail to capture the full range of contamination variability in tropical aquifer systems. Future studies should adopt multi-season sampling protocols that cover both wet and dry periods to produce more representative assessments of groundwater quality and contamination risk (ELSamadoni et al., 2025; Wali et al., 2024).

3.8.2 Weak Hydrochemical-Microbial Integration

Hydrochemical and microbial assessments remain poorly integrated in many tropical groundwater studies (Wali et al., 2020b, 2020a). The Cross River and Imo-Kwa-Ibo basin review noted the absence of broad water quality analysis based on water quality indices and the lack of studies modelling pollution or land use impacts on groundwater quality (Wali et al., 2020b). The Anambra Basin review identified similar gaps, noting that studies fell short of hydrogeochemical evolution analysis, WQI, heavy metals pollution index, and total hazard quotient evaluation (Wali et al., 2020a). In the Chittagong University study, physicochemical, geochemical, trace metal, and biological parameters were analysed together, representing one of the few integrated approaches in the literature.

In western Cuba, researchers tested an experimental modelling approach ranging from hydrogeology to microbiology to characterize a coastal carbonate aquifer, demonstrating the effectiveness of interdisciplinary integration (Nwamekwe et al., 2025). In the Pearl River Delta of China, isotopic geochemical measurements were integrated with high-throughput sequencing of 16S rRNA gene amplicons to evaluate the source of groundwater salinity and the influence of hydrogeochemical variations on microbial communities (Sang et al., 2019). The study concluded that comprehensive multidisciplinary research was a useful tool for tracing pollution sources and microbial processes (Sang et al., 2019). Most studies in tropical sandstone aquifer settings, by contrast, address either hydrochemistry or microbiology in isolation (Raza et al., 2024; Wali et al., 2020b, 2020a). The Thal Desert study in Pakistan combined physical, chemical, and microbial analysis of groundwater samples, but the microbial component was limited to semi-qualitative testing (Raza et al., 2024). Future research should adopt frameworks that systematically link hydrochemical evolution, fecal indicator bacteria, aquifer vulnerability, and health risk assessment within a single analytical structure (ELSamadoni et al., 2025; Nwamekwe et al., 2025; Sang et al., 2019).

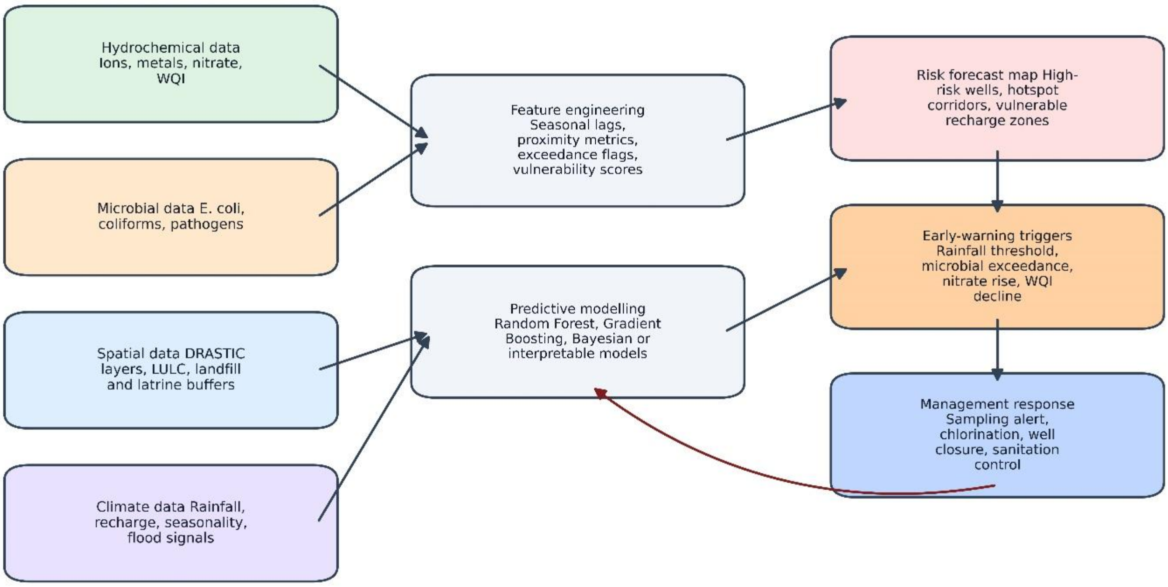
3.8.3 Need for Pathogen-Specific Monitoring

Most groundwater microbial assessments in tropical regions rely on indicator organisms such as total coliform, fecal coliform, and E. coli, without identifying specific pathogens (Adejuwon, 2025; Ochelebe et al., 2022; Raza et al., 2024). In Calabar, total Salmonella/Shigella and Vibrio cholerae were enumerated alongside standard fecal indicators, representing a more detailed approach than most studies (Ochelebe et al., 2022). In the Ibadan metropolis of Nigeria, the prevalent bacteria identified in groundwater included Klebsiella pneumoniae, Escherichia coli, Pseudomonas aeruginosa, and Staphylococcus aureus (Abdus-Salam et al., 2024). In northern Australia, culture and sequencing methods detected Burkholderia pseudomallei, the causative agent of melioidosis, in bores with elevated iron, alongside iron-oxidizing Gallionella and nitrifying Nitrospira in multi-species biofilms (Okpala et al., 2024).

The Pearl River Delta study applied high-throughput sequencing of 16S rRNA gene amplicons to characterize microbial communities along a salinity gradient, identifying class-level shifts from β-proteobacteria in freshwater to ε-proteobacteria in brackish water and Bacilli in saline water (Sang et al., 2019). These molecular approaches provide far greater resolution than standard culture-based methods. Future studies should include viral pathogens, protozoan parasites such as Cryptosporidium and Giardia, and antibiotic-resistant microorganisms in groundwater risk evaluation (ELSamadoni et al., 2025; Vucinic et al., 2022). Microbial pathogenic contamination of aquifers remains a globally important water quality problem, with no corresponding decrease in disease outbreak risks for untreated or inadequately treated groundwater observed in recent decades (Vucinic et al., 2022). Flow cytometry paired with fecal indicator bacteria analysis has demonstrated value for fingerprinting microbial pollution sources in aquifer systems and should be adopted more widely in tropical groundwater studies (Vucinic et al., 2022).

3.8.4 GIS, Machine Learning, and Early-Warning Models

GIS-based spatial analysis has proven effective for identifying contamination hotspots and vulnerable zones in tropical sedimentary basins (Iqbal et al., 2023; Nkwunonwo et al., 2024; Oke, 2020). In the Dahomey Basin, DRASTIC vulnerability mapping classified 21% of the area at high pollution risk, with sensitivity analysis validating the spatial outputs (Oke, 2020). In Quetta, Pakistan, land use land cover analysis on Google Earth Engine was combined with hydrogeochemical data to assess spatial distribution of groundwater quality and its vulnerability to pollution over a six-year period (Iqbal et al., 2023). In the Nile Delta of Egypt, remote sensing data helped detect and monitor changes in surface water bodies, vegetation cover, and land usage that impact groundwater systems, with land use and land cover analysis between 2014 and 2024 showing a decrease in agricultural areas from 81% to 75% coinciding with an increase in urban areas (ELSamadoni et al., 2025). Advanced geostatistical tools such as Kriging have been used to map spatial fluctuations of groundwater contaminants using point observations (Raza et al., 2024). Machine learning and predictive spatial models offer the next step in contamination forecasting and groundwater risk prioritization (ELSamadoni et al., 2025; Karunanidhi et al., 2021). The integration of remote sensing, environmental isotopic techniques, and water quality indicators (hydrochemical and microbiological) helps in understanding the current status of groundwater systems and investigating their responses to possible climatic changes (ELSamadoni et al., 2025). Future frameworks should combine GIS-based vulnerability mapping with machine learning algorithms trained on hydrochemical, microbial, land use, and climatic datasets to produce early-warning models for groundwater contamination in tropical sandstone aquifer systems (ELSamadoni et al., 2025; Iqbal et al., 2023; Oke, 2020).



Model updating loop: new field and laboratory results improve risk forecasts after each monitoring cycle.

Figure 4. GIS and machine-learning early-warning architecture for tropical sandstone aquifer contamination

Figure 4 is the architecture that links hydrochemical, microbial, spatial, and climate data to predictive modelling, risk maps, early-warning triggers, and adaptive groundwater management actions.

3.8.5 Climate-Sensitive Groundwater Frameworks

Climate variability intensifies recharge-driven contamination and groundwater vulnerability in tropical sedimentary basins (Batista et al., 2018; ELSamadoni et al., 2025; Nlend et al., 2021). In the Guarani Aquifer System of Brazil, stable isotope analysis during the strong 2014-2016 El Niño event revealed large variations in the isotopic composition of precipitation, with variations in deuterium excess in groundwater and surface water suggesting the occurrence of strong secondary evaporation during the infiltration process (Batista et al., 2018). In the Nile Delta, groundwater samples revealed a contribution from the recent Nile ranging between 46.23% and 76.92%, emphasizing the aquifer's reliance on the Nile River recharge system and indicating potential vulnerability to climatic changes that reduce recharge rates (ELSamadoni et al., 2025). In humid tropical regions, shallow urban aquifers under hyper-recharge equatorial conditions face strong anthropogenic constraints, with implications for groundwater resources potential and integrated water resources management strategies (Nlend et al., 2021).

In the Lake Malawi Basin, isotope hydrology reinforced water resource system conceptualization and revealed a complex interplay of meteoric water input, evaporative effects, recharge processes, and mixing dynamics (Banda et al., 2024). Seasonal rainfall intensity drives both chemical and microbial contaminant mobilization into shallow aquifers (Nakhle et al., 2021; Ochelebe et al., 2022). In Lao PDR, the highest E. coli concentrations were measured during the rainy season in catchments dominated by unstocked forest areas (Nakhle et al., 2021). Future groundwater risk assessment frameworks should integrate climate sensitivity by incorporating rainfall variability, recharge dynamics, and projected changes in precipitation patterns into vulnerability models (Batista et al., 2018; ELSamadoni et al., 2025). This integration is necessary to anticipate how shifting climatic conditions will alter contamination pathways and groundwater quality in tropical sandstone aquifer systems (Banda et al., 2024; ELSamadoni et al., 2025; Nlend et al., 2021).

Conclusion

This review establishes that groundwater risk in tropical sandstone aquifers cannot be judged reliably from hydrochemical evidence alone. Sandstone aquifers are productive water-bearing systems, but their porosity, shallow recharge conditions, shale interbeds, seasonal rainfall, and weak sanitary protection create coupled chemical and microbial vulnerability. The evidence reviewed shows that lithology controls major-ion evolution through silicate weathering, carbonate dissolution, cation exchange, and residence-time effects, while land use and sanitation introduce nitrate, heavy metals, coliforms, E. coli, and enteric pathogens into the same flow systems. A central finding is the mismatch between chemical acceptability and sanitary safety. Several aquifers met major physicochemical limits, including low TDS and acceptable major-ion chemistry, yet microbial evidence showed unsafe conditions. This makes WQI, Piper plots, Gibbs diagrams, and conventional WHO-based physicochemical classification necessary but incomplete. The Abeokuta case, where all 12 shallow wells recorded total coliform and E. coli despite generally acceptable physicochemical quality, provides direct evidence that chemical compliance does not guarantee potable safety.

The review further shows that microbial contamination is strongly controlled by source proximity, rainfall, and aquifer vulnerability. The sharp wet-season rise in bacterial counts near dumpsites, the 42 CFU/100 ml reduction in fecal coliform with increasing distance from pit latrines in Zanzibar, and the 21% high-vulnerability classification from DRASTIC mapping in the Dahomey Basin confirm that risk is spatially and seasonally structured. Therefore, groundwater protection must move from static water-quality reporting to integrated, risk-based surveillance. The major contribution of this review is the integration of hydrogeochemical evolution, microbial indicators, aquifer vulnerability, GIS mapping, and public-health interpretation into a unified assessment logic for tropical sandstone aquifers. The proposed framework, workflow, and risk matrix convert fragmented chemical and microbiological evidence into a practical decision-support structure for monitoring, treatment prioritization, source protection, and early-warning planning. Future work should prioritize multi-season datasets, pathogen-specific monitoring, molecular microbial tools, GIS-linked vulnerability models, and machine-learning-based early-warning systems. For communities dependent on untreated groundwater, the most defensible management strategy is not chemical testing alone, but a combined program of hydrochemical analysis, fecal indicator testing, sanitary inspection, vulnerability mapping, and targeted treatment. This integrated approach offers a stronger scientific basis for reducing waterborne disease risk and sustaining safe groundwater use in tropical sedimentary basins.

References

Abdus-Salam, M. O., AKINSANYA, Y. O., Salami, I. O., Adeniji, T. W., Falana, A. O., Omotunde, V. B., Gbadebo, A. M., & Gbadamosi, M. O. (2024). Entropy-Weighted Water Quality Index Assessment of Groundwater in Ibadan Metropolis, Nigeria. https://doi.org/10.21203/rs.3.rs-4597423/v1

Adejuwon, J. O. (2025). Contamination of Shallow Groundwater by Pit Latrine in Adatan Community, Abeokuta, Nigeria. World Water Policy, 11(3), 794–806. https://doi.org/10.1002/wwp2.70007

Adejuwon, J. O., & Odusote, A. A. (2023). Physicochemical characteristics and heavy metals of groundwater during the wet and dry seasons at the Lafarge cement factory environment, Sagamu, Ogun State, Nigeria. World Water Policy, 9(2), 178–203. https://doi.org/10.1002/wwp2.12100

Ali, R., Bünzli, M.-A., Colombo, L., Khattak, S. A., Pera, S., Riaz, M., & Valsangiacomo, C. (2018). Water quality before and after a campaign of cleaning and disinfecting shallow wells: a study conducted during and after floods in Khyber Pakhtunkhwa, Pakistan. Journal of Water Sanitation and Hygiene for Development, 9(1), 28–37. https://doi.org/10.2166/washdev.2018.272

Aweda, A. K., Jatau, B. S., & Goki, N. G. (2023). Groundwater geochemistry and hydrochemical processes in the Egbako aquifer, Northern Bida Basin, Nigeria.

RBRH, 28. https://doi.org/10.1590/2318-0331.282320230010

Bancessi, A., Catarino, L., Silva, M. J., Ferreira, A., Duarte, E., & Nazareth, T. (2020). Quality Assessment of Three Types of Drinking Water Sources in Guinea-Bissau. International Journal of Environmental Research and Public Health, 17(19), 7254. https://doi.org/10.3390/ijerph17197254

Banda, L. C., Kalin, R. M., & Phoenix, V. R. (2024). Isotope Hydrology and Hydrogeochemical Signatures in the Lake Malawi Basin: A Multi-Tracer Approach for Groundwater Resource Conceptualisation. Water, 16(11), 1587. https://doi.org/10.3390/w16111587

Batista, L. V., Gastmans, D., Sánchez-Murillo, R., Farinha, B. S., Santos, S. M. R. dos, & Kiang, C. H. (2018). Groundwater and surface water connectivity within the recharge area of Guarani aquifer system during El Niño 2014–2016. Hydrological Processes, 32(16), 2483–2495. https://doi.org/10.1002/hyp.13211

Chibuzor, S. N., Egboka, B. C. E., Anakwuba, E. K., Onuigbo, E. N., Odokuma-Alonge, O., Ben-Owope, O. A., & Orji, A. E. (2023). Hydrochemical and Geological Investigations of Some Gully Erosion- Prone Areas in Parts of Awka- Orlu Cuesta, Nigeria. https://doi.org/10.21203/rs.3.rs-2548569/v1

Chidiebube, I. N., Nwamekwe, C. O., Chukwuemeka, G. H., and Wilfred, M. (2025). Optimization Of Overall Equipment Effectiveness Factors in a Food Manufacturing Small and Medium Enterprise. Journal of Research in Engineering and Applied Sciences, 10(1), 836-845.

Chidiebube, I.N., Onyeka, N.C., Sunday, A.P., et al. (2025a) 'A comparative analysis of machine learning models for inventory demand forecasting in a food manufacturing SME', Indonesian Journal of Innovation Science and Knowledge, 2(3), pp. 35-48.

Chidiebube, I.N., Uzochukwu, M.G., Nwamekwe, C.O., et al. (2025b) 'Evaluating machine learning models for optimizing overall equipment effectiveness in food manufacturing SMEs', Jurnal Inovasi Teknologi Dan Edukasi Teknik, 5(2). https://hal.science/hal-05149408v1/file/igbokwe-nkemakonam-chidiebube-layout-jitet.pdf

Davraz, A., & Batur, B. (2021). Hydrogeochemistry characteristics of groundwater and health risk assessment in Yalvaç–Gelendost basin (Turkey). Applied Water Science, 11(4). https://doi.org/10.1007/s13201-021-01401-9

Elendu, P. N. (2023). Physico-Chemical Characteristics of Ground Water of Woji, Port Harcourt Rivers State, Nigeria. British Journal of Environmental Sciences, 11(4), 36–76. https://doi.org/10.37745/bjes.2013/vol11n43676

ELSamadoni, W., Hagagg, K., Isawi, H., & Zaher, A. (2025). Assessment of Microbiological Risks and Ecological impact Stressors on Shallow Groundwater Resources Using Environmental Isotopes and Multi-Source

Remote Sensing. https://doi.org/10.21203/rs.3.rs-6844998/v1

Emeka, U. C., Chikwendu, O. C., & Onyeka, N. C. (2025). Human-Centric Design Integration in Industry 5.0: A Framework for Resilient Smart Manufacturing. INTERNATIONAL JOURNAL, 3(4).

Emeka, U. C., Okpala, C., and Nwamekwe, C. O. (2025a). Circular Economy Principles'implementation in Electronics Manufacturing: Waste Reduction Strategies in Chemical Management. International journal of industrial and production engineering, 3(2), 29-42.

Eyankware, M. O., Obasi, P. N., & Ogwah, C. (2021). A Comparative Study of Groundwater between Geological Groups of Southern Benue Trough, Nigeria Using Modelling Approach. Journal of Environmental & Earth Sciences, 3(2), 72–86. https://doi.org/10.30564/jees.v3i2.3694

Ezeanyim, O. C., Ewuzie, N. V., Aguh, P. S., Nwabueze, C. V., and Nwamekwe, C. O. (2025). Effective Maintenance of Industrial 5-Stage Compressor: A Machine Learning Approach. Gazi University Journal of Science Part A: Engineering and Innovation, 12(1), 96-118. https://dergipark.org.tr/en/pub/gujsa/issue/90827/1646993

Ezeanyim, O.C., Nwabunwanne, E.C., Igbokwe, N.C. and Nwamekwe, C.O. (2025a) 'Patient flow and service efficiency in public hospitals: data-driven approaches, strategies, challenges, and future directions', Journal Health of Indonesian, 3(02), pp. 104–124. https://doi.org/10.58471/health.v3i02.228

Fantong, W. Y., Nenkam, T. L. L. J., Fouepe, A., Fru, E. C., Vassolo, S., Montcoudiol, N., Fodoué, Y., Haman, J. B. D., Carlier, C., Nbendah, P., & Nkeng, G. E. (2023a). Hydrogeochemistry of low agricultural soil yield in Sahelian and subtropical watersheds, Northern Cameroon. Journal of African Earth Sciences (And the Middle East), 199, 104823. https://doi.org/10.1016/j.jafrearsci.2022.104823

Igbokwe, N. C., and Nwamekwe, C. O. (2025). Application of Machine Learning in Predicting Emergency Obstetric Cases in Sub-Saharan Africa: An Early Appraisal. International Journal of Industrial Engineering, Technology and Operations Management, 3(1), 13-22.

Igbokwe, N. C., Christiana, C., Nweke, C. O. N., and Onyeka, C. (2025). Data-Driven Solutions for Shuttle Bus Travel Time Prediction: Machine Learning Model Evaluation at Nnamdi Azikiwe University. African Journal of Computing, Data Science and Informatics (AJCDSI), 1(1), 31-55.

Igbokwe, N. C., Nwamekwe, C. O., Ono, C. G., Nwabunwanne, E. C., & Aguh, P. S. (2024). The role of digital twins in optimizing renewable energy utilization and energy efficiency in manufacturing. Siber International Journal of Digital Business, 1(4), 93-111.

Igbokwe, N. C., Okeagu, F. N., Onyeka, N. C., Onwuliri, J. B., and Godfrey, O. C.

(2024a). Machine Learning-Driven Maintenance Cost Optimization: Insights from a Local Industrial Compressor Case Study. Jurnal Inovasi Teknologi dan Edukasi Teknik, 4(11), 2.

Igbokwe, N.C., Emmanuel, U.N. and Nwamekwe, C.O. (2025a) 'Advances in post-harvest fish processing: an appraisal of traditional and modern smoking techniques for improved quality and efficiency', Jurnal Integrasi Dan Harmoni Inovatif Ilmu-Ilmu Sosial', 5 (9), pp. 1-13. https://philarchive.org/rec/IGBAIP

Igbokwe, N.C., Nwamekwe, C.O. and Aguh, P.S. (2025b) 'Predictive modeling of manufacturing defects using machine learning: A comparative performance study in a manufacturing SME', African Journal of Advances in Engineering and Technology (AJAET), 1(02), pp. 93-115.

Iqbal, J., Amin, G., Su, C., Haroon, E., & Baloch, M. Y. J. (2023). Assessment of landcover impacts on the groundwater quality using hydrogeochemical and geospatial techniques. https://doi.org/10.21203/rs.3.rs-2771650/v1

Jolaosho, T. L., Mustapha, A. A., & Hundeyin, S. T. (2024). Hydrogeochemical evolution and heavy metal characterization of groundwater from southwestern, Nigeria: An integrated assessment using spatial, indexical, irrigation, chemometric, and health risk models. Heliyon, 10(19), e38364. https://doi.org/10.1016/j.heliyon.2024.e38364

Karunanidhi, D., Subramani, T., Roy, P. D., & Li, H. (2021). Impact of groundwater contamination on human health. Environmental Geochemistry and Health, 43(2), 643–647. https://doi.org/10.1007/s10653-021-00824-2

Kumar, M., Panday, D. P., Goswami, R., Neog, N., Bahukhandi, K. D., Zhang, J., & Bhattacharya, P. (2025). Dynamics of Arsenic Co-contamination in the Groundwater of the Eastern Himalayas: The Biogeochemical Drivers and GRACE-Based Evidence. Acs Es&t Water, 5(6), 2833–2847. https://doi.org/10.1021/acsestwater.4c00106

Lawal, A., Tijani, M. N., Snow, D. D., & D'Alessio, M. (2022). Quality and hydrochemical assessment of groundwater in geological transition zones: a case study from N.E. Nigeria. Environmental Science and Pollution Research, 30(4), 10643–10663. https://doi.org/10.1007/s11356-022-22762-x

Lima, C. de, Batista, L. V., Garpelli, L. N., Santos, V. dos, Quaggio, C. S., & Gastmans, D. (2023). Assessment of River-Aquifer Interaction and Nitrogen Contamination in an Agricultural Zone Located in the Guarani Aquifer System Outcrop Area. Anais Da Academia Brasileira De Ciências, 95(suppl 2). https://doi.org/10.1590/0001-3765202320220609

Mallick, J., Singh, C. K., Mesfer, M. K. A., Singh, V. P., & Alsubih, M. (2021a). Groundwater Quality Studies in the Kingdom of Saudi Arabia: Prevalent Research and Management Dimensions. Water, 13(9), 1266.

https://doi.org/10.3390/w13091266

Martínez-Santos, P., Martín-Loeches, M., García-Castro, N., Solera, D., Díaz-Alcaide, S., Montero, E., & García-Rincón, J. (2017). A survey of domestic wells and pit latrines in rural settlements of Mali: Implications of on-site sanitation on the quality of water supplies. International Journal of Hygiene and Environmental Health, 220(7), 1179–1189. https://doi.org/10.1016/j.ijheh.2017.08.001

Masoud, A. A., & Aldosari, A. (2020). Groundwater Quality Assessment of a Multi-Layered Aquifer in a Desert Environment: A Case Study in Wadi ad-Dawasir, Saudi Arabia. Water, 12(11), 3020. https://doi.org/10.3390/w12113020

Nakhle, P., Ribolzi, O., Boithias, L., Rattanavong, S., Auda, Y., Sayavong, S., Zimmermann, R., Soulileuth, B., Pando, A., Thammahacksa, C., Rochelle-Newall, E., Santini, W., Martinez, J., Gratiot, N., & Pierret, A. (2021). Effects of hydrological regime and land use on in-stream Escherichia coli concentration in the Mekong basin, Lao PDR. Scientific Reports, 11(1). https://doi.org/10.1038/s41598-021-82891-0

Nkwunonwo, U. C., Oyem, M. N., Anthony, T., Asano, N. O., & Ebinne, E. S. (2024). Geospatial Analysis and Physicochemical Assessment of Groundwater Quality Vulnerability to Municipal Solid Waste from Landfills. Air Soil and Water Research, 17. https://doi.org/10.1177/11786221241266039

Nlend, B., Celle-Jeanton, H., Huneau, F., Garel, É., Boum-Nkot, S. N., & Étamé, J. (2021). Shallow urban aquifers under hyper-recharge equatorial conditions and strong anthropogenic constrains. Implications in terms of groundwater resources potential and integrated water resources management strategies. The Science of the Total Environment, 757, 143887. https://doi.org/10.1016/j.scitotenv.2020.143887

Nwamekwe C. O., Ewuzie Nnamdi Vitalis, Igbokwe Nkemakonam Chidiebube, and Nwabueze Chibuzo Victoria. (2025a). Evaluating Advances in Machine Learning Algorithms for Predicting and Preventing Maternal and Foetal Mortality in Nigerian Healthcare: A Systematic Approach. International Journal of Industrial and Production Engineering, 3(1), 1-15. https://journals.unizik.edu.ng/ijipe/article/view/5161

Nwamekwe C. O., Ezeanyim O. C., and Igbokwe N. C. (2025b). Resilient Supply Chain Engineering in the Era of Disruption: An Appraisal. International Journal of Innovative Engineering, Technology and Science (IJIETS), 9(1), 11-23. https://hal.science/hal-05061524/

Nwamekwe, C. O., and Chikwendu, O. C. (2025). Circular economy strategies in industrial engineering: From theory to practice. International Journal of Multidisciplinary Research and Growth Evaluation, 6(1): 1773-1782. https://www.allmultidisciplinaryjournal.com/uploads/archives/202502121

03754_MGE-2025-1-288.1.pdf

Nwamekwe, C. O., and Igbokwe, N. C. (2024). Supply Chain Risk Management: Leveraging AI for Risk Identification, Mitigation, and Resilience Planning. International Journal of Industrial Engineering, Technology and Operations Management, 2(2), 41–51. https://doi.org/10.62157/ijietom.v2i2.38

Nwamekwe, C. O., and Nwabunwanne, E. C. (2025). Immersive Digital Twin Integration in the Metaverse for Supply Chain Resilience and Disruption Management. Journal of Engineering Research and Applied Science, 14(1), 95-105.

Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., and Sunday, A. P. (2025c). Resilience and Risk Management in Social Robot Systems: An Industrial Engineering Perspective. Culture education and technology research (Cetera), 2(2), 1-12.

Nwamekwe, C. O., Chidiebube, I. N., Godfrey, O. C., Celestine, N. E., and Aguh, P. S. (2025d). Human-Robot Collaboration in Industrial Engineering: Enhancing Productivity and Safety. Journal of Industrial Engineering and Management Research, 6(5), 1-20.

Nwamekwe, C. O., Chinwuko, C. E. and Mgbemena, C. E. (2020). Development and Implementation of a Computerised Production Planning and Control System. UNIZIK Journal of Engineering and Applied Sciences, 17(1), 168-187. https://journals.unizik.edu.ng/ujeas/article/view/1771

Nwamekwe, C. O., Edokpia, R. O., & Eboigbe, C. I. (2026). Integration of Machine Learning into Lean Six Sigma: A Systematic Review for Enhancing Predictive Analytics in the Pharmaceutical Industry. Siber Journal of Advanced Multidisciplinary, 3(4), 133-151.

Nwamekwe, C. O., Edokpia, R. O., and Igbinosa, E. C. (2025e). Exploring the Role of Artificial Intelligence in Enhancing Lean Manufacturing and Six Sigma for Smart Factories. International Journal of Industrial Engineering, Technology and Operations Management, 3(1), 1-12.

Nwamekwe, C. O., Ewuzie, N. V., Igbokwe, N. C., & Okpala, C. C. (2026). Evaluating the performances of various machine learning models for accurate production forecasting in the textile industry. International Journal of Technology, Health and Sustainability, 2(1), 138-148.

Nwamekwe, C. O., Ewuzie, N. V., Okpala, C. C., Ezeanyim, C., Nwabueze, C. V., Nwabunwanne, E. C. (2025f). Optimizing Machine Learning Models for Soil Fertility Analysis: Insights from Feature Engineering and Data Localization. Gazi University Journal of Science Part A: Engineering and Innovation, 12(1), 36-60. https://dergipark.org.tr/en/pub/gujsa/issue/90827/1605587

Nwamekwe, C. O., Ewuzie, N.V., Igbokwe, N. C., Nwabunwanne, E. C., and Ono, C. G. (2025g). Digital Twin-Driven Lean Manufacturing: Optimizing Value

Stream Flow. Letters in Information Technology Education (LITE), 8 (1), pp.1-13. https://hal.science/hal-05127340/

Nwamekwe, C. O., Nwabunwanne, E. C., Okeagu, F. N., and Ono, C. G. (2025h). Lean Manufacturing Principles in the Design and Production of Social Robots. International Journal of Industrial Engineering, Technology and Operations Management, 3(1), 23-34.

Nwamekwe, C. O., Okpala, C. C., and Nwabunwanne, E. C. (2025i). Design Principles and Challenges in Achieving Zero-Energy Manufacturing Facilities. Journal of Engineering Research and Applied Science, 14(1), 1-21.

Nwamekwe, C. O., Okpala, C. C., and Okpala, S. C., (2024a). Machine Learning-Based Prediction Algorithms for the Mitigation of Maternal and Fetal Mortality in the Nigerian Tertiary Hospitals. International Journal of Engineering Inventions, 13(7), PP: 132-138. https://www.ijeijournal.com/papers/Vol13-Issue7/1307132138.pdf

Nwamekwe, C. O., Uchenna, P. C., & Onyedika, S. C. Leveraging Emerging Technologies to Enhance Business Processes in Blue Economy Sectors: A Case Study of Anambra State's Industrial Landscape. International Journal of Technology, Health and Sustainability, 2(2), pp. 559-572

Nwamekwe, C. O., Uchenna, P. C., Onyedika, S. C. (2026). Leveraging Emerging Technologies to Enhance Business Processes in Blue Economy Sectors: A Case Study of Anambra State’s Industrial Landscape. International Journal of Technology, Health and Sustainability, 2(2), pp. 559-572. https://ijths.com/wp-content/uploads/IJTHS-0202024.pdf

Nwamekwe, C., Ewuzie, N., Igbokwe, N., Okpala, C., and U-Dominic, C. (2024b). Sustainable Manufacturing Practices in Nigeria: Optimization and Implementation Appraisal. Journal of Research in Engineering and Applied Sciences, 9(3). https://qtanalytics.in/journals/index.php/JREAS/article/view/3967

Ochelebe, I., Ekwere, A. S., & Edet, A. (2022). Bacteriological Assessment of Groundwater Quality Around a Major Municipal Dumpsite, Calabar, Se-Nigeria. https://doi.org/10.21203/rs.3.rs-1979506/v1

Odoh, B. I., Korie, J. I., Arukwe-Moses, C. P., Ahaneku, C. V., Azike, M. C., Muogbo, C. D., & Chibuzor, S. N. (2024). Assessing the Impact of Leachate Infiltration from Dumpsites into the Groundwater System of Agu-Awka and Environs, Southeastern Nigeria. Journal of Geography Environment and Earth Science International, 28(8), 141–160. https://doi.org/10.9734/jgeesi/2024/v28i8804

Ohwoghere-Asuma, O., Aweto, K. E., Chinyem, F. I., & Nwankwoala, H. O. (2018). Assessing the Protective Capacity of Aquifers Using Very-Low-Frequency Electromagnetic Survey. Geosciences, 8(5), 150. https://doi.org/10.3390/geosciences8050150

Oke, S. A. (2020). Regional Aquifer Vulnerability and Pollution Sensitivity Analysis of Drastic Application to Dahomey Basin of Nigeria. International Journal of Environmental Research and Public Health, 17(7), 2609. https://doi.org/10.3390/ijerph17072609

Okeagu, F., Nwamekwe, C., and Nnamani, B. (2024). Challenges and Solutions of Industrial Development in Anambra State, Nigeria. Iconic Research and Engineering Journals, 7(11), 467-472. https://www.irejournals.com/formatedpaper/1705825.pdf

Okolo, C. M., Onuora, I., Madu, F. M., & Obasi, P. N. (2024). Characterization of Dominant Hydrogeochemical Processes in Groundwater in Onitsha Area, Southeastern Nigeria. International Journal of Environment and Climate Change, 14(1), 43–53. https://doi.org/10.9734/ijecc/2024/v14i13806

Okpala C. C., Chukwudi Emeka Udu, and Charles Onyeka Nwamekwe. (2025). Sustainable HVAC Project Management: Strategies for Green Building Certification. International Journal of Industrial and Production Engineering, 3(2), 14-28. https://journals.unizik.edu.ng/ijipe/article/view/5595.

Okpala, C. C., Ezeanyim, O. C., and Nwamekwe, C. O. (2024). The Implementation of Kaizen Principles in Manufacturing Processes: A Pathway to Continuous Improvement. International Journal of Engineering Inventions, 13(7), 116-124. https://www.ijeijournal.com/papers/Vol13-Issue7/1307116124.pdf

Okpala, C. C., Udu, C. E., and Nwamekwe, C. O. (2025a). Artificial Intelligence-Driven Total Productive Maintenance: The Future of Maintenance in Smart Factories. International Journal of Engineering Research and Development (IJERD), (21)1, 68-74. https://www.ijerd.com/paper/vol21-issue1/21016874.pdf

Okpala, C., Onyeka, C. and Igbokwe, N.C. (2024a) 'The implementation of Internet of Things in the manufacturing industry: An appraisal', International Journal of Engineering Research and Development, 20(7), pp. 510-516.

Onyeka, N. C., and Emeka, N. (2025). Circular Economy and Zero-Energy Factories: A Synergistic Approach to Sustainable Manufacturing. Journal of Research in Engineering and Applied Sciences, 10(1), 829-835.

Onyeka, N. C., Vitalis, E. N., Chidiebube, I. N., U-Dominic, C. M., and Chibuzo, N. (2024). Adoption of Smart Factories in Nigeria: Problems, Obstacles, Remedies and Opportunities. International journal of industrial and production engineering, 2(2), 68-81. https://journals.unizik.edu.ng/ijipe/article/view/4167

Rathinasamy, V., Mohammad, E. T., & Komoo, I. (2018). Review on Rock Aquifers Researches Conducted in Malaysia. Matec Web of Conferences, 250, 01007. https://doi.org/10.1051/matecconf/201825001007

Raza, I., Khalid, P., Ehsan, M. I., Ahmad, Q. A., Khurram, S., Zainab, R., & Farooq,

S. (2024). Geospatial interpolation and hydro-geochemical characterization of alluvial aquifers in the Thal Desert, Punjab, Pakistan. Plos One, 19(8), e0307025. https://doi.org/10.1371/journal.pone.0307025

Sang, S., Dai, H., Hu, B. X., Hao, Y., Zhou, T., & Zhang, J. (2019). The Study of Hydrogeochemical Environments and Microbial Communities along a Groundwater Salinity Gradient in the Pearl River Delta, China. Water, 11(4), 804. https://doi.org/10.3390/w11040804

Seidu, J., & Ewusi, A. (2020). Assessment of Groundwater Quality and Health Risk of Heavy Metals: A study from the Tarkwa Mining Area, Ghana. Ghana Mining Journal, 20(2), 1–10. https://doi.org/10.4314/gm.v20i2.1

Vitalis, E. N., Nwamekwe, C. O., Chidiebube, I. N., Chibuzo, N., Nwabunwanne, E. C., and Ono, C. G. (2024). Application Of Machine-Learning-Based Hybrid Algorithm for Production Forecast in Textile Company. Jurnal Inovasi Teknologi dan Edukasi Teknik, 4(12), 1-9.

Vucinic, L., O'Connell, D., Teixeira, R., Coxon, C., & Gill, L. (2022). Flow Cytometry and Fecal Indicator Bacteria Analyses for Fingerprinting Microbial Pollution in Karst Aquifer Systems. Water Resources Research, 58(5). https://doi.org/10.1029/2021wr029840

Wali, S. U., Alias, N., & Harun, S. (2020). Quality reassessment using water quality indices and hydrochemistry of groundwater from the Basement Complex section of Kaduna Basin, NW Nigeria. Sn Applied Sciences, 2(10). https://doi.org/10.1007/s42452-020-03536-x

Wali, S. U., Alias, N., & Harun, S. (2024). Seasonal Analysis of Shallow Groundwater Using Multivariate Statistics in a Semiarid Basin, Northern Nigeria. https://doi.org/10.21203/rs.3.rs-3940193/v1

Wali, S. U., Dankani, I. M., Abubakar, S. D., Gada, M. A., Umar, K. J., Usman, A. A., & Shera, I. M. (2020a). Reassessing Groundwater Potentials and Subsurface water Hydrochemistry in a Tropical Anambra Basin, Southeastern Nigeria. Journal of Geological Research, 2(3), 1–24. https://doi.org/10.30564/jgr.v2i3.2141

Wali, S. U., Dankani, I. M., Abubakar, S. D., Gada, M. A., Umar, K. J., Usman, A. A., & Shera, I. M. (2020d). Re-examination of Hydrochemistry and Groundwater Potentials of Cross River and Imo-Kwa-Ibo Intersecting Tropical Basins of SouthSouth Nigeria. Journal of Geological Research, 2(3), 25–42. https://doi.org/10.30564/jgr.v2i3.2142

Wali, S. U., Dankani, I. M., Abubakar, S. D., Gada, M. A., Usman, A. A., Shera, I. M., & Umar, K. J. (2020g). Review of groundwater potentials and groundwater hydrochemistry of semi-arid Hadejia-Yobe Basin, North-eastern Nigeria. Journal of Geological Research, 2(2). https://doi.org/10.30564/jgr.v2i2.2140

Xiao, S., Wang, J., Xiao, Y., Yang, S., Zhang, Y., Wang, J., Chen, H., Hu, W., Wang, L., Zhu, G., Su, Y., & Zhao, D. (2025). Characterization of strontium-rich groundwater in a typical alpine basin on Tibetan Plateau: Implications for sustainable exploitation and development. Plos One, 20(9), e0331449. https://doi.org/10.1371/journal.pone.0331449

Zainol, N. F. M., Zainuddin, A. H., Looi, L. J., Aris, A. Z., Isa, N. M., Sefie, A., & Yusof, K. M. K. K. (2021). Spatial Analysis of Groundwater Hydrochemistry through Integrated Multivariate Analysis: A Case Study in the Urbanized Langat Basin, Malaysia. International Journal of Environmental Research and Public Health, 18(11), 5733. https://doi.org/10.3390/ijerph18115733