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Assessing the impact of COVID-19 restrictions on the microbial quality of an urban water catchment and the associated probability of waterborne infections

Akebe Luther King Abia<sup>a,b,⁎</sup>, Memory Tekere<sup>a</sup>

<sup>a</sup> College of Agriculture and Environmental Sciences, University of South Africa, Florida, South Africa
<sup>b</sup> Environmental Research Foundation, Westville 3630, South Africa

HIGHLIGHTS

- We assessed the probability of infection from polluted water during COVID-19 lockdown.
- The <i>Escherichia coli</i> counts increased between 2019 (pre-COVID) and 2021 (post-lockdown).
- No significant increase was observed between 2019 and 2020 (lockdown year).
- The probability of infection showed an overall similar trend as the microbial counts.
- Thus, lockdown did not increase the risk of waterborne infections in the studied area.

ABSTRACT

The World Health Organization reported that COVID-19 cases reached 611,421,786 globally by September 23, 2022. Six months after the first reported case, the disease had spread rapidly, reaching pandemic status, leading to numerous preventive measures to curb the spread, including a complete shutdown of many activities worldwide. Such restrictions affected services like waste management, resulting in waste accumulation in many communities and increased water pollution. Therefore, the current study investigated if lockdown impacted surface water microbial quality within an urban water catchment in South Africa. Using quantitative microbial risk assessment, the study further assessed changes in the probability of infection (Pi) with gastrointestinal illnesses from exposure to polluted water in the catchment. <i>Escherichia coli</i> data for 2019, 2020 and 2021 – pre-COVID, lockdown, and post-lockdown periods, respectively – were collected from the area’s wastewater treatment management authorities. The Pi was determined using a beta-Poisson model. Mean overall <i>E. coli</i> counts ranged from 2.93 ± 0.16 to 5.30 ± 1.07 Log10 MPN/100 mL. There was an overall statistically significant increase in microbial counts from 2019 to 2021. However, this difference was only accounted for between 2019 and 2021 (<i>p</i> = 0.008); the increase was insignificant between 2019 and 2020, and 2020 and 2021. The Pi revealed a similar trend for incidental ingestion of 100 mL and 1 mL of polluted water. No statistically significant difference was observed between the years based on multiple exposures. Although the overall microbial load and Pi estimated within the catchment exceeded the local and international limits recommended for safe use by humans, especially for drinking and recreation, these were not significantly affected by the COVID-19 restrictions. Nevertheless, these could still represent a health hazard to immunocompromised individuals using such...
1. Introduction

COVID-19, caused by Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), is among the most severe pandemics humanity has experienced in recent years. Starting in 2019, the disease rapidly spread globally and was declared a pandemic in March 2020, with close to 120,000 cases in 114 countries barely six months after the first case was reported (WHO, 2020). Without any known cure or vaccine, drastic preventive measures were implemented globally, including social distancing, international travel ban, and hard lockdown, to stop the spread of the disease (Haiider et al., 2020). Lockdown measures in many countries meant the total closure of public facilities like schools, churches, non-essential shops and services (ECDC, 2022).

Although many countries tried to maintain essential services such as waste management and water supply, the pandemic placed tremendous pressure on these services due to sick personnel who had to quarantine, the reduced number of workers to be present at the workplace at any given time, and the loss of personnel to the infection. These resulted in stockpiling of waste at households and communities, creating a sanitation problem (Sarkodie and Owusu, 2021), with wastewater treatment plants receiving higher volumes of solid waste, which probably impacted their functioning capacity (Mohamed et al., 2022; Parida et al., 2022; Sarkodie and Owusu, 2021). While some studies reported an overall global improvement in surface water bodies’ quality due to imposed restrictions, a relatively high degree of land pollution was also reported (Yang et al., 2022). Furthermore, waste recycling reduced drastically, resulting in increased pressure on these services due to sick personnel who had to quarantine, the reduced number of workers to be present at the workplace at any given time, and the loss of personnel to the infection. These resulted in stockpiling of waste at households and communities, creating a sanitation problem (Sarkodie and Owusu, 2021), with wastewater treatment plants receiving higher volumes of solid waste, which probably impacted their functioning capacity (Mohamed et al., 2022; Parida et al., 2022; Sarkodie and Owusu, 2021). While some studies reported an overall global improvement in surface water bodies’ quality due to imposed restrictions, a relatively high degree of land pollution was also reported (Yang et al., 2022). Furthermore, waste recycling reduced drastically, resulting in increased pollution of water bodies (Manoiu et al., 2022; Rume and Islam, 2020). Many water supply services were also interrupted, resulting in some populations not having water for extended periods (DPME, 2020).

Most developing countries are challenged by a complete absence of, or the presence of inefficient, waste management systems (Ako et al., 2010; Gwensi, 2021; Montgomery and Elimelech, 2007; Tilley et al., 2013). Furthermore, millions of people in these countries still lack access to safe drinking water (Hunter et al., 2009, 2010; Lee and Schwab, 2005; UNICEF and WHO, 2015; Wright et al., 2004). Thus, many people have resorted to usually polluted surface water bodies as alternative water sources and, at times, as the only water sources for personal and household hygiene (Abia et al., 2017). The result of the abovementioned conditions is a high disease burden in these countries, especially in resource-limited communities (Gundry et al., 2003; Gwensi et al., 2015; Hunter et al., 2009, 2010; Irda Sari et al., 2018; Jensen and Jayasinghe, 2004). While many studies have evaluated the impact of the current COVID-19 pandemic on different sectors, there is a lack of information on its potential impact on the health risk associated with exposure to poor surface water, especially in areas where water treatment and supply were affected. Thus, the current study evaluated such impact by estimating the probability of infection due to exposure to polluted water in a wastewater treatment plant and surface water bodies within the same catchment area in South Africa before and during the pandemic.

2. Materials and methods

2.1. Study site

This study was conducted in the Pietermaritzburg urban water catchment, South Africa. The main river in this catchment is the Msunduzi River, a tributary to the uMgeni River, Durban’s primary water source. The Msunduzi River hosts the famous Duzi Canoe Marathon, an event that receives national coverage (Cross and Coombes, 2013; Jensen and Jayasinghe, 2004). Apart from this, the river also serves as a water source for many industries within the catchment. The rapid industrialisation and population growth around the area have resulted in the development of high-density informal settlements along the river course. Given the unplanned nature of these settlements, they are characterised by a gross lack of essential services such as water supply and waste management, hence depend on the river for their water and sanitation needs. The Msunduzi River has many tributaries, the main one being the 9 km long Baynespruit (Ramburran, 2018). Also located within this catchment is an urban wastewater treatment plant (WWTP) servicing the city of Pietermaritzburg in the Msunduzi Municipality, KwaZulu-Natal. The WWTP, its operation and the general weather conditions around the area have previously been described (Mbanga et al., 2020). The WWTP discharges directly into the Msunduzi River.

2.2. Site monitoring and data collection

The WWTP authority monitors 20 points consisting of 17 sites upstream from the discharge point (eight on the main Msunduzi River and nine on the tributaries), the final effluent discharge point, and two sites downstream from the discharge point (Fig. 1 and Table S1; Supplementary Materials). Water samples are collected from each site weekly and analysed for microbial and physicochemical parameters. The microbiological quality of the sampling points is determined using Escherichia coli as the indicator organism. The WWTP uses the Colilert®-18/Quanti-Tray®-2000 system from IDEXX for enumeration (IDEXX Laboratories (Pty) Ltd., Johannesburg, South Africa). Therefore, E. coli data for 2019 (pre-COVID), 2020 (Lockdown Year) and 2021 (post-lockdown) were obtained from the WWTP management for this study. A total of 2392 data points were analysed, consisting of 2019 (n = 960), 2020 (n = 568), and 2021 (n = 864).

2.3. Quantitative microbial risk assessment

The risk of exposure to untreated contaminated water from each sampling site was assumed to occur during work (occupational hazard) within the WWTP, recreation (e.g., canoeing and swimming), bathing and laundry, and consumption at the household level within the informal settlements. Furthermore, infection in this context was assumed to be gastrointestinal due to ingestions of microbiologically contaminated water. Given that the WWTP does not test for the various E. coli pathotypes, it was assumed that only 8 % of the E. coli were pathogenic based on previous studies (Abia et al., 2016; Howard et al., 2006; Mbanga et al., 2020). Therefore, the beta-Poisson dose-response model previously described (Haas et al., 1999) was applied to assess the probability of infection (Pi) due to single incidental/intentional ingestion of 1 mL of occupational and recreational exposure) and 100 mL of (informal settlement) using the formula $P_i = 1 - (1 + N/\beta)^{-\alpha}$, $N$ being the mean number of ingested organisms and $\alpha$ and $\beta$ organism-specific parameters, in this case, E. coli O157:H7 (Haas et al., 1999). The risk of infection was further estimated by assuming weekly exposure to contaminated water at these sites for one year (52 weeks) using the formula $P(n) = 1 - (1 - P_i)^n$, “n” being the number of exposures (Haas et al., 1999).

2.4. Statistical analysis

Statistical analysis was performed using the Statistical Package for Social Sciences 27 (SPSS, IBM Corporation, Armonk, New York, USA). Data was Log10 transformed before calculating the means and computing...
analysis. One site (WDV021; Darvill old effluent) with less than three months of sampling was excluded from all calculations. The maximum most-probable number (MPN) value in the IDEXX table was assumed for all values greater than the Quanti-Tray® 2000 quantification limit, while values below the quantification limit were considered zero. The difference in the mean microbial counts was determined using a paired t-test. The probability of infection between the sampling sites per year was compared using the Kruskal-Wallis test. All statistics were considered significant at an alpha less than 0.05.

3. Results

3.1. Mean E. coli count per site

The highest mean annual E. coli count throughout the study was recorded at Site RBS003 (5.30 ± 1.07 Log_{10} MPN/100 mL) located on the Baynespruit, while the least mean annual count was recorded at the WWTP discharge point (Final effluent; 2.93 ± 0.16 Log_{10} MPN/100 mL) (Fig. 2). The mean annual E. coli counts, the standard deviations, and
maximum and minimum values for each of the sites and throughout the sampling years are shown in Table S2 (Supplementary Materials). Overall, there was a general increase in the mean annual _E. coli_ count from 2019 to 2021. However, the difference was only statistically significant between 2019 and 2020 (_p_ = 0.04), 2019 and 2021 (_p_ = 0.008), while no statistically significant difference was observed between 2020 and 2021 (_p_ = 0.09).

### 3.2. Quantitative microbial risk assessment

The sampling sites showed different _Pi_ values throughout the study based on exposure to a single dose and multiple weekly doses of 100 mL and 1 mL of polluted water (Table S3, Supplementary Materials). The _Pi_ based on ingestion of a single dose of 100 mL of polluted water ranged between 21.29 and 98.20, 13.34 and 98.56, and 62.51 and 97.86 for 2019, 2020, and 2021, respectively (Table 1a). Based on the weekly ingestion of the same water quantity of water over one year, the _Pi_ was 100 %.

#### 3.3. Comparison of the probability of infection between sites and years

#### 3.3.1. Overall comparison between years

Although there was a general increase in the _Pi_ from 2019 to 2021, this difference was only statistically significant between 2019 and 2020 (_p_ = 0.001), and 2019 and 2021 (_p_ = 0.001) for a single exposure to 1 mL, and between 2019 and 2021 (_p_ = 0.001), and 2020 and 2021 (_p_ = 0.033) for a single exposure to 100 mL of polluted water (Table 2). In addition, no statistically significant differences were recorded between the years for multiple exposures to 100 mL and 1 mL (Table 2).

#### 3.3.2. Comparison between years per site

Statistical differences were observed in the probability of infection between the years at some sites for a single exposure to 100 mL and 1 mL of polluted water (Table 3) and multiple exposures to 1 mL of polluted water (Table 4). Based on multiple comparisons, the differences between 2019 and 2021 accounted for the overall statistically significant differences observed at most sites, except for sites RMD007 and RMD008, where significant differences were also observed between 2019 and 2020 (single exposure), and RMD008 for multiple exposures. No statistically significant differences were observed for exposure to multiple doses of 100 mL.

### Table 1a

| Sampling site | Probability of infection |
|---------------|-------------------------|
|               | 2019                    | 2020 | 2021 |
| RMD006        | 91.29                   | 82.84 | 79.69 | 83.50 | 97.36 | 84.90 |
| RMD007        | 94.20                   | 87.18 | 98.12 | 90.03 | 97.30 | 93.70 |
| RMD008        | 94.36                   | 87.41 | 98.28 | 93.89 | 97.84 | 93.88 |
| RS003         | 97.23                   | 89.85 | 97.60 | 91.43 | 97.52 | 92.67 |
| RMD011        | 94.57                   | 70.16 | 94.28 | 38.05 | 94.12 | 84.56 |
| RMD013        | 93.73                   | 73.08 | 95.72 | 61.26 | 92.67 | 85.23 |
| RS003         | 94.74                   | 82.26 | 97.84 | 83.09 | 95.48 | 89.42 |
| RDS004        | 94.83                   | 73.96 | 93.75 | 78.38 | 95.35 | 89.13 |
| RD005         | 94.54                   | 89.27 | 95.00 | 92.92 | 96.20 | 90.83 |
| RMD014        | 93.82                   | 85.57 | 95.36 | 73.48 | 93.14 | 85.69 |
| RMD015        | 94.64                   | 83.44 | 95.19 | 78.34 | 94.15 | 83.11 |
| RMD016        | 94.96                   | 84.81 | 95.07 | 78.16 | 93.99 | 83.34 |
| RS001         | 96.37                   | 84.39 | 96.87 | 81.99 | 97.58 | 91.65 |
| RS002         | 97.81                   | 89.31 | 97.35 | 91.71 | 97.68 | 95.11 |
| RS003         | 98.20                   | 96.96 | 98.56 | 96.59 | 97.86 | 96.62 |
| RMD017        | 96.90                   | 94.76 | 96.32 | 93.39 | 97.05 | 93.80 |
| WD002         | 97.51                   | 21.29 | 97.98 | 13.34 | 95.00 | 62.51 |
| RMD018        | 97.10                   | 86.82 | 96.42 | 84.91 | 95.13 | 70.17 |
| RMD019        | 96.21                   | 86.75 | 94.82 | 89.97 | 94.44 | 87.25 |

### Table 1b

| Sampling site | Probability of infection |
|---------------|-------------------------|
|               | 2019                    | 2020 | 2021 |
| RMD006        | 50.57                   | 21.69 | 79.71 | 22.14 | 83.78 | 26.61 |
| RMD007        | 65.20                   | 33.45 | 88.40 | 44.39 | 83.43 | 62.44 |
| RMD008        | 64.14                   | 34.24 | 89.41 | 41.90 | 86.74 | 63.45 |
| RS003         | 82.99                   | 43.62 | 85.24 | 50.80 | 84.77 | 56.98 |
| RMD011        | 67.28                   | 7.06  | 65.69 | 0.92  | 64.76 | 25.71 |
| RMD013        | 62.64                   | 8.93  | 73.98 | 3.70  | 58.03 | 27.50 |
| RS003         | 68.28                   | 20.48 | 86.70 | 22.23 | 72.57 | 41.83 |
| RDS004        | 68.77                   | 9.61  | 62.71 | 14.19 | 71.76 | 40.62 |
| RDS005        | 68.16                   | 41.19 | 97.66 | 58.28 | 76.79 | 47.96 |
| RD004         | 63.11                   | 28.44 | 71.86 | 9.23  | 59.44 | 28.79 |
| RMD015        | 67.71                   | 23.02 | 70.88 | 14.13 | 64.93 | 22.26 |
| RMD016        | 69.53                   | 26.37 | 70.19 | 13.91 | 64.04 | 22.79 |
| RS001         | 77.79                   | 25.28 | 80.79 | 53.04 | 85.11 | 51.86 |
| RS002         | 86.54                   | 41.34 | 83.71 | 52.12 | 85.76 | 70.39 |
| RMD003        | 88.93                   | 81.35 | 91.15 | 79.16 | 86.82 | 79.34 |
| RMD017        | 80.97                   | 68.37 | 77.44 | 61.43 | 81.92 | 63.01 |
| WD002         | 84.68                   | 0.33  | 87.59 | 0.17  | 69.75 | 4.03  |
| RMD018        | 82.22                   | 32.28 | 78.10 | 26.64 | 70.50 | 7.06  |
| RMD019        | 76.88                   | 32.05 | 68.75 | 44.12 | 66.57 | 33.70 |

### Table 2

| Pairs | Statistical significance (p-values) |
|-------|-------------------------------------|
|       | Single exposure | Multiple exposure |
|       | 100 mL | 1 mL | 100 mL | 1 mL |
| 2019-2020 | 0.367 | 0.001 | 0.231 | 0.188 |
| 2019-2021 | 0.001 | 0.001 | 0.318 | 0.103 |
| 2020-2021 | 0.033 | 0.257 | 0.231 | 0.080 |

* The difference is statistically significant at alpha less than 0.05.
The COVID-19 pandemic has affected several service deliveries, including waste management globally, with reported adverse implications on natural ecosystems, especially surface water bodies. Thus, the current study evaluated the impact of COVID-19 lockdown measures on the microbial quality and associated probability of infection in water bodies within a water catchment in KwaZulu-Natal, South Africa. There was an overall statistically significant increase in the mean *E. coli* counts from 2019 (pre-COVID-19) to 2020 and 2021 (COVID-19 years). In addition, over 50% of the sites showed an overall statistically significant difference in the probability of infection between the years, although this difference was mainly between 2019 and 2021, while only two sites showed a statistically significant difference between 2019 and 2020.

### 4.1. Mean *E. coli* count per site

Surface water bodies continue to suffer from severe pollution due to anthropogenic activities linked to rapid population growth and urbanisation (Fayiga et al., 2018; Garbossa et al., 2017), thus events that disrupt normal service delivery, especially regarding sanitation, would exacerbate the problem. The COVID-19 pandemic is one of the most recent natural events that affected both humans and their environment. However, unlike other natural events like floods (Nagels et al., 2002), earthquakes (Devane et al., 2014), and droughts (Jackson et al., 2011) that almost always negatively impact the environment, COVID-19 had some positive effects and in some cases no effect at all. For example, an Indian study observed that COVID-19 restriction reduced pollution of numerous physicochemical parameters in coastal areas, while some metals and biological pollutants remained unchanged (Selvam et al., 2020). Another study in Italy reported that the COVID-19 restrictions contributed to clear water in a lagoon, possible due to reduced shipping that resulted in reduced turbidity (Braga et al., 2020). Similarly, a review of 100 peer-reviewed scientific publications revealed that air and water quality improved globally, except in a few instances (Yang et al., 2022). These effects have been attributed solely to the restrictive measures implemented to curb the spread of the infection, such as travel bans, hard lockdown, and extended homestays that reduced waste production by industries and agriculture, for example (Balamurugan et al., 2021; Yang et al., 2022).

Despite these positive effects, some negative environmental impacts were observed elsewhere. For example, Zambrano-Monserrate et al. reported that the lockdown measures affected waste management services, resulting in the accumulation of solid waste, with consequent land and water pollution (Zambrano-monserrate et al., 2020). Similarly, waste management services were noted to have been affected, and as a consequence, large volumes of untreated waste were discharged into surface water bodies, leading to pollution (Manoiu et al., 2022; Rume and Islam, 2020).

In the current study, there was an overall increase in the *E. coli* concentration from 2019 to 2021 at most of the sampling sites within the catchment area studied. However, the observed increase was mostly accounted for between 2019 and 2021 (*p* = 0.008), as this increase was not statistically significant between 2020 and 2021 (*p* = 0.09). Only two sites, RMD007 and RMD008, showed statistically significant increases between 2019 and 2020. RMD007 is situated below Kwa Pata, an informal settlement within the catchment. This site is poorly serviced and lacks waste management services, resulting in waste dumping within the surrounding wetlands (Singh and Bartholomew, 2014). On the other hand, RMD008 is at the Edendale weir (Table S1, Supplementary Materials). Edendale is one of the largest towns in Pietermaritzburg; the Edendale Hospital and industries in this area discharge their waste into the Msunduzi River as it flows past Edendale (Alfin, 2017; Gwala, 1989). Both sites are upstream of the WWTP, on the main Msunduzi River.

The lack of a statistically significant difference in the mean *E. coli* counts between 2019 and 2020 indicates that the pandemic did not significantly impact the microbial count in the first year. Also, the marked increase in 2021 could have been due to the ease of lockdown measures, allowing people to return to their normal activities, resulting in increased waste generation and pollution beyond pre-covid levels. Nevertheless, the lockdown measures affected the sampling of the WWTP authorities within this catchment. This was observed by a lack of sampling in 15 of its monitoring points between April and July when the restrictions were implemented. However, the overall observation revealed that the sites with the highest microbial loads were upstream from the WWTP, while the effluent and downstream sites recorded comparatively lower mean microbial counts. Therefore, the disruptions did not affect the overall functioning of the WWTP. Similar studies have been reported (Yazdian and Jamshidi, 2021).

It should, however, be noted that although there was no apparent effect on the microbial load, the concentrations recorded throughout the study were still above the WHO and South Africa's recommended values of zero *E. coli* in any water meant for drinking or domestic use (DWAF, 1996; WHO. World Health Organization, 2017). This, therefore, could represent a risk of infection upon ingestion without any treatment, especially in places with limited access to potable water or where the water supply was interrupted because of the pandemic.

### 4.2. Quantitative microbial risk assessment

Despite the valuable contribution of epidemiological studies in determining disease spread, these methods are limited by their high time and financial demands (Yillia et al., 2009) and inappropriateness in cases of surface waters with diffused pollution sources (Ashbolt et al., 2010). These limitations make quantitative microbial risk assessment (QMRA) a useful complementary approach, providing a rapid health risk evaluation associated with polluted water and assisting prompt decision-making to protect human life (Soller et al., 2015).

In the current study, we evaluated the risk of infection from exposure to polluted water within an urban catchment between 2019 and 2021 to determine if the COVID-19 pandemic restriction impacted the possibility of people getting sick from using polluted water in that catchment. A survey in South Africa reported that water supply services were interrupted (DPME, 2020). Also, many informal settlements are located within the studied water catchment. Informal settlements are usually characterised by a gross lack of basic sanitation and water supply facilities, obliging many people living in such places to resort to polluted surface water for their daily needs (Abia et al., 2015, 2016). Thus, we anticipated that interrupted water supply and lack of access to safe water in these settings would increase the use of polluted water from this catchment, increasing the risk of these people getting sick during the COVID-19 lockdown.

The probability of infection at all the sampling points and for all the years (Tables 1a and 1b) was above the WHO recommended limit of $10^{-4}$ for drinking water (Abia et al., 2016). Also, a comparison between years showed no statistically significant increase in the risk between 2019 and 2020, except for exposure to a single dose of 1 mL, while significant...
difficulties were observed between 2019 and 2021, and 2020 and 2021 (Table 2). However, multiple comparisons at the various sites (Tables 3 and 4) revealed that less than ten sites showed an overall increase, and the difference between 2019 and 2021 accounted for this. Only two sites showed a statistically significant increase in the probability of infection between 2019 and 2020 (Tables 3 and 4). These sites also recorded a significant increase in the mean microbial count between 2019 and 2020 and this translated to the higher Pi, which is calculated from the mean microbial counts. As previously indicated, these sites were mostly influenced by an informal settlement (RMD007) and Pietermaritzburg's largest township (RMD007), both of which lacked access to adequate services like waste management. Like the mean microbial count data, the computations of the Pi revealed that the COVID-19 restrictions did not increase the risk of infection due to exposure to polluted water within the catchment. This is the first report on estimating the probability of infection through the accidental or intentional consumption of polluted water during the COVID-19 pandemic.

Nevertheless, several other factors like the immune system and the individual's age could affect disease outcome upon exposure. Therefore, while these results suggest no increased risk, COVID-19 patients and other immunocompromised individuals in these places could be more vulnerable due to their already sick status. Thus, the present results should be interpreted with care as the risk of infection does not necessarily translate to disease development in all individuals. It should also be noted that some sites were not sampled during the hard lockdown, and this could affect the overall mean microbial count observed, hence the risk of infection.

5. Conclusion

Although lockdown measures implemented during the COVID-19 pandemic had devastating effects on the livelihood of families and the national and global economy, results of the current study reveal that this was not the case with the microbial quality of water in an urban catchment in KwaZulu-Natal, South Africa. Furthermore, the measures implemented did not increase the risk of infection of individuals due to exposure to varying doses of polluted water within the catchment. It would appear that easing the restrictions instead accounted for the overall increase in the microbial load and probability of infection between 2019 and 2021. Given the general approach used to estimate the risk of infection in the current study, it is recommended that further studies be conducted to understand different disease conditions such as diarrhoea in this study area during the period of study and establish a link between such infections to hygiene and sanitation conditions, and consumption of polluted water.

CRediT authorship contribution statement

All authors contributed equally to the manuscript.

Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Finding

None.
