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Sanitary inspection and microbial health risks associated with enteric bacteria in groundwater sources in Ilara-Mokin and Ibule-Soro, Nigeria

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ABSTRACT

This study set out to determine the sanitary risk scores and microbial health risks associated with wells and boreholes in Ilara-Mokin and Ibule-Soro, Nigeria. Water samples ($n = 96$) were collected over a period of five months to determine the levels of enteric bacteria and to perform a Quantitative Microbial Risk Assessment (QMRA) of drinking water quality. Sanitary risk scores revealed `medium' and `low' overall risks for the wells and boreholes, respectively. Three risk factors (faulty fence; small apron; pollution sources) exhibited high significant ($p < 0.01$) association with the presence of *E. coli* and thermotolerant coliforms in water samples from the wells. *E. coli* and *Salmonella* ranged from 1.82 to 2.28 and 2.15 to 2.63 $\log_{10}$ CFU/100 ml respectively in water from the wells, but were below detection limit in water from the boreholes. *Shigella* and *Campylobacter* were detected in all water samples. Estimated risks of infection associated with *Shigella* (2.1×10^{-2} to 2.3×10^{-1}) were higher than those of *Campylobacter* (6.7×10^{-2} to 1.9×10^{-1}) and *Salmonella* (1.9×10^{-3} to 5.6×10^{-3}). Adaption of water safety plans may be advantageous in these settings, since intentional ingestion of water from the wells and boreholes may pose potential risks of diarrheal illness to humans.

Key words: drinking water, enteric bacteria, human health, sanitary inspection, water safety plan

HIGHLIGHTS

- Sanitary risks and water samples were collected from wells and boreholes.
- Microbial risk assessment was used to evaluate human dose-response data.
- Sanitary risk scores correlated positively with microbial water quality.
- Risk factors exhibited significant association with the presence of *E. coli*.
- Estimated risks of infection associated with *Shigella* were higher than those of *Campylobacter* and *Salmonella*.

INTRODUCTION

Faecal contamination of drinking water sources has been adjudged to pose significant risks to human health (WHO 2006; 2017). In many low- and middle-income countries, households use pit-latrine, pour-flush toilets leading to a pit or septic tank, while some households in poor neighbourhoods practice open defecation. These factors, including inadequate hygiene, sewage disposal systems, high population density, improper industrial waste disposal, flooding during wet seasons, runoff through soil infiltration, and failing septic systems, may all contribute to the faecal contamination of drinking water sources (Nwabor *et al.* 2016; Olalemi & Akinwumi 2022). *Escherichia coli*, thermotolerant coliforms, and intestinal enterococci represent the classic bacterial indicators of the presence of faecal pollution in drinking water (Ashbolt *et al.* 2001; Sinclair *et al.* 2012). Other enteric bacteria that may occur in faecally contaminated drinking water include *Salmonella*, *Shigella*, *Campylobacter*, *Clostridium*, *Vibrio*, etc. The WHO guideline for drinking water quality recommends that *E. coli* must not be detected in 100 ml of drinking water.

Water safety planning is a proactive risk assessment and risk management approach that helps to ensure the safety of drinking water, i.e., achieve drinking water quality targets and reduce incidences of contamination (Bartram 2009; WHO 2023). Different risk assessment methods may be applied in water safety planning. Examples include sanitary inspection, descriptive risk assessment, semi-quantitative risk assessment, and quantitative microbial risk assessment (QMRA) (WHO/UNICEF 2012; WHO 2023).

Sanitary inspection

The World Health Organization (WHO) defined sanitary inspection as an on-site examination of a water system to determine the actual and potential sources of contamination (WHO 1996). Sanitary inspection has also been described as a visual survey of risk factors that may likely contribute to faecal contamination of water systems (Cronin *et al.* 2006; Kelly *et al.* 2021). The use of standardized sanitary inspection as a tool has been recommended to increase safe water provision and improvement of water quality at sources (Lloyd & Bartram 1991; WHO 2022). This is carried out using specially designed forms for comprehensive risk-based assessment of water systems (WHO 2004; Mushi *et al.* 2012; Odjegba *et al.* 2020). The sanitary inspection form consists of questions on potential risk factors surrounding the water source (WHO 1997). In complex water systems, water treatment processes, chlorine residuals, risks at the water catchment, and pressure in the water distribution system may be included. High risk scores imply that the water supply is at high risk of contamination and may require remedial action in order to improve and protect the water supply (WHO 1997; Bartram *et al.* 2009; Mushi *et al.* 2012; Kelly *et al.* 2020).

Studies have previously validated sanitary risk scores against the measured indicators of water quality (Kelly *et al.* 2020). Howard *et al.* (2003) reported a significant relationship between the total sanitary risk score and the median level of faecal contamination in shallow protected springs in Kampala, Uganda. Cronin *et al.* (2006) observed a positive correlation between sanitary risk scores and the level of faecal indicator bacteria, specifically thermotolerant coliforms, in groundwater in Lichinga, Northern Mozambique. They suggested that interventions focused on hygiene practices at the wellhead and proper wellhead protection may yield rapid improvements in water quality. Similarly, Mushi *et al.* (2012) reported that sanitary inspection of wells remarkably predicted the level of bacterial faecal contamination of water from the wells in the tropical peri-urban environment of Tanzania.

Contrarily, some studies have shown that sanitary risk scores do not necessarily translate to microbiological contamination of groundwater sources. For example, Ercumen *et al.* (2017) reported that the concentration and presence of *E. coli* in some shallow boreholes in rural Bangladesh had no positive correlation with sanitary scores. These authors observed that individual risk factors measuring the integrity of the wellhead were associated with the overall water quality but still had no predictive value for the presence of *E. coli*. Daniel *et al.* (2020) reported results from a field pilot study using sanitary inspection forms and water quality in Bushenyi-Ishaka, Uganda and compared the median levels of risk and median concentrations of *E. coli* found in springs and taps. They found that risks were higher for taps than springs, but that concentrations of *E. coli* were in springs. Misati *et al.* (2017) also observed no significant associations between the overall sanitary survey scores or their individual components and the levels of thermotolerant coliforms in rural drinking water sources (dug wells, springs, and rainwater) in Kisii Central, Kenya. However, they stated that sanitary surveys may be used to identify potential hazards and contribute to a comprehensive risk management approach in water quality testing for water safety plans (WSPs).

Quantitative microbial risk assessment

QMRA is a tool that has been promoted to understand public health risks in water supply (Havelaar & Melse 2003) and has been applied in low- and middle-income countries (Owens *et al.* 2020). QMRA is composed of four steps: hazard identification, dose-response determination, exposure assessment, and risk characterization. QMRA has been used to estimate disease burden risks associated with human exposure to pathogens. It can, therefore, be a useful tool in the management of water safety for human health protection (Soller 2006; Olalemi *et al.* 2021).

Study aim

Residents who rely on the wells and boreholes in Ilara-Mokin and Ibule-Soro, Nigeria report illnesses that they suspect are caused by contaminated water. This study, therefore, aimed to determine the sanitary risks and microbial health risks associated with the samples of wells and boreholes in both communities. The objectives were to measure the levels of enteric bacteria in water samples; evaluate sanitary risk scores; assess the relationship between potential risk factors and contamination levels; estimate the risks of gastrointestinal infections associated with the ingestion of water; and adapt steps for the development of drinking water safety plans.

METHODS

Description of the study area

The study sites were located in the towns of Ibule-Soro and Ilara-Mokin in Ifedore Local Government Area, Ondo State, Nigeria. The towns are approximately 6 km apart and 14–20 km northwest of Akure, the capital of Ondo State (Figure 1). Ibule-Soro and Ilara-Mokin have populations of 30,000 and 40,000, respectively. However, the specific wells and boreholes sampled in this study served an approximate population of 600 people in Ilara-Mokin and 800 people in Ibule-Soro. There are no previous records of water quality from the study sites, but anecdotal reports of waterborne disease. Water from the wells and boreholes is not treated and collected by the local community, who primarily use water for drinking and other domestic purposes within the household, such as washing, bathing, cleaning, and flushing. Vulnerable groups within the households relying on water include the elderly and children below 5 years (Kumar *et al.* 2022). Submersible pumps abstract water from boreholes while non-submersible pumps are used for wells. The installation depths of well and borehole levels in Ilara-Mokin and Ibule-Soro vary from 8 m (due to shallow depth of the basement rock) to 20 m (due to deep depth weathering) (Table 1).

Collection of water samples from the wells and boreholes

Water samples from the wells were taken directly and samples from the boreholes were taken from taps connected to the pumps, after running the water for several minutes. Samples were collected over 15 weeks from November 2021 to March 2022. November to February were dry months (i.e., with a very low amount of rainfall), whereas March was a wet month and the beginning of the rainy season. A total of 96 water samples were collected over the study period; 1 sample from each of the 8 sources was collected per week for 12 weeks. Approximately 1 L of water was aseptically collected with sterile screw-capped bottles from each water source. Thereafter, water samples were transported in a cool box with ice packs to the laboratory for analyses, within 1 h. For quality assurance, sterile distilled water was used as the negative control.

Enumeration of enteric bacteria in water samples from the wells and boreholes

The concentrations of *E. coli*, thermotolerant coliforms, *Salmonella*, *Shigella*, and *Campylobacter jejuni* in the water samples from the wells and boreholes were determined using membrane filtration following standard methods (APHA 2012). One

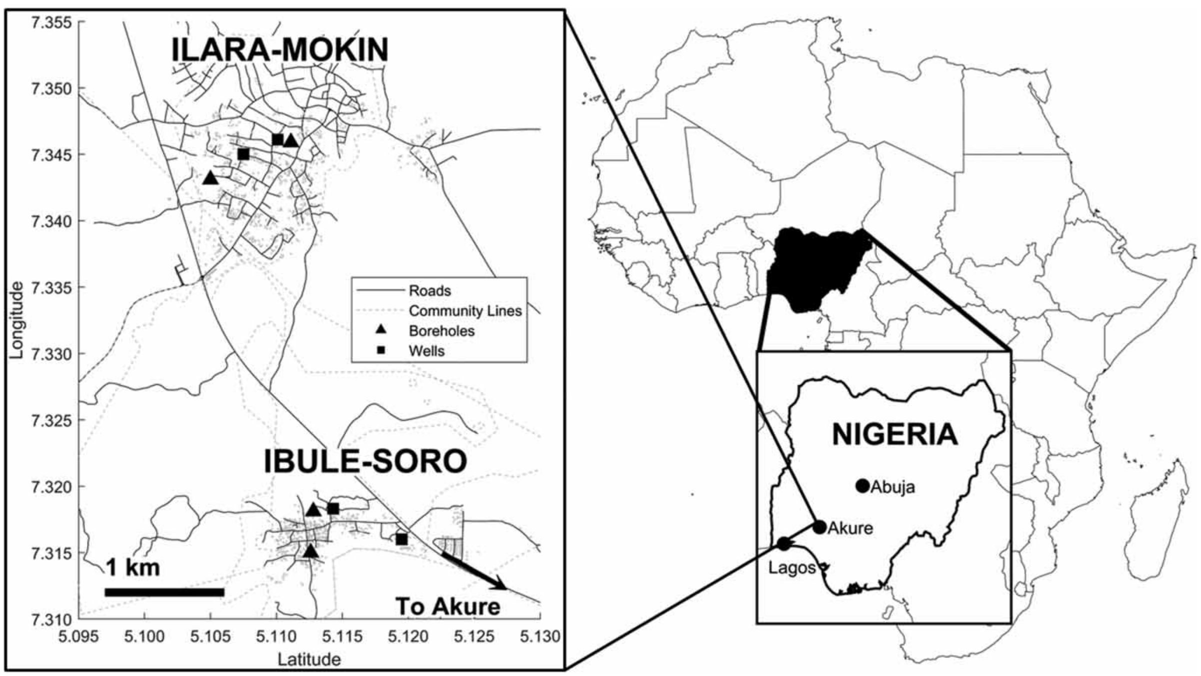

Figure 1 | Map of Nigeria within the African continent. The towns of Ilara-Mokin and Ibule-Soro are located approximately 14–20 km northwest of the city of Akure.

Table 1 | Features of the wells and boreholes at the study sites

Study site	Water source	Water depth (m)	Wellhead	Drawdown (m)	Hazard sources close by
Ilara-Mokin	Well 1	16	Covered	7.5	Recharged by a river approximately 45 m from the well
	Well 2	8	Covered	0.6	Sited about 5 m from an abattoir
	Borehole 1	20	–	10.0	
	Borehole 2	18	–	11.0	
Ibule-Soro	Well 1	14	Covered	5.3	
	Well 2	12	Covered	6.1	
	Borehole 1	19	–	9.0	
	Borehole 2	17	–	8.7	

hundred millilitre (100 ml) of water samples were filtered through membrane filters (0.45 μm); after which, the filters were placed on freshly prepared selective media: membrane lauryl sulphate agar (MLSA), eosin methylene blue (EMB) agar, membrane faecal coliform agar (m-FC), *Salmonella Shigella* agar (SSA), and charcoal cefoperazone deoxycholate agar (CCDA). Agar plates were incubated at 37 °C for 24 h (MLSA, EMB), 44 °C for 24 h (m-FC), and 37 °C for 24 h (SSA, CCDA). The selective media used had components that enabled the growth and enumeration of the specific bacteria of interest. *Salmonella* had colourless colonies with a black centre, whereas colonies of *Shigella* were clear, colourless, and transparent. *Campylobacter* had a greyish-white colour with a metallic sheen. Thermotolerant coliforms had purple colonies and *E. coli* had a greenish metallic sheen in the confirmed test. All colonies were counted, calculated, and expressed as colony-forming units (CFUs) in 100 ml^{-1} of water.

Sanitary inspection of the wells and boreholes

An on-site sanitary inspection of the wells and boreholes in Ibule-Soro and Ilara-Mokin was carried out prior to and during sampling. The sanitary inspection forms were drawn from the latest WHO guidance and adapted to local conditions taking into account the nature of the water supply. Questions in the forms, included in Supplementary Tables S1 and S2, were designed to answer with either a 'yes' or 'no'. A 'yes' answer scored one point suggesting that there is a significant risk of contamination, whereas a 'no' answer scored zero points suggesting that there is no significant risk of contamination. All scores were summated into a total sanitary inspection score that represented the risk of faecal contamination of water in each sampling site. The risk scores were classified into categories, namely, very high (9–10), high (6–8), medium (4–5), and low (0–3) (Mushi *et al.* 2012). Relationships between risk factors and the presence of *E. coli* and thermotolerant coliforms in the water samples from the wells and boreholes were assessed using the risk ratio (RR).

Microbial risk assessment

Salmonella, *Shigella*, and *Campylobacter* are considered as pathogens that may be responsible for gastrointestinal illnesses in humans. *Salmonella* is the etiological agent of typhoid fever with an infectious dose of approximately 10^5 cells and non-typhoidal salmonellosis with an infectious dose of about 10^3 cells (Ryan & Ray 2004; Bronze & Greenfield 2005). *Shigella* causes shigellosis in humans with symptoms ranging from mild to severe and acute diarrhoea. The ingestion of 10–100 viable organisms may result in infection (Crockett *et al.* 1996). *Campylobacter* is the etiological agent of campylobacteriosis, also known as *Campylobacter* enteritis, that presents symptoms such as fever, headache, abdominal pain, muscle ache, nausea, vomiting, and diarrhoea. *C. jejuni* has been reported to be responsible for more than 80% of *Campylobacter* infections. Ingestion of about 500 viable *Campylobacter* cells may cause an infection (Medema *et al.* 1996).

To determine the human health risks associated with water usage in Ibule-Soro and Ilara-Mokin, microbial risk assessment methods were applied to the water samples collected to evaluate human dose-response data for *Campylobacter*, *Shigella*, and *Salmonella* (Table 2). The beta-Poisson model assumes that the value defined by the dose-response curve is variable and accounts for the variations in the level of infectivity of the pathogen and sensitivity of the host in their interaction (Haas *et al.* 1999). The beta-Poisson model stated as Equation (1) was used to determine the probabilities of infection associated with exposure to *Campylobacter*, *Shigella*, and *Salmonella* for each water sample collected from the wells and boreholes. The annual probabilities of infection as a result of consuming water from the wells and boreholes were then determined

Table 2 | Dose-response models used for estimating the microbial health risks from pathogen exposures in water from the wells and boreholes sampled

Pathogens	Model	Parameters	Reference
Salmonella	Beta-Poisson	$\alpha = 0.3126$; $\beta = 23{,}600$	Haas *et al.* (1999)
Shigella	Beta-Poisson	$\alpha = 0.2099$; $\beta = 1{,}120$	Crockett *et al.* (1996)
Campylobacter	Beta-Poisson	$\alpha = 0.145$; $\beta = 896$	Medema *et al.* (1996)

using Equation (2).

$$P_{\mathrm{i}} = 1 - \left(1 + \frac{N}{\beta}\right)^{-\alpha} \quad (1)$$

$$P_{\mathrm{A}} = 1 - (1 - P_{\mathrm{i}})^{365} \quad (2)$$

where P_{i} is the probability of infection; α, β are parameters defining the dose-response curve; N is the exposure (colony-forming unit); and P_{A} is the annual probability of infection.

For exposure assessment, human health risks from using water from the wells and boreholes for drinking and other domestic purposes were estimated. Ingestion of one litre (1 L) of unboiled water per day was assumed for intentional consumption and the benchmark for estimating human health risks. For simplicity, it was assumed that individuals drink from the same water source every day of the year.

Statistical analysis

Data were transformed to $\log_{10}$ and then examined using general descriptive statistics. One-way analysis of variance (ANOVA) was carried out and means were separated by Duncan's new multiple range test using SPSS version 23.0. The RR was calculated for sanitary risk factors versus the presence of *E. coli* and thermotolerant coliforms in water samples from the wells and boreholes. The dose-response models stated above were used to estimate the risk of infection.

RESULTS

Enteric bacteria in water samples from the wells and boreholes

A total of 96 water samples were successfully collected from four wells and four boreholes at Ibule-Soro and Ilara-Mokin during the study period (Supplementary Tables S3–S7). Overall, water samples from the wells had a higher number of positives for enteric bacteria than the boreholes (Figure 2). The mean load of *E. coli* was below the detection limit of 1 CFU/100 ml in water samples from the boreholes, but ranged from 1.82 to 2.28 $\log_{10}$ CFU/100 ml in 48% of water samples from the wells. Similarly, the mean load of *Salmonella* was below the detection limit of 1 CFU/100 ml in water samples from the boreholes, but ranged from 2.15 to 2.63 $\log_{10}$ CFU/100 ml in 63% of water samples from the wells. The mean load of thermotolerant coliforms ranged from below 1 to 2.28 $\log_{10}$ CFU/100 ml in 10% of water samples from the boreholes, whereas in 75% of water samples from the wells, the mean load of thermotolerant coliforms ranged from 2.82 to 3.15 $\log_{10}$ CFU/100 ml. *Shigella* was detected in water samples from the wells (100%) and boreholes (40%), and *C. jejuni* was detected in water samples from the wells (96%) and boreholes (48%). While the mean load of *Shigella* ranged from 2.07 to 3.42 $\log_{10}$ CFU/100 ml, those of *C. jejuni* ranged from 2.74 to 3.44 $\log_{10}$ CFU/100 ml in water samples.

Sanitary risk scores for the wells and boreholes

Sanitary inspection revealed a risk score category of 'low' (a risk score of 3) for all boreholes and 'medium' (risk scores of 4–5) for all wells in Ilara-Mokin and Ibule-Soro. The second well located at Ilara-Mokin (IMW2) presented the highest risk score of 5, while all other wells had risk scores of 4. These scores did not change over the study period. Of the risk factors surveyed, 'other sources of pollution' and 'a missing or faulty fence' were observed at all water supplies, with risk factors 'small apron less than 1 m in radius' also very common. By contrast, 'the presence of latrine within 10 m' from the wells and boreholes was the least common (Table 3).

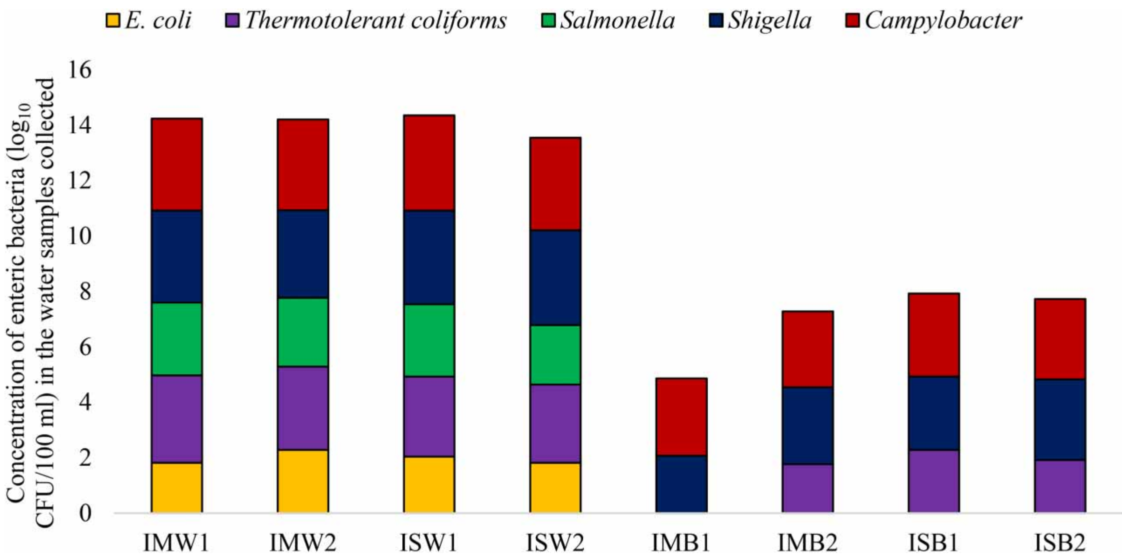

Figure 2 | Stacked column showing the mean concentration of enteric bacteria ($\log_{10}$ CFU/100 ml) in the water samples collected from IMW1 – Ilara-Mokin Well 1; IMW2 – Ilara-Mokin Well 2; ISW1 – Ibule-Soro Well 1; ISW2 – Ibule-Soro Well 2; IMB1 – Ilara-Mokin Borehole l; IMB2 – Ilara-Mokin Borehole 2; ISB1 – Ibule-Soro Borehole 1; ISB2 – Ibule-Soro Borehole 2; ($n = 12$ samples per source).

Table 3 | Sanitary risk scores and frequency of individual sanitary risk factors at the wells and boreholes

Risk factors	Water sources								Frequency	% of Observations
	IMW1	IMW2	ISW1	ISW2	IMB1	IMB2	ISB1	ISB2		
Latrine within 10 m	0	1	0	0	0	0	0	0	1	12.5
Latrine uphill	0	0	0	0	0	0	0	0	0	0
Other source of pollution within 10 m	1	1	1	1	1	1	1	1	8	100
Ponding within 2 m	0	0	0	0	0	0	0	0	0	0
Cracked or dirty drainage channel	0	0	0	0	0	0	0	0	0	0
Missing or faulty fence	1	1	1	1	1	1	1	1	8	100
Small apron (< 1 m)	1	1	1	1	1	1	1	0	7	87.5
Spilt water in apron area	1	1	1	1	0	0	0	1	5	62.5
Cracked or damaged apron	0	0	0	0	0	0	0	0	0	0
Unsanitary cover	0	0	0	0	0	0	0	0	0	0
Total risk score	4	5	4	4	3	3	3	3		
Risk score category	Med.	Med.	Med.	Med.	Low	Low	Low	Low		

Key: Med., Medium; 'Yes' – 1; 'No' – 0; IMW1, Ilara-Mokin Well 1; IMW2, Ilara-Mokin Well 2; ISW1, Ibule-Soro Well 1; ISW2, Ibule-Soro Well 2; IMB1, Ilara-Mokin Borehole l; IMB2, Ilara-Mokin Borehole 2; ISB1, Ibule-Soro Borehole 1; ISB2, Ibule-Soro Borehole 2.

At the regional level, a relative measure of risk must be derived using grading schemes that combine the microbial water quality results and the results of sanitary inspection. This is important in order to assign a degree of priority to the individual intervention and improvement of the water system. WHO (2022) suggests that water supplies can be categorized on the basis of the percentage of water samples that tested negative for *E. coli* with category boundaries varying according to the population served. For a population of less than 5,000 people, Category A – 90%, Category B – 80%, Category C – 70%, and Category D – 60%. Using this approach, water from the boreholes at Ilara-Mokin and Ibule-Soro may be categorized as 'A', while water from the wells may be categorized as 'D'. WHO (2022) also notes that combining the water quality and sanitary inspection data can be used to prioritize community drinking water supplies for remedial action as shown in Table 4.

To assess if individual risk factors correlated with the level of water contamination, two water quality targets were selected: (1) whether they met the WHO guidelines on drinking water, specifically on *E. coli* and thermotolerant coliforms levels (i.e., less than 1 CFU/100 ml) or (2) substantially exceeded the limit (i.e., greater than 100 CFU/100 ml). Only three risk factors (other sources of pollution; a missing or faulty fence; small apron less than 1 m in radius) exhibited high significant ($p < 0.01$) association with the presence of *E. coli* and thermotolerant coliforms in water samples from the wells and boreholes. Spilt water accumulation in the apron area also had a high significant ($p < 0.01$) association except when the concentration of *E. coli* was equal to or greater than 100 CFU/100 ml. The presence of a latrine within 10 m showed no association with the level of *E. coli* and thermotolerant coliforms in the water from the wells and boreholes. Table 5 presents risk ratios and *p*-values for the most significant sanitary risk factors with regard to the measured values of *E. coli* and thermotolerant coliforms.

Risk of infection from ingestion of water from the wells and boreholes

Figure 3 presents the mean probability values of infection from a single exposure to *Salmonella*, *Shigella,* and *Campylobacter* through the ingestion of 1 L of unboiled water per day. The mean probability of *Salmonella* infection from the wells resulted in low values (0.019–0.056). As *Salmonella* values were below the detection limit, probabilities of *Salmonella* infection from the boreholes could not be calculated. In contrast, the mean probability of *Shigella* and *Campylobacter* infections from the ingestion of 1 L of unboiled water per day was more significant. In all well water samples, the mean probability of *Shigella* and *Campylobacter* infections was calculated to be 1. Water samples from the boreholes resulted in a range of mean probabilities for *Shigella* and *Campylobacter* infections (0.21–1), which were higher in Ibule-Soro than in Ilara-Mokin. Overall, the risk of infection was significantly higher for *Shigella* and *Campylobacter* than for *Salmonella*.

The mean annual probabilities of infection as a result of consuming water from the wells and boreholes contaminated with *Salmonella*, *Shigella*, and *Campylobacter* were determined in order to compare the levels of risk of infections associated with the pathogens. Results revealed that the mean annual probability of *Salmonella*, *Shigella*, or *Campylobacter* infection due to the ingestion of 1 L of unboiled water per day from the wells and boreholes was 1.0 for each pathogen (Supplementary Table S9).

If each person relying on water from the wells and boreholes sampled at Ilara-Mokin (approximately 600 people) was exposed to 1,000 CFU of *Shigella*, *Campylobacter*, and *Salmonella* via water from the wells and boreholes once in a year,

Table 4 | Priority of remedial actions of community drinking water supplies based on a grading system of microbial quality and sanitary inspection risk scores (Lloyd & Bartram 1991; WHO 2022)

E. coli with category boundaries	Sanitary inspection risk score (susceptibility of supply to contamination from human and animal faeces)			
	0 – 2	3 – 5	6 – 8	9 – 10
A				
B				
C				
D				

Low risk: no action required	Intermediate risk: low action priority	High risk: higher action priority	Very high risk: urgent action required

Table 5 | Sanitary risk factors that exhibited highly significant association with the presence of *E. coli* and thermotolerant coliforms in water samples collected

	E. coli ≤ 1 CFU/100 ml			*E. coli* ≥ 100 CFU/100 ml			Thermotolerant coliforms ≤ 1 CFU/100 ml			Thermotolerant coliforms ≥ 100 CFU/100 ml		
Risk factors	**RR**	**95% CI**	***p*-value**	**RR**	**95% CI**	***p*-value**	**RR**	**95% CI**	***p*-value**	**RR**	**95% CI**	***p*-value**
Latrine within 10 m	6.08	0.97, 38.16	0.532	1.92	0.30, 12.43	0.815	4.58	0.73, 28.88	0.533	3.42	0.54, 21.71	0.540
Other sources of pollution within 10 m	0.76	0.68, 0.85	0.001	0.24	0.17, 0.34	0.001	0.57	0.48, 0.68	0.001	0.43	0.34, 0.54	0.001
Missing or faulty fence	0.76	0.68, 0.85	0.001	0.24	0.17, 0.34	0.001	0.57	0.48, 0.68	0.001	0.43	0.34, 0.54	0.001
Small apron (<1 m)	0.87	0.65, 1.16	0.001	0.27	0.17, 0.42	0.001	0.65	0.48, 0.89	0.001	0.39	0.28, 0.55	0.001
Spilt water in apron area	1.22	0.71, 2.11	0.001	0.38	0.20, 0.72	0.027	0.91	0.52, 1.60	0.001	0.69	0.39, 1.24	0.002

Key: RR, risk ratio; CI, confidence interval.

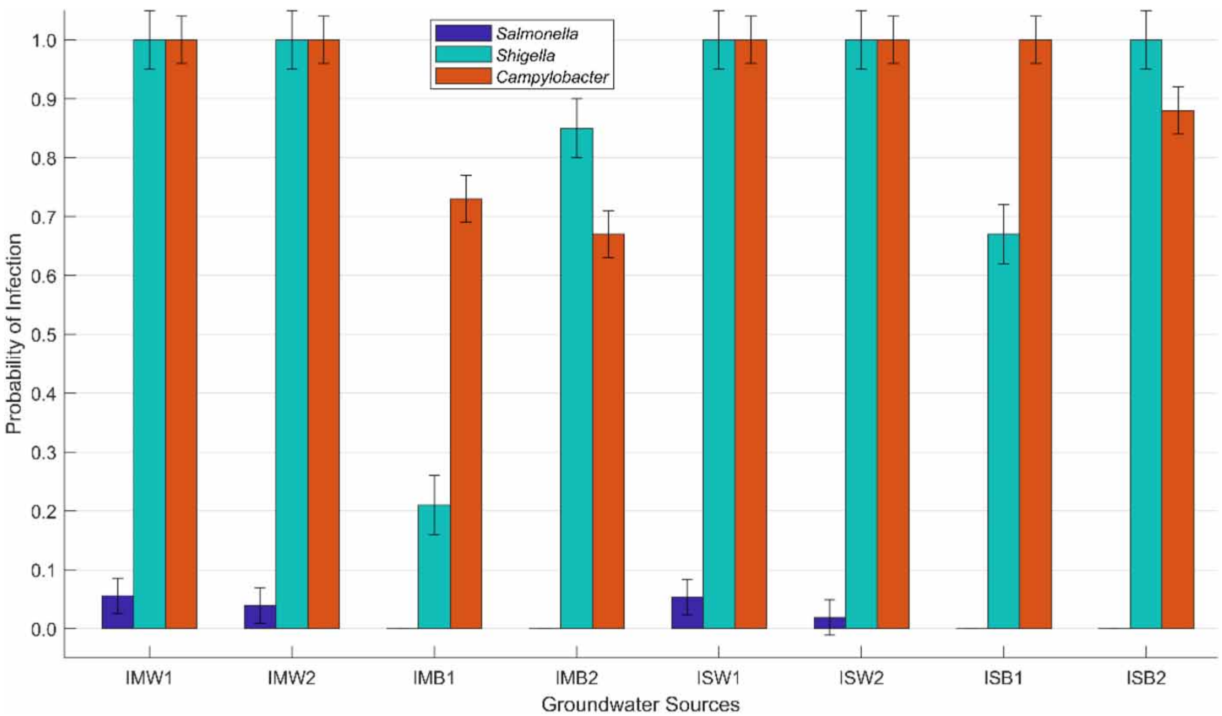

Figure 3 | Probability of infection (P_i) from a single exposure to *Salmonella*, *Shigella*, and *Campylobacter* through intentional ingestion of water (1 L) from the wells or boreholes using Equation (1) (IMW1, Ilara-Mokin Well 1; IMW2, Ilara-Mokin Well 2; IMB1, Ilara-Mokin Borehole l; IMB2, Ilara-Mokin Borehole 2; ISW1, Ibule-Soro Well 1; ISW2, Ibule-Soro Well 2; ISB1, Ibule-Soro Borehole 1; ISB2, Ibule-Soro Borehole 2). Error bars are calculated as standard deviations.

and assuming that there was uniform risk, the predicted annual cases of infection would be 75 cases, 62 cases, and 8 cases, respectively. Comparatively, if each person relying on water from the wells and boreholes sampled at Ibule-Soro (approximately 800 people) was exposed to 1,000 CFU of *Shigella*, *Campylobacter*, and *Salmonella* via water from the wells and boreholes once a year, and assuming that there was a uniform risk, the predicted annual cases of infection would be 100 cases, 82 cases, and 10 cases, respectively.

DISCUSSION

This study investigated the sanitary risks and microbial health risks associated with the wells and boreholes in Ilara-Mokin and Ibule-Soro in Ondo State, Nigeria. The study aimed to understand the likely risks to health, expressed as disease burden risk, associated with water supplies in the communities and to support the development of drinking water safety plans. The data show that, while all sources have poor microbial quality, water from the boreholes is of intermediate risk and low priority for action, whereas water from the wells is of very high risk and requires urgent action. The absence of *E. coli* in water from the boreholes despite the presence of pathogens demonstrates the limitation of using *E. coli* to predict the presence of enteric pathogens in line with previous studies (Dore *et al.* 2003; Olalemi *et al.* 2016).

The study provides a further case study on how sanitary inspection and water quality data can be combined to categorize water supplies in terms of risk, similar to the work by Howard *et al.* (2003) which shows how statistical analysis of combined data allows priority sanitary risks to be identified. The findings of this study showed that specific risk factors (namely, individual risk factors of other sources of pollution, a missing or faulty fence, and a small apron less than 1 m in radius) correlated positively with the microbial water quality of the wells and boreholes. This finding is in agreement with several studies on faecal contamination and the sanitary inspection risk scores of shallow protected springs in Kampala, Uganda (Howard *et al.* 2003), shallow hand-dug wells in Lichinga, Northern Mozambique (Cronin *et al.* 2006), and wells in peri-urban tropical lowlands in Tanzania (Mushi *et al.* 2012). It should be noted, however, that because this study was of limited length and could not integrate weather data, these conclusions should only be treated as preliminary.

The limitations of this study are the low number of selected wells and boreholes in Ilara-Mokin and Ibule-Soro, and the number of water samples collected. The relationship between sanitary risk scores or individual sanitary risk factors and water quality may change if a larger number of wells and boreholes as well as more longitudinal data were available. Furthermore, the age of the wells and boreholes may also affect individual risk factors, especially those related to components of the groundwater sources (such as apron, cover, and drainage channel) that may deteriorate over time, thus affecting the water quality. A further assumption made was that individuals drink from the same water source every day. Consumers in Nigeria are known to vary their supplies due to factors such as seasonality, water availability, and cost. Future works should consider the use of multiple sources to more accurately reflect the quality of water consumed throughout the year.

The findings of this study can be used to develop WSPs for the water supplies in this region, and for similar water supplies across Nigeria, which the WHO (2017) recommends as the best way to manage water safety. The study identified which sanitary risk factors are most important to address, to improve water quality, because of their association with failure to meet the water quality targets. Using this data will allow the identification of control measures for these types of supply and potentially inform critical limits. For instance, Nguyen *et al.* (2022) evaluated the experience of implementing WSPs in Vietnam using a mixed-methods approach and observed a decrease in the levels of *E. coli* in 61% of the water supplies and an improvement in disinfectant residual in treated water in 83% of the water supplies. The data on pathogens suggest that health-based targets should not be solely based on the levels of *E. coli*, but take into account that enteric pathogenic bacteria may be present in water supplies in the absence of detectable *E. coli*.

Findings from this study showed that the water supply from the boreholes at Ilara-Mokin and Ibule-Soro with minimal treatment may meet health-based targets, while water supply from the wells requires adequate treatment in order to control risks and meet health-based targets. The sanitary inspection data for boreholes guide consumers on how to identify which areas to target and manage for water safety, and so provide the basis for developing a WSP that can be shared with users and operators.

The failure of dug wells to meet the required water quality and the evidence of sanitary risks again help to inform the development of a WSP. Addressing the sanitary risks associated with poor proper wellhead completion could yield rapid improvements in water quality. Other control measures that may be adapted include the reduction of pollutants, prevention of pollution of the aquifer, wellhead and sanitary completion, improving the fencing around the area and the quality of concrete works, controlling human and animal activities around the wells, as well as maintaining the minimum safe distance between the water source and potential sources of pollution (e.g., latrine, dumpsites, abattoir). In addition, it is likely that, to secure safe water, some form of household water treatment may be required.

For both types of water supply, it may be difficult to develop individual WSPs for specific water supplies as the level of technical skills among community operators may be limited. In such cases, it will be worth considering the development of 'model' technology WSPs that can be applied to all water supplies of the same type, as has been previously applied in countries such as Bangladesh (Mahmud *et al.* 2007).

Validation will be required to assess the effectiveness of control measures in reducing risks posed by the identified hazards during sanitary inspection. This is likely to be best done through repeated assessment of water quality and sanitary risks of a sample of supplies under the most challenging conditions, most commonly during periods of heavy rainfall. Operational monitoring to determine the performance of the control measures at appropriate time intervals is necessary for the overall safety of the drinking water supply system. This will ensure that corrective actions or interventions are undertaken in response to the control measures moving outside the operational limit.

CONCLUSION

This study showed that water quality was generally poor for the water supplies in Ilara-Mokin and Ibule-Soro, but that wells were worse than boreholes and are, therefore, a higher priority for action. *Shigella* and *Campylobacter* were detected in all water samples, irrespective of the source, but *E. coli* and *Salmonella* were only detected in water samples collected from the wells. This suggests that *E. coli* offer limited benefits as an indicator of pathogen presence. The estimated risks of infection associated with *Shigella* were higher than those of *Campylobacter* and *Salmonella.* The sanitary risk scores revealed 'low' and 'medium' for the boreholes and wells, respectively, and correlated positively with the microbial water quality of the water sources. The sanitary inspection data can be used to identify control measures to improve water safety and help in defining critical limits. The results of the QMRA exercise suggest that health-based targets may need to be set on the basis of pathogens and not solely on *E. coli*, given their apparently poor predictive power as an indicator of pathogen presence.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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