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Influence of On-Site Sanitation Systems on Shallow Groundwater Quality in Kimpwena Settlement, Solwezi District, Zambia

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ABSTRACT

Shallow groundwater is a primary source of domestic water for millions of peri-urban households across sub-Saharan Africa. Unfortunately, its quality is increasingly compromised by the widespread use of on-site sanitation systems. This study assessed the influence of pit latrines on shallow groundwater quality in Kimpwena Settlement, Solwezi District, Zambia, using a descriptive cross-sectional design that combined GIS spatial analysis with laboratory water quality assessment. Four sentinel shallow wells (n = 4), purposively selected to represent a range of distances (6 - 29 m) from the nearest sanitation facilities, were sampled during the rainy season and analysed for physicochemical parameters: pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate (NO_3^-), and phosphate (PO_4^{3-}) as well as microbial indicators, including faecal coliforms and total coliforms. A sentinel-site approach was employed to identify contamination gradients rather than generate statistically representative estimates of groundwater quality. Results were benchmarked against Zambia Bureau of Standards ZS 190:2010 and WHO 2017 drinking water guidelines. GIS analysis confirmed that all sampled wells were located within 30 m of sanitation facilities, in non-compliance with recommended separation distances. Groundwater was universally acidic (pH 4.71 - 5.30), and phosphate concentrations exceeded permissible limits at three of four wells (1.6 - 3.2 mg/L; limit: 1.0 mg/L). Severe microbial contamination was detected at the well with the shortest proximity to sanitation, recording faecal coliforms of 224 CFU/100 mL and total coliforms of 320 CFU/100 mL, suggesting an inverse distance-contamination relationship. EC, TDS, and nitrate concentrations were within acceptable limits across all locations, likely reflecting seasonal dilution and denitrification dynamics. These findings demonstrate that inadequate separation distances, combined with permeable soils and high sanitation density, appear to contribute to groundwater contamination in Kimpwena Settlement. The study recommends stricter enforcement of siting regulations, infrastructure upgrades, enhanced well protection, and community-centered awareness programs to safeguard groundwater quality and protect public health in peri-urban Zambia.

Keywords: groundwater contamination, on-site sanitation, pit latrines, shallow wells, GIS, peri-urban Zambia, physicochemical parameters, microbial indicators, separation distance

1. INTRODUCTION

Access to safe drinking water remains a fundamental challenge in rapidly growing peri-urban and rural settlements across sub-Saharan Africa, where millions of households depend entirely on shallow groundwater for domestic use (MacDonald et al., 2021). In many low-income settlements where piped water infrastructure is limited or absent, shallow wells and hand-dug boreholes are the primary and often the only source of water for drinking, cooking, and hygiene. Zambia is a clear example of this dependency: rapid population growth, unplanned settlement expansion, and chronic underinvestment in formal water supply networks have deepened reliance on shallow groundwater in peri-urban and rural areas (Mulenga et al., 2017; Hinton et al., 2024). Yet the quality of this critical resource is increasingly threatened by the very sanitation systems meant to protect public health.

On-site sanitation systems, predominantly pit latrines and septic tanks are the dominant means of waste disposal across African settlements that lack centralised sewerage. While these systems improve sanitation access and reduce open defecation, their proximity to shallow water sources creates pathways for chemical and microbial contamination of groundwater (Graham & Polizzotto, 2013; Lapworth et al., 2017). When poorly designed, inadequately sited, or not properly maintained, on-site sanitation facilities generate leachate rich in faecal pathogens, nitrate, phosphate, and other contaminants that can infiltrate shallow aquifers through vertical percolation, lateral seepage, and preferential flow paths (Robertson, 2021). The risk is made worse in areas with shallow water tables, permeable sandy soils, and high densities of sanitation infrastructure, conditions typical of many rapidly expanding peri-urban settlements in eastern and southern Africa.

Research consistently demonstrates a spatial relationship between well-latrine proximity and contamination outcomes. Studies in African peri-urban environments consistently demonstrate elevated faecal coliform counts and microbial contamination exceeding safe limits in wells located near sanitation facilities (Wechuli, 2022). In Zambia, similar patterns have been observed in Lusaka, where shallow wells adjacent to poorly maintained

latrines showed elevated microbial loads and chemical contamination exceeding WHO microbial standards (Sorensen et al., 2015; Reaver et al., 2020; Chuunda & Kamweneshe, 2025). Spatial modelling further suggests that the number of groundwater sources at risk of faecal contamination in Sub-Sahara Africa will increase as informal settlements expand without adequate sanitation planning (Mbae et al., 2023).

Despite growing evidence at the regional scale, localised data for smaller peri-urban settlements remain scarce, limiting the ability of authorities and communities to design targeted interventions. Kimpwena Settlement in Solwezi District, North-Western Province of Zambia, is one such under-studied community. With an estimated population of 5,199 residents served by approximately 47 sanitation facilities and reliant on shallow wells for domestic water supply, Kimpwena exhibits the hallmarks of high groundwater vulnerability: informal and unregulated housing, permeable soils, and widespread use of pit latrines without formal zoning or enforcement of safe siting guidelines. No empirical study has yet quantified the influence of on-site sanitation on groundwater quality in this settlement, a gap that this study directly addresses.

This study therefore aimed to:

(i) map the spatial distribution of on-site sanitation systems and shallow wells in Kimpwena Settlement;

(ii) determine the physicochemical and microbial quality of groundwater from selected sentinel wells; and

(iii) assess the relationship between proximity of sanitation facilities and groundwater contamination levels. By generating site-specific evidence, the study aims to inform local water safety planning, sanitation management policy, and broader discussions on protecting shallow groundwater in peri-urban Zambia.

2. LITERATURE REVIEW

2.1 Groundwater Pollution in Peri-Urban Contexts

Groundwater pollution refers to the introduction of chemical, physical, or biological substances into aquifers at concentrations that compromise water safety for human consumption or ecological function (Lapworth et al., 2017). Shallow wells are particularly vulnerable due to limited natural attenuation and short travel distances for contaminants (Graham & Polizzotto, 2013; Lapworth et al., 2017). Generally, contamination may arise from point sources, such as an individual pit latrine or septic tank, or from non-point sources, particularly the cumulative loading from clusters of latrines in densely populated informal settlements (Rama et al., 2022). Unlike surface water contamination, groundwater pollution typically evolves gradually and persists for extended periods due to the slow movement and limited natural flushing capacity of subsurface environments Lapworth et al., 2017).

The susceptibility of shallow wells is determined by a combination of soil permeability and texture, depth to the water table, recharge rates, and aquifer type (Graham & Polizzotto, 2013; Rama et al., 2022). Sandy soils, which are prevalent in many Zambian peri-urban settings, facilitate rapid downward percolation with minimal filtration, while shallow water tables shorten the vertical travel distance for pathogens and dissolved pollutants. Seasonal rainfall further accelerates infiltration, overwhelming natural attenuation processes and generating temporary spikes in microbial and chemical contamination. The public health consequences are severe: waterborne diseases including diarrhoea, cholera, typhoid, and dysentery represent leading causes of morbidity and mortality in communities relying on unprotected shallow wells (Graham & Polizzotto, 2013).

2.2 On-Site Sanitation Systems and Contamination Pathways

Pit latrines and septic tanks dominate sanitation provision across rural and peri-urban sub-Saharan Africa, accounting for a substantial proportion of sanitation infrastructure in communities without centralised sewerage networks (Graham & Polizzotto, 2013). While such systems are cost-effective and operationally simple, their capacity to protect adjacent groundwater depends critically on proper design, maintenance, and siting relative to water sources (Robertson, 2021).

Contaminant transport from pit latrines occurs through several interconnected mechanisms. Direct vertical infiltration is the primary pathway: liquid effluent percolates downward through the soil profile until it reaches the water table (Chua et al., 2022). In areas with shallow aquifers, the short travel distance increases the probability of both microbial and chemical pollutants contaminating groundwater (Kirori et al., 2022). Lateral seepage is a secondary mechanism through which effluent spreads horizontally, potentially reaching wells located some distance from the latrine. Preferential flow paths including soil fractures, decayed root channels, and macropores can accelerate contaminant movement, enabling pathogens and nutrients to travel more rapidly than expected under uniform soil conditions (Rama et al., 2022). Surface runoff during heavy rainfall events provides an additional pathway, particularly for poorly cased or uncovered wells that receive contaminated water from surrounding areas (Lapworth et al., 2017; Gwenzi et al., 2023). Septic tanks, while generally offering improved containment compared to pit latrines, similarly contribute to groundwater contamination when structural integrity is compromised or drain field effluent is discharged near shallow wells (Robertson, 2021).

2.3 Key Physicochemical and Microbial Indicators

Groundwater quality assessment relies on a suite of physicochemical and microbial parameters to evaluate the extent of contamination and associated health risks. Among physicochemical indicators, pH reflects the acidity or alkalinity of groundwater and influences the solubility and mobility of contaminants. Shallow wells near pit latrines frequently exhibit abnormal pH values attributable to organic acid production during anaerobic

decomposition of faecal matter (Robertson, 2021). Electrical conductivity (EC) measures the ability of water to conduct electrical current proportional to dissolved ion concentrations and elevated EC values often signal increased ionic loading from sanitation leachate. Total dissolved solids (TDS) provide a composite measure of dissolved inorganic and organic matter, while turbidity indicates the presence of suspended particles and correlates with microbial contamination risk since pathogens tend to adhere to particulate matter (Graham & Polizzotto, 2013).

Nitrate (NO_3^-) is one of the most widely used chemical tracers of sanitation-related groundwater contamination, arising from the nitrification of ammonium released from faecal matter. Elevated nitrate in drinking water is linked to methemoglobinemia in infants and to chronic health complications, with WHO (2017) guidelines specifying a limit of 50 mg/L. Phosphate (PO_4^{3-}) is a characteristic constituent of latrine leachate; although generally less mobile than nitrate due to adsorption onto soil particles, phosphate can migrate through sandy soils and accumulate in shallow aquifers under high loading conditions (Lapworth et al., 2017; Gwenzi et al., 2023). Microbial indicators, particularly faecal coliforms and total coliforms provide the most direct evidence of groundwater contamination from faecal sources. The presence of faecal coliforms, especially Escherichia coli, confirms faecal pollution and signals elevated risk of waterborne disease (WHO, 2017; Graham & Polizzotto, 2013). Both ZS 190:2010 national standards and WHO guidelines mandate zero coliforms in drinking water.

2.4 Spatial Analysis and GIS in Groundwater Studies

The spatial arrangement of wells and sanitation facilities is a critical determinant of groundwater contamination risk. Proximity between these infrastructure elements drives contaminant loading, and geographic information systems (GIS) have become essential tools for visualising these spatial relationships, delineating contamination risk zones, and guiding targeted interventions (Graham & Polizzotto, 2013; Rama et al., 2022). GIS-based distance analysis enables precise quantification of well-latrine separation, while buffer zone mapping identifies areas where compliance with recommended minimum distances is inadequate.

Empirical evidence across Africa consistently demonstrates the significance of spatial proximity. In peri-urban Kenya, 65% of shallow wells were found within 15 m of pit latrines, with these wells exhibiting consistently higher microbial loads (Kirori et al., 2022). Investigations in Ghana identified a clear inverse relationship between well-latrine distance and nitrate concentrations in shallow aquifers (Annan et al., 2022). In Zambia, Chuunda & Kamweneshe, (2025) documented elevated nitrate and faecal coliform concentrations in wells within 10 m of latrines in Lusaka, while Reaver et al. (2021) reported elevated turbidity and microbial contamination in wells near clustered sanitation facilities. The WHO (2017) recommends a minimum separation distance of 30 m between sanitation facilities and wells, but this threshold is routinely violated in informal peri-urban settlements, creating persistent public health risks.

2.5 Knowledge Gaps

Despite the growing body of evidence on sanitation-related groundwater contamination, significant knowledge gaps remain. First, localised data for small peri-urban settlements such as Kimpwena are scarce, limiting the transferability of findings from larger or more extensively studied communities. Second, most existing studies examine either microbial or chemical contamination in isolation, leaving a gap in holistic integrated assessments that capture the full spectrum of contamination (Mbae et al., 2023). Third, few studies have systematically combined GIS-based spatial mapping with simultaneous physicochemical and microbial water quality assessment within a single study framework. Fourth, the role of site-specific hydrogeological conditions including soil permeability, water table depth, and seasonal variability in modulating contamination outcomes at the local scale remains inadequately documented for many Zambian settlements. This study addresses these gaps by applying an integrated spatial-laboratory methodology to Kimpwena Settlement, providing context-specific evidence to inform water safety and sanitation planning in Solwezi District.

2.6 Conceptual framework

A conceptual framework provides a visual and theoretical representation of the relationship between key variables in a study. It guided the research by clarifying how independent variables influence the dependent variable and the potential moderating factors that can alter this relationship (Creswell, 2014). In this study, the conceptual framework illustrates how on-site sanitation systems influence groundwater quality in Kimpwena Settlement, Solwezi District (Figure 1).

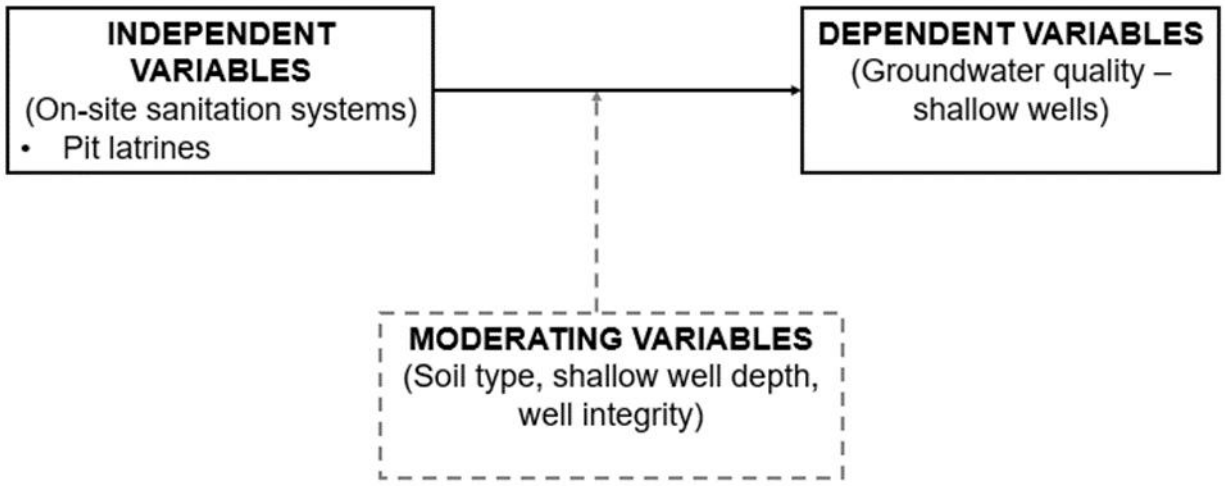


Figure 1 Conceptual framework - influence of on-site sanitation systems on groundwater quality in Kimpwena settlement, Solwezi district

In this framework, the independent variable is the on-site sanitation system, defined by factors such as its type, construction, spatial distribution, and proximity to groundwater sources. The moderating variables include soil permeability, groundwater depth, hydrogeological conditions, well protection status, and the structural integrity of the sanitation facilities, all of which determine the ease with which contaminants can move through the subsurface environment.

The dependent variable is groundwater quality, measured through physicochemical and microbial indicators. The framework assumes that wells located closer to sanitation facilities, particularly within 10 metres are more susceptible to contamination. As distance increases, the influence of sanitation systems on groundwater quality is expected to diminish due to natural filtration and attenuation processes.

Accordingly, the study first maps the spatial distribution of sanitation systems and shallow wells to establish their relative locations. It then analyses physicochemical and microbial parameters of groundwater from selected wells to measure contamination levels. Finally, the relationship between sanitation proximity and groundwater quality is assessed to determine whether closer wells exhibit higher contamination. The conceptual framework therefore illustrates how sanitation system characteristics and environmental conditions interact to influence groundwater quality in Kimpwena Settlement.

3. MATERIALS AND METHODS

3.1 Study Area

The study was conducted in Kimpwena Settlement, located in Solwezi District, North-Western Province of Zambia. With an estimated population of 5,199 residents, Kimpwena is a rapidly growing peri-urban settlement characterised by informal housing patterns, limited access to piped water supply, and heavy reliance on shallow wells as the primary source of domestic water. Approximately 47 on-site sanitation facilities, predominantly pit latrines and septic tanks, serve the settlement. The area is underlain by permeable, sandy soils typical of the region, which facilitate rapid infiltration of leachate but offer limited natural attenuation of contaminants. The shallow water table often accessible at depths of less than 10 m increases groundwater vulnerability to pollution from nearby sanitation infrastructure. Close spacing between residential structures and the absence of formal land-use zoning result in sanitation facilities and shallow wells being co-located in close proximity, often below the WHO (2017) recommended 30 m separation distance.

3.2 Research Design

A descriptive cross-sectional research design was employed, integrating three complementary methodological components: (i) GIS-based spatial mapping and proximity analysis; (ii) sentinel well identification based on distance-gradient stratification; and (iii) laboratory-based physicochemical and microbiological water quality analysis. This design enabled systematic assessment of contamination patterns in a resource-sensitive manner appropriate to the field context. The cross-sectional approach provided a snapshot of groundwater conditions at the time of sampling, facilitating direct comparison of contamination levels across wells representing distinct proximity categories.

3.3 Sampling Strategy and Sentinel Well Selection

All wells and sanitation facilities within Kimpwena Settlement were geolocated using handheld GPS receivers (Garmin eTrex 10). Collected coordinate data were imported into QGIS 3.x for spatial analysis. Within the GIS environment, 10 m and 20 m buffer zones were generated using the Buffer tool to delineate contamination risk zones, and wells were initially classified into three proximity-based strata: high-risk (<10 m from a sanitation facility), moderate-risk (10 - 20 m), and low-risk (>20 m). This stratification was consistent with established WHO guidance and empirical evidence on safe separation distances.

Due to the overlapping spatial distributions of wells and sanitation facilities observed in the field, the study adopted a distance-gradient approach rather than strict categorical stratification. Four sentinel wells were purposively selected to represent a continuum of separation distances from 6 m to 29 m. Well eligibility criteria required that each well:

(i) was actively used for domestic purposes;

(ii) was physically accessible for sampling;

(iii) had a depth not exceeding 25 m; and

(iv) had not been recently treated with disinfectants. Wells that were abandoned, sealed, or inaccessible were excluded, as were deep boreholes exceeding 25 m depth.

The study employed a sentinel-site design in which selected wells were used to examine contamination patterns across a range of well-sanitation separation distances. The approach was intended to provide detailed insight into potential contamination gradients within the settlement and to generate evidence for further investigation

3.4 Water Sampling Protocol

Sampling was conducted in January 2026 during the peak rainy season. Water samples were collected from each sentinel well using sterile 500 mL borosilicate glass bottles, pre-sterilised by pressure-steam autoclaving at 121 °C for 20 - 30 minutes. Each bottle was labelled with well identification number, GPS coordinates, sampling date, and time. Prior to sampling, each well was purged for 2 - 3 minutes to remove stagnant water and ensure collection of fresh groundwater representative of current aquifer conditions. Samples were collected aseptically to minimise contamination, and bottles were filled to approximately 75% capacity. All samples were transported in an insulated cooler maintained at approximately 4 °C and delivered to the laboratory within six hours of collection, consistent with standard sample preservation requirements (American Public Health Association [APHA], 2017).

3.5 Physicochemical Analysis

Physicochemical parameters were analysed in the laboratory following APHA (2017) Standard Methods for the Examination of Water and Wastewater. Parameters measured included: pH using a digital pH meter (Hanna HI98127); electrical conductivity (EC) using a conductivity meter (Hanna HI99301); turbidity using a portable turbidimeter (HACH 2100Q); total dissolved solids (TDS) using a handheld TDS meter; nitrate (NO_3^-) concentrations using UV spectrophotometry; and phosphate (PO_4^{3-}) concentrations using the ascorbic acid colorimetric method. All results were expressed in mg/L, except pH (dimensionless), EC (µS/cm), and turbidity (NTU). Measured values were compared against ZS 190:2010 national drinking water standards and WHO (2017) guidelines.

3.6 Microbiological Analysis

Microbial contamination was assessed using the Membrane Filtration Technique, following WHO (2017) protocols. The parameters analysed were total coliforms and faecal coliforms, both reported as colony-forming units per 100 mL (CFU/100 mL). Filtration utilised 0.45 µm membrane filters with a sterile membrane filtration apparatus. Membranes were incubated on differential media: MacConkey agar and Eosin Methylene Blue (EMB) agar at 37 °C for total coliforms and 44 °C for faecal coliforms, each for 24 hours. Colony counts were performed and results compared against ZS 190:2010 and WHO standards, which mandate zero coliforms in drinking water.

3.7 Data Analysis

Given the purposively selected sample of four sentinel wells, analysis focused on descriptive statistics and pattern recognition along the distance gradient rather than inferential statistical comparison between predefined proximity categories. The analysis examined:

(i) variation in contamination levels with increasing distance from sanitation facilities;

(ii) identification of distance thresholds associated with elevated contamination risk; and

(iii) alignment between spatial proximity measures and physicochemical/microbial indicators. Parameter results were tabulated and spatial mapping from QGIS was used to contextualise contamination patterns relative to the distribution of sanitation infrastructure.

3.8 Ethical Considerations

Ethical clearance was sought from local authorities including the Solwezi District Council and traditional community leadership. The study adhered to principles of voluntary participation, informed consent, and confidentiality. Verbal and written consent was obtained from owners of sampled wells. Participants' anonymity was maintained by removing personal identifiers from GPS and laboratory records. All digital and physical data were stored securely. Study results were communicated to community stakeholders to support improved water safety and sanitation planning.

4. RESULTS

4.1 Spatial Distribution of On-Site Sanitation Systems and Shallow Wells

GIS mapping of Kimpwena Settlement revealed a clustered and largely unregulated spatial arrangement of both on-site sanitation systems and shallow wells across the residential landscape (figure 2). Sanitation facilities and water points were closely co-located within residential clusters, with little evidence of adherence to recommended siting guidelines.

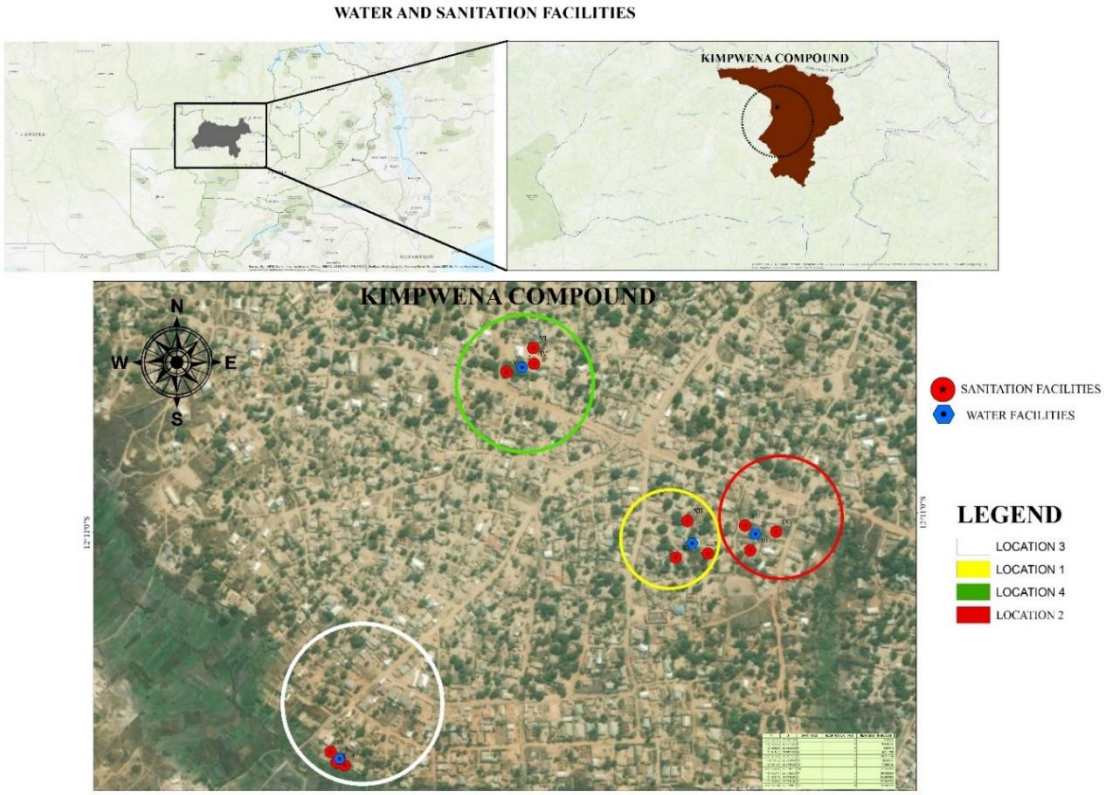


Figure 2: Spatial distribution of on-site sanitation systems and shallow wells

All four sampled wells were situated within 30 m of the nearest sanitation facility, falling below the WHO (2017) and ZS 190:2010 (ZABS, 2019) recommended minimum separation distance of 30 m for pit latrines and similar on-site sanitation systems. Measured well-sanitation distances ranged from 6.00 m to 29.40 m across all sampling locations (Table 1).

Table 1: Distances Between Shallow Wells and Nearest Sanitation Facilities in Kimpwena Settlement

Location	Distance Range (m)	Mean Distance (m)	Risk Classification
Location 1 (Yellow Zone)	24.01 - 29.40	27.00	Moderate-High Risk
Location 2 (Red Zone)	17.40 - 26.30	21.83	Moderate-High Risk
Location 3 (White Zone)	6.00 - 14.00	10.17	High Risk
Location 4 (Green Zone)	16.20 - 28.71	21.80	Moderate-High Risk

Note: All distances fall below the WHO (2017) and ZS 190:2010 recommended minimum separation distance of 30 m.

Location 3 exhibited the shortest well-sanitation distances (6.00 - 14.00 m; mean = 10.17 m), indicating the highest intrinsic vulnerability to groundwater contamination. Location 4 (mean = 21.80 m) and Location 2 (mean = 21.83 m) showed intermediate distances, while Location 1 (mean = 27.00 m) recorded the greatest average separation among the sampled wells, though still below the 30 m threshold. The spatial clustering of sanitation facilities and wells within residential areas reflects the informal settlement pattern of Kimpwena, characterised by high housing density, limited available land, and the absence of formal zoning enforcement.

4.2 Physicochemical Quality of Groundwater

pH values recorded across all four sampling locations ranged from 4.71 to 5.30, universally below the acceptable range of 6.5 - 8.0 specified by ZS 190:2010, indicating that all sampled groundwater sources were acidic and unsuitable for drinking without treatment (Table 2). Location 2 recorded the lowest pH (4.71), followed by Location 4 (5.12), Location 3 (5.29), and Location 1 (5.30).

Electrical conductivity values ranged from 130 µS/cm (Location 4) to 270 µS/cm (Location 3), all noticeably below the ZS 190:2010 permissible limit of 1500 µS/cm, and all locations were classified as satisfactory for EC. A notable gradient was observed, with Location 3 recording the highest EC value, a pattern that, while within standard, suggests comparatively greater ionic loading at this well, consistent with its shorter proximity to sanitation facilities.

Total dissolved solids ranged from 74 mg/L (Location 4) to 156 mg/L (Location 3), all well within the ZS 190:2010 limit of 1000 mg/L. As with EC, a spatial gradient was evident, with TDS increasing from Location 4 toward Location 3, mirroring the pattern of decreasing well-sanitation distance.

Turbidity levels showed considerable variability: Locations 2 and 4 recorded 0 NTU, Location 1 recorded 2 NTU (both satisfactory within the ≤5 NTU limit), while Location 3 recorded 8 NTU, exceeding the permissible standard. The elevated turbidity at Location 3 indicates the presence of suspended particulate matter, consistent with heightened contamination pressure from nearby sanitation facilities.

Nitrate concentrations were extremely low across all locations, ranging from 0.0 to 0.1 mg/L, far below the ZS 190:2010 standard of 10 mg/L. This result was unexpected given the prevalence of pit latrines, which are widely recognised sources of nitrate in shallow groundwater. Potential explanations include dilution from seasonal groundwater recharge, denitrification under anaerobic aquifer conditions, and site-specific soil chemistry limiting nitrification.

Phosphate concentrations exceeded the ZS 190:2010 standard of 1.0 mg/L at three of four locations: Location 1 (1.6 mg/L), Location 2 (2.4 mg/L), and Location 3 (3.2 mg/L). Location 4 recorded exactly 1.0 mg/L and was classified as satisfactory. A clear spatial gradient was observed, with phosphate concentrations increasing progressively with decreasing well-sanitation distance, from Location 4 (greatest mean distance; 1.0 mg/L) to Location 3 (shortest mean distance; 3.2 mg/L).

Table 2: Summary of Physicochemical Water Quality Parameters for All Sampling Locations

Parameter	Location 1	Location 2	Location 3	Location 4	ZS 190:2010 Standard
pH	5.30 (F)	4.71 (F)	5.29 (F)	5.12 (F)	6.5–8.0
EC (µS/cm)	140 (P)	230 (P)	270 (P)	130 (P)	≤1500
TDS (mg/L)	78 (P)	231 (P)	156 (P)	74 (P)	≤1000
Turbidity (NTU)	2 (P)	0 (P)	8 (F)	0 (P)	≤5.0
Nitrate (mg/L)	0.1 (P)	0.1 (P)	0.0 (P)	0.0 (P)	≤10
Phosphate (mg/L)	1.6 (F)	2.4 (F)	3.2 (F)	1.0 (P)	≤1.0

Note: P = Satisfactory (Pass); F = Unsatisfactory (Fail). EC = Electrical Conductivity; TDS = Total Dissolved Solids; NTU = Nephelometric Turbidity Units.

4.3 Microbiological Quality of Groundwater

Microbiological analysis revealed marked differences in contamination across sampling locations. Faecal coliforms were detected only at Location 3, which recorded 224 CFU/100 mL, a severe exceedance of the zero-tolerance standard. Locations 1, 2, and 4 returned no detectable faecal coliforms (Table 3). Total coliform counts similarly identified Location 3 as the most heavily contaminated well (320 CFU/100 mL), while Location 4 recorded a moderate total coliform count of 32 CFU/100 mL despite being negative for faecal coliforms. Locations 1 and 2 were fully compliant with zero total coliform counts.

Table 3: Microbiological Water Quality Results for All Sampling Locations

Parameter	Location 1	Location 2	Location 3	Location 4	ZS 190:2010 Standard
Faecal Coliforms (CFU/100 mL)	0 (P)	0 (P)	224 (F)	0 (P)	0 (absent)
Total Coliforms (CFU/100 mL)	0 (P)	0 (P)	320 (F)	32 (F)	0 (absent)

Note: P = Satisfactory (Pass); F = Unsatisfactory (Fail). CFU = Colony-Forming Units.

4.4 Relationship Between Proximity of Sanitation Facilities and Groundwater Contamination

The findings of this study suggest an inverse distance-contamination relationship across the sampled wells. Location 3, with the shortest mean well-sanitation distance (10.17 m), consistently exhibited the highest contamination levels across multiple parameters: highest turbidity (8 NTU), highest phosphate concentration (3.2 mg/L), highest EC (270 µS/cm), highest TDS (156 mg/L), and the only well with detectable faecal coliforms (224 CFU/100 mL) and the highest total coliform count (320 CFU/100 mL). Conversely, Location 4 (mean distance 21.80 m), while still non-compliant for total coliforms and phosphate, recorded comparatively lower contamination levels for all other parameters.

Location 1, which had the greatest mean separation distance (27.00 m), recorded zero microbial contamination and satisfactory turbidity. However, its phosphate concentration (1.6 mg/L) still exceeded ZS 190:2010 limits, indicating that even at the largest distances observed in this study, chemical contamination from sanitation sources was not fully absent. This suggests that the 30 m separation distance recommended by WHO and ZS 190:2010 may be insufficient under the specific hydrogeological conditions of Kimpwena Settlement, where permeable sandy soils and shallow water tables facilitate more rapid contaminant transport than the standard distance accounts for.

The spatial gradient documented in this study, where contamination intensity diminished progressively with increasing well-sanitation distance, though not reaching safe levels within the observed range is consistent with the distance-decay model of groundwater contamination from point sources. Notably, the absence of nitrate exceedances across all locations, despite detectable phosphate and microbial contamination at closer wells, highlights the importance of parameter-specific contamination dynamics and the potential role of anaerobic denitrification in nitrogen transformation within the aquifer.

5. DISCUSSION

5.1 Spatial Vulnerability of Groundwater in Kimpwena Settlement

The spatial mapping results confirm that Kimpwena Settlement`s groundwater infrastructure carries a high degree of inherent contamination vulnerability. The universal non-compliance with the 30 m separation distance with well-sanitation distances ranging from as little as 6 m to a maximum of 29.40 m, reflects a settlement pattern where informal housing has developed without formal land-use planning or enforcement of sanitation siting regulations. These findings are consistent with spatial studies in comparable African peri-urban contexts, where limited land availability, unregulated housing growth, and weak institutional enforcement routinely result in well-latrine distances well below recommended minima (Kirori et al., 2022).

The clustering of sanitation facilities and wells within densely occupied residential zones creates conditions for cumulative contamination loading, where the aggregate leachate contribution from multiple latrines in close proximity compounds individual contamination risks. This is particularly relevant at Location 3, where the mean well-sanitation distance of 10.17 m likely exposes the well to the simultaneous influence of multiple nearby pit latrines, as evidenced by the compound contamination pattern across microbial, turbidity, and phosphate parameters. Annan et al. (2022) and Robertson (2021) have similarly observed that cumulative loading from clustered latrines generates higher contamination intensities than isolated individual facilities, underscoring the importance of settlement-level spatial analysis rather than point-to-point distance measurement alone.

5.2 Physicochemical Contamination Dynamics

The universal acidity of groundwater samples (pH 4.71 - 5.30) is a significant finding with implications for both water safety and the interpretation of other quality parameters. Acidic conditions in shallow groundwater may be generated by carbon dioxide and organic acids produced during anaerobic decomposition of faecal organic matter, which, when introduced to the subsurface, can lower the pH of adjacent groundwater, consistent with the broader literature on sanitation-related groundwater chemistry (Back et al., 2018; Kirori et al., 2022). However, an alternative explanation deserves consideration: the sandy, low-organic-matter soils characteristic of the Kimpwena region may lack adequate buffering capacity to neutralise naturally generated acidity, creating a background hydrogeochemical condition of low pH that is further depressed by sanitation-related organic inputs. Lapworth et al. (2017) note that acidic groundwater enhances the solubility and mobility of trace metals such as lead and manganese, a concern that warrants investigation in future studies. From a practical perspective, the low pH also compromises the efficacy of household chlorination, since chlorine disinfection is less effective at pH values below 6.5 (WHO, 2017).

Phosphate emerged as the most widespread chemical indicator of sanitation-related contamination in this study, with exceedances at three of four wells ranging up to 3.2 times the permissible limit. The spatial gradient of phosphate (1.0 - 3.2 mg/L across locations ordered by increasing well-sanitation proximity) provides compelling chemical evidence that latrines are contributing phosphate to the shallow aquifer. Although phosphate is generally less mobile than nitrate due to its adsorption affinity for iron and aluminium oxides in soil, the permeable sandy soils of Kimpwena Settlement offer limited adsorption capacity, facilitating its migration to groundwater under the high loading conditions created by multiple nearby latrines (Graham & Polizzotto, 2013). Lapworth et al. (2017) similarly identified phosphate as a reliable tracer of sanitation-derived contamination in sandy-soil peri-urban settings.

The unexpectedly low nitrate concentrations (0.0 - 0.1 mg/L) across all sampled wells stand in contrast to many African peri-urban studies where nitrate exceedances near latrines are frequently reported. Several mechanisms may account for this. First, sampling was conducted during a transitional period, and seasonal recharge dilution can reduce nitrate concentrations even in contaminated wells (Kirori et al., 2022). Second, anaerobic aquifer conditions conducive to denitrification can effectively remove nitrate from solution before it reaches sampling depth (Rama et al., 2022). Third, ammonium, which was not measured in this study, may represent the dominant form of nitrogen in the aquifer, with limited conversion to nitrate under the prevailing geochemical conditions. These results reinforce the view that nitrate alone is an unreliable indicator of sanitation-related contamination across all hydrogeological contexts.

The compliance of EC and TDS values with national standards across all wells, despite concurrent microbial and phosphate exceedances, further illustrates the heterogeneous nature of sanitation-related groundwater contamination. Low EC and TDS do not indicate the absence of contamination; they reflect the relatively modest ionic loading at the current stage of settlement development and the diluting effect of groundwater throughflow in the sandy aquifer. This cautions against the use of EC as a sole proxy for sanitation impact, a point similarly raised by Graham & Polizzotto (2013) and Back et al. (2018).

5.3 Microbiological Contamination and Public Health Implications

The detection of faecal coliforms at 224 CFU/100 mL and total coliforms at 320 CFU/100 mL at Location 3 represents the most acute public health finding of this study. These values confirm unequivocal faecal contamination of the water source and indicate a severe and immediate risk of waterborne disease transmission to residents consuming water from this well without prior treatment (WHO, 2017). Location 3`s short mean distance of 10.17 m from sanitation facilities creates the conditions most favourable to microbial transport: minimal subsurface travel distance for pathogens, reduced opportunity for natural die-off and filtration, and high likelihood of well exposure to runoff from adjacent latrines during rainfall events. These results are directly consistent with the findings of Kirori et al. (2022), who documented faecal coliform counts exceeding 200 CFU/100 mL in Kenyan wells within 10 m of latrines, and with Reaver et al. (2020), who found microbiologically unsafe shallow wells adjacent to unlined latrines in Lusaka District, Zambia.

The detection of total coliforms at Location 4 (32 CFU/100 mL) in the absence of faecal coliforms warrants a different interpretation. Total coliforms include both faecal and environmental (non-faecal) bacterial groups. Their presence without accompanying faecal coliforms suggests that Location 4 may be experiencing intrusion of environmental bacteria through inadequate well protection, a compromised casing, absent or damaged cover, or insufficient drainage apron rather than direct faecal infiltration from adjacent latrines (Robertson, 2021). This distinction matters for intervention design: while Location 3 requires urgent attention to the sanitation-groundwater proximity problem, Location 4 may be adequately addressed through structural well improvements. The clean microbiological results at Locations 1 and 2, despite their sub-standard well-sanitation distances, may reflect the natural attenuation provided by the greater separation distance (means >21 m), though the persistence of phosphate exceedances at both locations indicates that chemical contamination pathways remain active.

5.4 Adequacy of the 30 m Separation Distance Standard

The findings suggest that contamination may persist at distances approaching 30 m under the hydrogeological conditions of Kimpwena Settlement. For example, even at the largest observed distances (24.01 - 29.40 m at Location 1), phosphate contamination persisted above permissible limits, suggesting that contamination plumes from pit latrines can extend beyond 24 m in the permeable sandy soils of the study area. Graham & Polizzotto (2013) and Rama et al., (2022) have argued that site-specific hydrogeological assessments should inform separation distance recommendations, as the standard 30 m guideline was derived under generalised soil conditions and may be insufficient in highly permeable substrates with shallow water tables. This finding has direct implications for local planning authorities, who should consider adopting context-specific siting standards, potentially extending the minimum separation distance or requiring lined latrines and sealed septic systems in settings where sandy soils and shallow water tables prevail.

5.5 Broader Implications for Peri-Urban Water Safety in Zambia

The results from Kimpwena Settlement contribute to a growing body of evidence that groundwater contamination from on-site sanitation is a systemic challenge across Zambian peri-urban areas. The patterns documented here mirror findings from Lusaka (Reaver et al., 2021), and the broader sub-Saharan African peri-urban context (Kirori et al., 2022; Robertson, 2021), confirming that the intersection of informal settlement patterns, high sanitation density, permeable soils, and shallow water tables creates persistent groundwater vulnerability that transcends any single locality. Mbae et al. (2023) project that these risks will intensify as informal settlements expand unless proactive spatial planning and sanitation infrastructure improvements

are prioritised. The policy implications are clear: protecting groundwater in peri-urban Zambia requires integrated water-sanitation governance frameworks that link land-use planning, sanitation regulation, and water source protection under a coherent institutional mandate.

6. CONCLUSIONS

This study provides the first empirically grounded, spatially integrated assessment of shallow groundwater quality and on-site sanitation influence in Kimpwena Settlement, Solwezi District, Zambia. The results lead to four primary conclusions, which should be interpreted in light of the small sentinel sample size and single-season sampling design:

First, GIS spatial analysis confirmed that all sampled wells are located within 30 m of sanitation facilities (range: 6.00 - 29.40 m), universally failing to comply with WHO and ZS 190:2010 recommended minimum separation distances. The spatial clustering of latrines and wells reflects the informal and unregulated nature of settlement development in Kimpwena, creating an inherently high-vulnerability groundwater environment.

Second, the results imply that physicochemical and microbiological quality of shallow groundwater in Kimpwena is compromised. Universal groundwater acidity (pH 4.71 - 5.30), widespread phosphate exceedances at three of four wells, and severe microbial contamination at the well closest to sanitation facilities (faecal coliforms: 224 CFU/100 mL; total coliforms: 320 CFU/100 mL) render multiple water sources unsafe for domestic consumption without treatment. EC, TDS, and nitrate values were within acceptable limits, reflecting the relatively early stage of ionic loading and possible denitrification dynamics.

Third, the findings suggest an inverse distance-contamination relationship, with wells at shorter separation distances exhibiting higher contamination levels across microbial, turbidity, and phosphate parameters. The persistence of phosphate exceedances even at the greatest distances observed (>24 m) suggests that the 30 m standard may be insufficient under the local hydrogeological conditions.

Fourth, on-site sanitation systems have a measurable and significant influence on shallow groundwater quality in Kimpwena Settlement. Without targeted interventions, the risk to public health is likely to increase as the settlement continues to grow.

These findings emphasise the urgent need for: stricter enforcement of sanitation siting regulations with site-specific separation distances; upgrading of sanitation infrastructure to lined pits and sealed septic systems; structural improvement of shallow wells; community education on water safety and safe sanitation practices; and establishment of a routine groundwater quality monitoring programme in Kimpwena. Future research should address seasonal variability in contamination levels, include additional parameters such as ammonium and heavy metals, employ larger sample sizes, and integrate hydrogeological modelling to improve spatial predictions of contamination risk.

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