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Seasonal Variations of Microbial Water Quality from Shallow Wells and Prevalence of Water-Related Diseases

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Abstract

Microbiological contamination of drinking water remains a critical global health concern, contributing to approximately five million deaths annually. In Sub-Saharan Africa, inadequate access to safe drinking water sources results in over one million deaths each year, with nearly 90% occurring among children. This study investigated the seasonal variation of microbial water quality from shallow wells and the prevalence of water-related diseases. Water samples were collected during the dry and wet seasons and analyzed for total coliforms and *Escherichia coli* using the membrane filtration method. Additionally, water temperature and pH were measured onsite. The mean total coliform count increased from 79 CFU/100 mL in the dry season to 124 CFU/100 mL in the wet season, while the mean *E. coli* count increased from 26 CFU/100 mL to 55 CFU/100 mL. In both seasons, total coliform and *E. coli* counts exceeded the World Health Organization's zero threshold for coliforms in drinking water. The prevalence of water-related diseases was higher during the wet season, aligning with the increased microbial contamination. The bacteriological contamination of shallow wells indicates that these water sources are contaminated and unsuitable for human consumption. The findings underscore the need for point-of-use water treatment using various methods, including chlorination and slow sand filtration to safeguard public health.

Keywords

Escherichia coli, Shallow Wells, Microbiological Water Quality, Water-Related Diseases

1. Introduction

Water quality, particularly the microbiological quality of groundwater, is a key determinant of public health (Atobatele & Owoseni, 2023; Genter et al., 2023). In many low and middle-income countries, groundwater serves as a primary source of drinking and domestic use, yet it remains highly vulnerable to contamination (Abanyie et al., 2023; Bagordo et al., 2024; Wu et al., 2025; Syifa et al., 2025; Tadele & Tekile, 2025). Globally, about 2.2 billion people cannot access safe drinking water (WHO, 2019; WHO/UNICEF, 2021), with the majority recorded in Sub-Saharan Africa. In this region, bacterial contamination of drinking water sources remains a major public health challenge, particularly in rural communities where many households depend on unimproved water sources, such as shallow wells (Gwimbi et al., 2019; Machona et al., 2025). These sources are highly susceptible to fecal contamination, increasing the risk of waterborne diseases if water from them is consumed without prior treatment (Javaid et al., 2022; Kwikima, 2024; Breternitz et al., 2024).

Contamination of water sources affects water quality and threatens human health, economic development and social prosperity (Sahoo & Goswami, 2024; Bazaanah & Mothapo, 2024). In Zambia, out of a population of 13 million, approximately 6 million people, particularly those living in settlements, lack access to clean water and sanitation (UN-Habitat, 2023). This significant disparity puts these populations at high risk for diarrheal diseases linked to contaminated water. By 2019, it was estimated that 1.8 billion people still consumed contaminated water and 2.4 billion people lacked adequate sanitation worldwide (WHO, 2019). Ensuring the microbiological safety of groundwater sources remains a significant challenge, especially for vulnerable populations (Lund Schlamovitz & Becker, 2021). The struggle to extend safe water services to impoverished communities increases their risk of exposure to contaminated drinking water.

A wide range of pathogenic microorganisms can be found in groundwater, with bacteria being the primary cause of waterborne disease outbreaks (Njuguna, 2016). Notable bacterial pathogens include *Salmonella* spp., *Shigella* spp., *Vibrio cholerae*, and *Escherichia coli* (*E. coli*). Among these, *Escherichia coli* (*E. coli*) bacteria is widely recognized as a key indicator of fecal contamination in drinking water, its presence suggests potential contamination from human or animal waste. *E. coli* can persist in water for 4 to 12 weeks, depending on the environmental conditions (Khan & Gupta, 2020; Suehr et al., 2020; Yang et al., 2025). Studies have shown that seasonal variations may significantly influence microbial water quality, affecting the transport, survival and concentration of pathogenic bacteria (Dongzagla et al., 2021; Ayeni et al., 2023; Caballero et al., 2024; Thilakarathna et al., 2025). During the wet season, increased rainfall and surface runoff introduce contaminants from surrounding areas into groundwater, leading to higher microbial loads. In contrast, the dry season can result in a concentration effect due to reduced water volume, potentially increasing the presence of harmful bacteria in stagnant water (Bouchaou et al., 2024; Water and Development, 2024). These seasonal fluctuations heighten public health risks, contributing to the spread of waterborne infections such as diarrhea, cholera, and typhoid (Siamalube et al., 2024). High contamination levels in groundwater sources are usually linked to the proximity of pit latrines, as well as flooding events during the wet season (Ashuro et al., 2021). In contexts where groundwater is the main source of water, the use of pit latrines is highly discouraged unless specific conditions such as a deep water table or soil characteristics that limit contaminant migration are met (Islam Farhan & Alim Miah, 2024). While increasing the distance between wells and sanitation systems could help mitigate contamination, this solution is often impractical in informal settlements where space is limited and regulatory frameworks are weak (Mwevura et al., 2021).

The World Health Organization (WHO) emphasizes the need for routine monitoring of microbial indicators, such as *E. coli*, to assess water quality and minimize health risks (WHO/UNICEF, 2015). Additionally, physicochemical parameters including temperature and pH play a critical role in determining water safety (Shamsudin et al., 2017; Kothari et al., 2020; Volf et al., 2024). Understanding seasonal variations in microbial contamination is essential for developing effective water management strategies and improving water treatment practices, particularly in communities that depend on groundwater sources. The failure to monitor water resources and sanitation services could hinder the goal of improving water and sanitation as outlined in the Zambian 8th National Development Plan (MFNP, 2022). Therefore, the aim of this study was to investigate the seasonal variations in the microbiological quality of shallow well water and prevalence of water-related diseases, focusing on indicator bacteria and key physicochemical parameters in order to contribute to strategies for enhancing and monitoring water safety in affected communities.

2. Methods

2.1. Study Area

The study was conducted in the Copperbelt province in Kitwe district in Ipusukilo informal settlement in Zambia, located at latitude 12˚45' S and longitude 28˚20' E (**Figure 1**). The area has a population of 31,405 distributed in three distinct zones stretching along the Kafue River basin. The region experiences a mean annual temperature of 23˚C and an average annual precipitation of 1226 mm (Banda, 2023).

2.2. Sampling Procedure

Administratively, Ipusukilo settlement is divided into three distinct sections (Macwani et al., 2009). The areas of interest were the zones using shallow well water for their drinking use. Based on this criterion, Zones 1 (Southeast), 2 (Southwest), and 3 (Northwest) were purposively selected as strata. A total of 16 wells were then randomly selected from these zones for microbial water quality sampling. Water samples were collected in triplicate from each site in October (dry season) and December (wet season). Giving a total of 48 water source samples in the dry and wet season. GPS coordinates for the sampled shallow wells were collected and are presented in Figure 1.

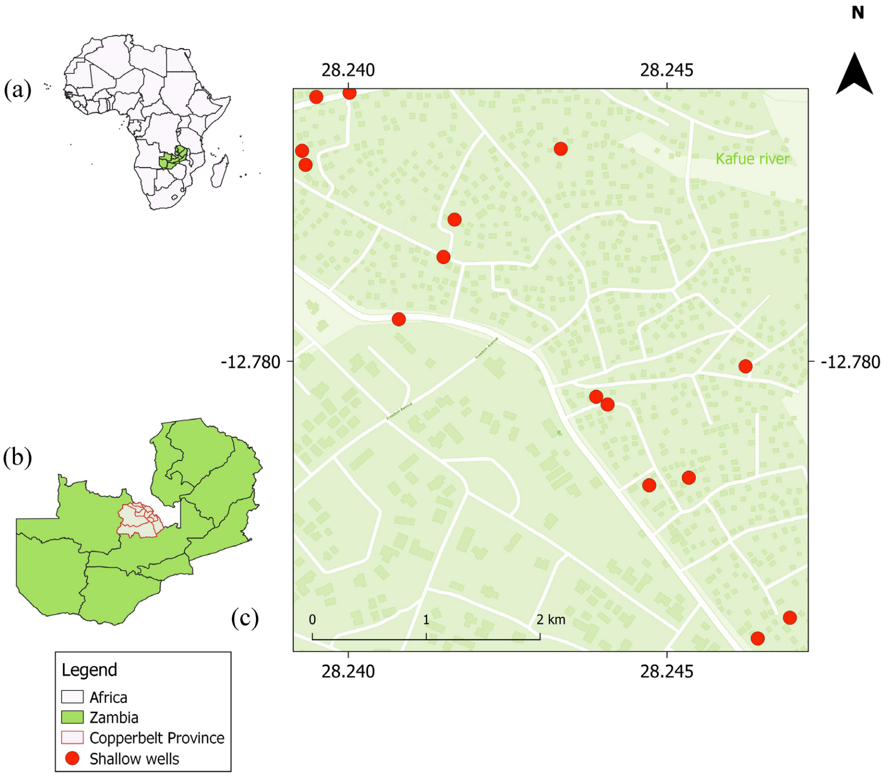

Figure 1. Location of Zambia in the African continent (a). Location map of the country Zambia (b). Sampled shallow wells in Ipusukilo settlement (c).

2.3. Physicochemical Parameter Analysis

The pH and temperature of water were measured on-site using a multi-parameter. This was done by dipping the electrode of the calibrated instrument into the sample and allowing it to stabilize to give a reading. It was then rinsed with deionized water before being used to measure other samples.

2.4. Microbial Analysis

The sample collection procedures were based on the American Public Health Association (APHA, 2005) standards. Water samples for microbial analysis were collected using sterilized 500 ml high-density polyethylene (HDPE) bottles to avoid contamination. Sterile gloves were worn, and care was taken to avoid contact with the bottle's interior. The bottles were rinsed with the sampled water and sealed after filling. Samples were stored in a cool box at 4˚C and transported to the Department of Environmental Engineering Laboratory at Copperbelt University for analysis within six hours.

The Membrane Filtration Technique was used to analyze water quality from shallow wells for total coliform and *E. coli* concentrations. The setup included a filter holder, a 0.45 µm sterile membrane filter, and a vacuum pump. A 100 mL water sample was drawn through the membrane filter, which collected coliform bacteria. This filter was then placed onto a selective growth medium using forceps (APHA, 2005). For total coliform detection, M-Endo Agar was used and incubated at a temperature range of 35˚C to 37˚C for 24 hours. *E. coli* was identified using HiChrome and incubated at 35˚C for 24 hours. After incubation, the petri dishes were removed and examined for bacterial growth. The colonies were then counted using a colony counter. On M-Endo Agar, total coliform colonies appeared as red or pink with a metallic sheen, while *E. coli* colonies displayed a blue color on HiChrome.

The total bacterial count in every 100 mL was reported as Colony Forming Units (CFU) per 100 mL calculated using the formula:

$$\frac{\text{CFU}}{100\ \text{mL}} = \frac{\text{Number of CFU}}{\text{Volume of water filtered}} \times 100\ \text{mL} \tag{1}$$

2.5. Sanitary Survey

A sanitary survey was conducted at each sampling site during water sample collection process. The sanitary survey followed a standardized format that was adopted by Lloyd & Bartram (1991). The sanitary scores from shallow wells were plotted against *E. coli* counts to evaluate their relationship.

2.6. Prevalence of Water-Related Diseases

Clinical health records from the health facility in the settlement were reviewed to identify the most prevalent water-related diseases a year before the study period. The data collected included the age and the specific disease recorded during the dry and wet seasons. The prevalence rates of water-related diseases were calculated using the equation below:

$$PR = \frac{P}{N} \times 100 \tag{2}$$

where PR denotes the prevalence rate, P denotes all persons with a specific condition at one point in time, and N means population in the target area.

2.7. Data Analysis

Descriptive statistics, including the mean and standard deviation, were used to summarize the data on microbial water quality. The Shapiro-Wilk test was performed to assess data normality. Furthermore, Pearson correlation tests were conducted to explore the relationships between total coliform and *E. coli* levels and the physicochemical parameters of water during both dry and wet seasons. A paired t-test was used to determine if there were any significant seasonal variations in microbial water quality. All statistical analyses were conducted using R Studio software.

2.8. Ethical Consideration

The study protocol was approved by the Ethics Committee of Egerton University EUISERC/APP/364/2024 and the Ethics Committee of the Tropical Diseases Research Centre TDREC237/10/24. Authorization to conduct the study was granted by the Zambia National Health Research Council NHRA-1612/05/10/2024 and the Zambia Provincial District Health Office.

3. Results and Discussion

3.1. Physicochemical Water Quality

Temperature varied slightly between seasons, measuring 27.2˚C ± 0.5˚C in the wet season and 27.5˚C ± 0.3˚C in the dry season **Table 1**. Shallow wells exhibited higher temperatures in both seasons, likely due to their proximity to the surface and direct exposure to the sun (Morris et al., 2003). Mean pH values remained within the WHO guideline range of 6.5 - 8.5. The pH increased from 6.6 ± 0.5 in the dry season to 7.2 ± 0.5 in the wet season. The high mean pH value recorded in the wet season is likely due to increased organic matter dissolution following rainfall events, as suggested by Chauque et al. (2021).

Table 1. Summary of physicochemical parameters of shallow wells.

Parameter	Dry Season	Wet Season	WHO limit
Temperature (˚C)	27.5 ± 0.3	27.2 ± 0.5	
pH	6.6 ± 0.5	7.2 ± 0.5	6.5 - 8.5

3.2. Microbiological Water Quality

Total coliform counts were 79 ± 24 CFU/100 mL in the dry season and 124 ± 40 CFU/100 mL in the wet season. *Escherichia coli*, a key indicator of microbial contamination, measured 26 ± 16 CFU/100 mL in the dry season and 55 ± 20 CFU/100 mL in the wet season. Both exceeded the WHO guideline of 0 CFU/100 mL, indicating bacterial contamination (**Figure 2**).

The presence of *E. coli* in a water source suggests fecal contamination and the potential presence of harmful pathogens and other bacteria that can cause water-related diseases. The results revealed that contamination of drinking water with *E. coli* was 87.5% and 100% during the dry and wet seasons, respectively. Shallow wells, particularly in informal settlement areas, are highly susceptible to contamination due to their limited depth (Nayebare et al., 2022). Several studies have reported fecal contamination of shallow wells. For instance, research conducted by Haramoto (2018) in Nepal found that 100% of the sampled shallow wells contained detectable levels of *E. coli*, a finding that aligns with the results of the current study. Similarly, Segut et al. (2024) reported that 80.6% of shallow wells in Kenya were contaminated with fecal coliforms, which is notably higher than the 60% contamination rate observed in shallow wells in Ethiopia (Gizachew et al., 2020).

3.3. Seasonal Variation

The World Health Organization (WHO) provides guidelines to help assess the safety of drinking water based on classified risk levels of *E. coli* contamination

(WHO, 2017). Water that falls into the high-risk category is considered unsafe and has a higher chance of causing waterborne diseases (Saima et al., 2023; Yang et al., 2025). In this study, 75% of shallow wells during the dry season fell within the high-risk category (11 - 100 CFU/100 mL). Contamination levels worsened in the wet season, where all sampled shallow wells (100%) exceeded the WHO zero threshold for safe drinking water, placing them in the high-risk category (**Table 2**).

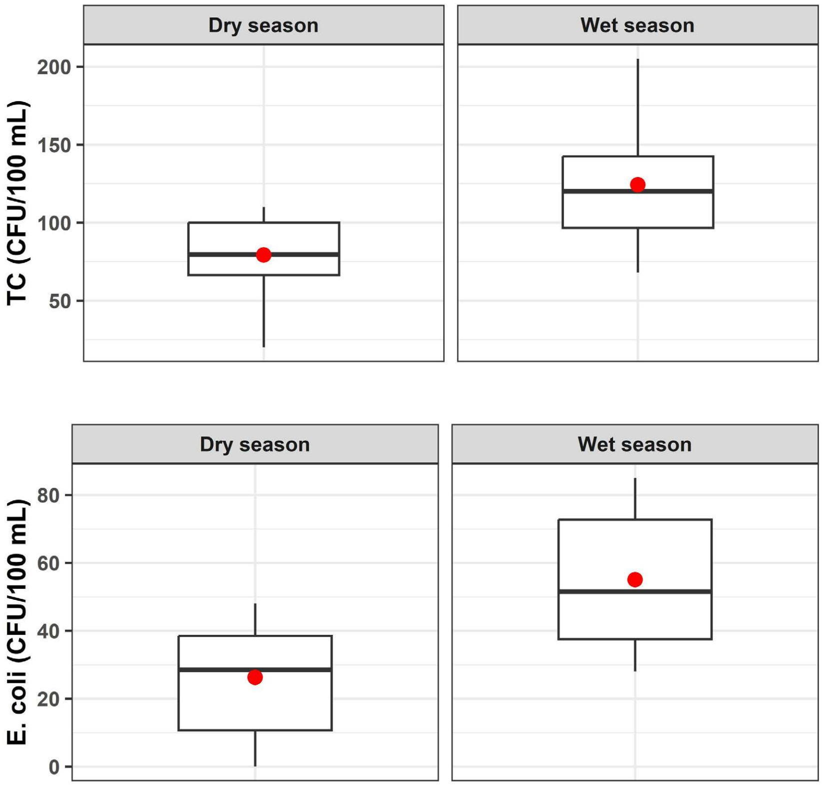

Figure 2. Box plots displaying total coliforms (upper panel) and *E. coli* (lower panel) for shallow wells during the dry and wet seasons. The red dot represents the mean counts for each category.

Table 2. Percentage distribution of *E. coli* contamination risk levels in shallow wells.

E. coli counts (CFU/100 mL)	Percentage (Dry season)	Percentage (Wet season)	Risk
0	12.5%	-	Low risk/safe
1 - 10	12.5%	-	Intermediate risk
11 - 100	75%	100%	High risk

A paired t-test revealed significant seasonal variation of bacteria counts in water sources. Total coliform counts were lower during the dry season than the wet season ($p < 0.001$) and *E. coli* counts were lower during the dry season than during the wet season ($p < 0.001$) (**Table 3**).

Table 3. Paired t-test comparing total coliform and *E. coli* concentrations between the dry and wet seasons.

Parameter	Pair	*t*
Total coliforms (CFU/100 mL)	Dry/Wet	−14.38**
E. coli (CFU/100 mL)	Dry/Wet	−9.69**

**Significant at $p < 0.001$.

The seasonal fluctuation observed underscores the heightened vulnerability of drinking water sources to microbial contamination during the wet season, thereby posing significant public health risks (Berihun et al., 2023). The relationship between rainfall patterns and water quality deterioration has been observed in several regions including, Ghana, Nigeria, Guatemala, and Sri Lanka. Studies have shown that the wet season significantly increases microbial contamination in water sources (Dongzagla et al., 2021; Ayeni et al., 2023; Caballero et al., 2024; Thilakarathna et al., 2025). This trend suggests that increased rainfall not only facilitates the transport of pathogens but also creates favorable conditions for bacterial proliferation, further compromising water quality.

The role of hydrogeological factors in influencing water quality cannot be overlooked. During the wet season, rising water tables, increased infiltration, surface runoff, and rapid recharge of shallow aquifers facilitate the transport of pathogens into groundwater. These wells, which often lack adequate casing or protective barriers, become highly susceptible to contamination from surrounding environments, particularly from sanitation facilities such as pit latrines (Machona et al., 2025). Rainwater infiltration can introduce fecal matter from human waste into groundwater supplies, significantly increasing bacterial loads. The absence of effective drainage systems in settlement areas further exacerbates the situation, allowing contaminated water to stagnate and seep into drinking water sources (McGill et al., 2019; Awuah, 2024).

The complexities of groundwater quality dynamics have also been illustrated by Kanyerere et al. (2012), who noted that in Malawi, variations in seasonal patterns of contamination can be attributed to localized environmental conditions and sanitation practices. However, the findings of this study contrast with results from Uganda (Nayebare et al., 2022), where higher microbial counts were reported during the dry season. The high *E. coli* counts during the dry season were attributed to the greater accumulation of fecal matter at the land surface and less-diluted, fecally contaminated recharge. In some arid and semi-arid regions, reduced availability of water during the dry season may lead to water stagnation and higher concentrations of contaminants, explaining the observed differences (Bouchaou et al., 2024; Water and Development, 2024).

3.4. Relationship between Microbial and Physiochemical Parameters

The relationship between microbial and physicochemical parameters was assessed using the Pearson correlation coefficient to evaluate the strength of association between *E. coli*, total coliforms, temperature, and pH. The correlation coefficient ranges between −1 and +1. A correlation coefficient of ±0.1 to ±0.39 represents a weak linear relationship, while a coefficient between ±0.4 and ±0.69 indicates a moderate correlation. A strong correlation is observed within the ±0.7 to ±0.89 range and coefficients from ±0.9 to ±1.0 reflect a very strong linear association (Schober & Schwarte, 2018). The results of the statistical testing for the relationship between the variables are presented in **Figure 3**.

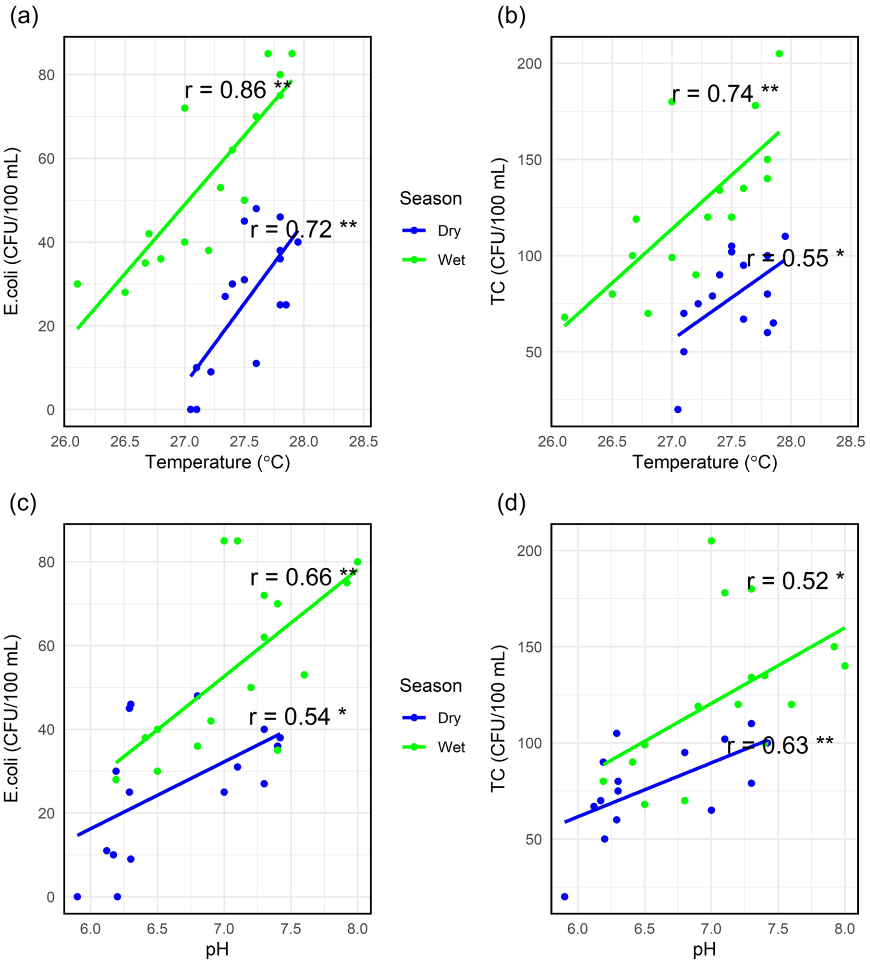

Figure 3. Relationships between physicochemical parameters and *E. coli* (left), total coliform (right) across the dry and wet seasons. Significant results are marked with an asterisk: $p < 0.05$ (*), $p < 0.01$ (**).

Temperature significantly influenced microbial proliferation more so than die-off, as evidenced by the positive correlation with coliform bacteria. Specifically, *E. coli* showed a significant positive correlation with temperature during the dry season (r = 0.72, $p = 0.002$; **Figure 3(a)**) and the wet season (r = 0.86, $p = 0.001$). Additionally, pH was also positively correlated with *E. coli* during both the dry season (r = 0.54, $p = 0.032$) and the wet season (r = 0.66, $p = 0.005$; **Figure 3(c)**). For total coliforms, a positive correlation was observed with temperature in the dry season (r

= 0.55, *p* = 0.028; **Figure 3(b)**) and wet season (r = 0.74, *p* = 0.001), and with pH in both the dry (r = 0.63, *p* = 0.009) and wet seasons (r = 0.52, *p* = 0.041; **Figure 3(d)**). These findings are consistent with those of Shamsudin et al. (2017) in Malaysia, who reported a strong correlation between *E. coli* and both pH (r = 0.9) and temperature (r = 0.76), highlighting the role of these physicochemical parameters in supporting microbial growth when sufficient nutrients are present. Similarly, a mean temperature of 32˚C was associated with increased *E. coli* counts in Kenya (Powers et al., 2023), Bangladesh and Nepal, but decreased *E. coli* counts in Tanzania (Charles et al., 2022). The pH of water can influence the survival and growth of coliform bacteria in water (Suehr et al., 2020). In this study, the pH levels recorded from shallow wells fell within the World Health Organization accepted range of 6.5 to 8.5 for drinking water. Exceeding this range can negatively impact the survival and proliferation of coliform bacteria (Hong et al., 2010). The positive correlation identified in this study aligns with findings from Nigeria by Olalemi et al. (2021) who demonstrated a similar positive relationship between *E. coli* and pH levels in well water. Additionally, the results agree with the work of Youssef et al. (2014) in Morocco, who reported a comparable positive correlation.

3.5. Sanitary Survey

A sanitary survey was conducted for each of the selected shallow wells using the sanitary survey questionnaire (Lloyd & Bartram, 1991). The total risk scores obtained were compared to the established risk categories (Etang, 2000; WHO, 2017) and are presented in **Table 4**. These scores remained unchanged throughout the study period. The results indicated that 50% of the wells were classified as high risk, while 12.5% were categorized as very high risk, with scores ranging from 9 to 10. Additionally, 18.75% of the wells fell into the intermediate risk category, whereas the remaining 18.75% were classified as low risk.

Table 4. Sanitary survey of the shallow wells in the study area.

Risk*	Frequency (%)	Remedial action
Very high risk	2 (12.5)	Urgent action
High risk	8 (50)	High action priority
Intermediate risk	3 (18.75)	High action priority
Low risk	3 (18.75)	Low action priority
No risk	0 (0)	No action

*Sanitary risk score: 9 - 13 = very high; 6 - 9 = high; 3 - 5 = intermediate; 0 - 2 = low (Lloyd & Bartram, 1991).

The sanitary risk scores from shallow wells were plotted against *E. coli* counts, revealing a positive non-significant correlation during the dry season (*p* = 0.106) and the wet season (*p* = 0.434) (**Figure 4**). The lack of statistical significance supports the limitation of sanitary surveys in predicting water quality as reported by Snoad et al. (2017) and Misati et al. (2017). The findings of this study indicate that while the overall sanitary risk score did not correlate with *E. coli* presence, specific risk factors such as proximity of the well to the pit latrine ($p = 0.025$), exposed rope and bucket ($p = 0.025$) and poorly sealed well walls ($p = 0.05$) showed a significant association with *E. coli* presence. These findings contrast with those of Luby et al. (2008), where individual risk factors did not show a significant association with microbial water quality, but agree with the findings of Ercumen et al. (2017) in Bangladesh, where individual components of the sanitary risk were associated with the presence of *E. coli*. Similarly, Tadele & Tekile (2025) identified five risk factors associated with the presence of coliforms. This suggests that while the composite sanitary risk score may not correlate with *E. coli* presence, specific sanitary risk factors can significantly be associated with microbial water contamination.

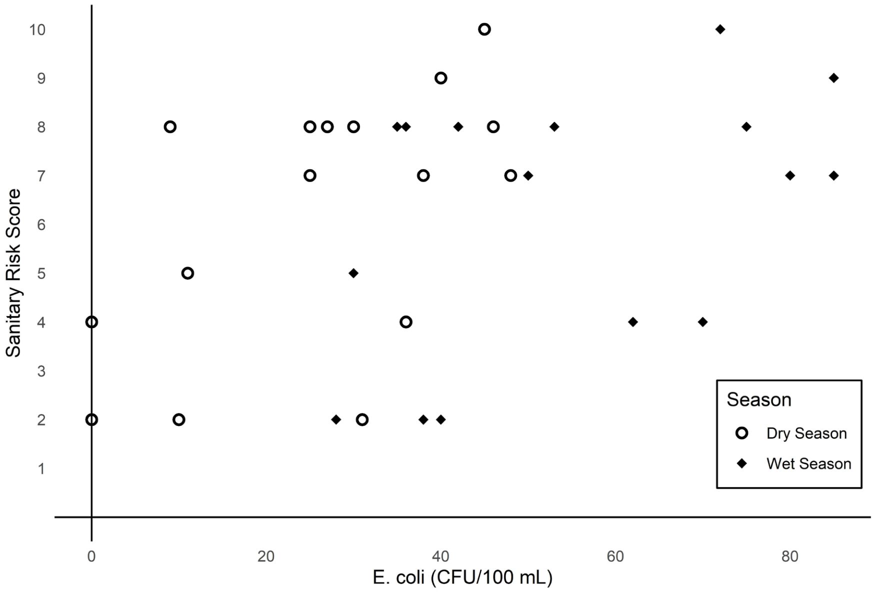

Figure 4. Scatter plot of *E. coli* counts versus sanitary risk scores.

The shallow wells in the study area are hand-dug, and water is drawn manually using a rope and a plastic bucket. The repeated use of the rope, which often comes into contact with the ground before being submerged back into the water, can introduce bacteria from contaminated surfaces, further compromising water quality (Gnimadi et al., 2024). Additionally, most wells in the study area are of the open type and lack protective brick or stone linings along the sides, a feature similarly observed by Grönwall et al. (2010).

Physical barriers, such as concrete covers and slabs for shallow wells, may provide protection against surface runoff contaminated with fecal matter. However, in areas with a high water table, the risk of well contamination is heightened by underground seepage, particularly when well walls are inadequately sealed. This risk is further exacerbated when wells are located near pit latrines, as the use of pit latrines has been recognized as a contributing factor to groundwater contamination (Elisante & Muzuka, 2016; Rivett et al., 2022; Hinton et al., 2024; Odewade et al., 2025). It is recommended that wells should be located at least 30 meters or more, away from pit latrines (Tillett, 2013; Ngasala et al., 2021; Nenninger et al., 2023). In Ipusukilo, where the water table is high the proximity of wells to pit latrines may likely increase the risk of contamination from fecal matter. A study by Ashuro et al. (2021) in Ethiopia, found that the presence of latrines uphill from water sources was associated with fecal coliform contamination, likely due to the downward movement of contaminants through surface runoff or groundwater seepage. This implies that the landscape and hydrological dynamics play a critical role in the extent of fecal contamination.

3.6. Prevalence of Water-Related Diseases

The prevalence rates of water-related diseases based on the season are presented in **Figure 5**. The most prevalent water-related disease during the dry season was diarrhea, with 245 cases reported. The most prevalent diseases in the wet season were cholera and diarrhea. The seasonal fluctuation highlights the significant public health risks posed by waterborne diseases, particularly during the wet season when microbial contamination peaks (Siamalube & Ehinmitan, 2024). Water-related diseases pose a major threat to public health in areas with limited access to safe drinking water, sanitation, and hygiene (Battersby et al., 2019; WHO, 2024). The consumption of contaminated drinking water is a major transmission route for pathogens responsible for diseases such as diarrhea, cholera, typhoid fever, and dysentery (Mapingure et al., 2024). *E. coli*, a fecal indicator bacterium, is strongly associated with gastrointestinal infections, which can lead to severe dehydration and in extreme cases, mortality, particularly among young children and older individuals (Okesanya et al., 2024). The increased prevalence of *E. coli* contamination in the wet season observed in this study is consistent with higher incidences of waterborne disease outbreaks during periods of heavy rainfall. This highlights the importance of implementing effective water treatment, improving sanitation, and implementing public health interventions to mitigate the risks associated with microbial contamination and ensure access to safe drinking water.

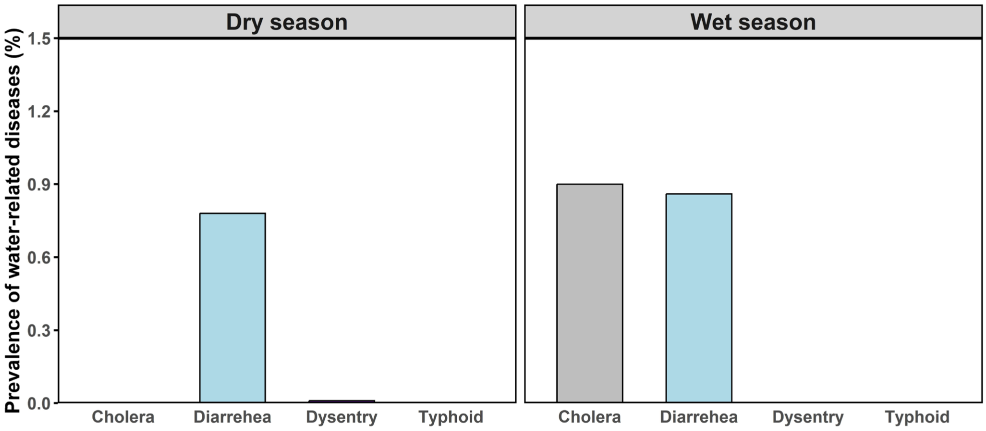

Figure 5. Prevalence of water-related diseases in the study area during the dry and wet season.

4. Conclusion

The high bacteriological contamination observed in the study area renders shallow well water unsuitable for human consumption without prior treatment. In both seasons, *E. coli* and total coliform levels exceeded WHO guidelines, underscoring the persistent microbial risks associated with these water sources. Seasonal variations played a role in microbial water quality, with higher contamination levels observed during the wet season. This seasonal influence suggests that increased surface runoff and rising groundwater levels may contribute to fecal contamination, further exacerbating the risk of waterborne diseases. Our findings reveal that the prevalence of water-related diseases was higher during the wet season, aligning with the elevated microbial contamination levels.

To reduce the risks of water-related diseases and ensure safer drinking water, we recommend strengthening WASH (Water, Sanitation, and Hygiene) infrastructure by expanding access to piped water and enhancing well protection measures. Local authorities should establish clear guidelines for well construction to ensure wells are properly built and protected from contamination sources. Additionally, community education programs should emphasize the importance of concrete well covers to prevent surface runoff infiltration, and raise awareness on risks associated with well water contamination. Furthermore, regular microbial water quality monitoring is also crucial for identifying contamination trends between seasons and guiding targeted sanitation improvements.

Limitations

The selected microbial indicators are essential for assessing microbial contamination in water. However, this study did not account for all potential pathogens that could pose significant health risks. This underscores the need for further research incorporating additional microorganisms, such as *Vibrio cholerae*, *Salmonella* spp., and *Shigella* spp., to improve the comprehensiveness of water quality assessments across various settlements.

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Conflicts of Interest

The authors declare no conflicts of interest.

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