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Analyses of drinking water quality during a protracted cholera epidemic in Malawi – a cross-sectional study of key physicochemical and microbiological parameters

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ABSTRACT

Anecdotal evidence and available literature indicated that contaminated water played a major role in spreading the prolonged cholera epidemic in Malawi from 2022 to 2023. This study assessed drinking water quality in 17 cholera-affected Malawi districts from February to April 2023. Six hundred and thirty-three records were analysed. The median counts/100 ml for thermotolerant coliform was 98 (interquartile range (IQR): 4–100) and that for *Escherichia coli* was 0 (IQR: 0–9). The drinking water in all (except one) districts was contaminated by thermotolerant coliform, while six districts had their drinking water sources contaminated by *E. coli*. The percentage of contaminated drinking water sources was significantly higher in shallow unprotected wells (80.0% for *E. coli* and 95.0% for thermotolerant coliform) and in households (55.8% for *E. coli* and 86.0% for thermotolerant coliform). Logistic regression showed that household water has three times more risk of being contaminated by *E. coli* and two and a half times more risk of being contaminated by thermotolerant coliform compared to other water sources. This study demonstrated widespread contamination of drinking water sources during a cholera epidemic in Malawi, which may be the plausible reason for the protracted nature of the epidemic.

Key words: cholera epidemic, household drinking water, Malawi, physicochemical and microbiological parameters, water contamination, water quality

HIGHLIGHTS

- This study established the situation of drinking water quality during the protracted cholera epidemic in Malawi from 2022 to 2023.
- Its recommendations were used to reorganize ongoing response interventions, which resulted in the control of the epidemic and are useful in the planning of future cholera preparedness and response efforts.
- The data generated from the study would serve as a baseline for future studies.

GRAPHICAL ABSTRACT

1. BACKGROUND

Safe drinking water is defined as safe for drinking, preparing food, washing, and personal hygiene (Bos *et al.* 2016). De Zuane *et al.* and the World Health Organization (WHO) have set out the basic parameters for determining and monitoring the quality of safe water, namely, physical, chemical, microbiological, and radiological parameters (Table 1) and estimate that a

Table 1 | Water quality monitoring parameters defined by the Malawi Standard Board (2013)

	Parameter	**Definition**	**Unit of measurement**	**Malawi acceptable levels**[a]
Physical	Turbidity	This is the cloudiness of the water due to silt, clay, organic material, plankton, and other particulate materials.	NTU	0.1–1
	Total dissolved solids		mg/l	500
	Electrical conductivity	This is a measure of the ability of water to carry or conduct electricity.	μS/cm	0–3,500
	Temperature	It is an indicator of how warm or cold water is. Warm water (17 °C and above) seems to be more favourable for *Vibrio cholerae* replication.	°C	Below 20
Chemical	pH	This is a measure of how acidic or basic water is. *Vibrio cholerae* does not survive for long in acidic water.	NA	6.5–8.5
	Free residual chlorine	This is the amount of chlorine (a water purification chemical), which is available in chlorine-treated water. It does not naturally exist in water.	mg/l	0.2–0.5
Microbiological	Thermotolerant coliform	The presence of coliforms in water is an indicator of faecal pollution of the water.	Count/100 ml	0 (it should not be detectable in any 100 ml water sample)
	Escherichia coli	The presence of *E. coli* in water is an indicator of faecal pollution of the water.	Count/100 ml	0 (it should not be detectable in any 100 ml water sample)

[a] Malawi acceptable limits is based on the second edition of the Malawi Drinking Water Specification document (document no. MS214:2013), which is available at: Drinking water specification_Malawi.pdf.

person needs 50–100 l of water per day to meet basic requirements such as drinking, cooking, hygiene, and washing of clothes (De Zuane 1997; Howard *et al.* 2020). Safe water is critical in public health, particularly in preventing and controlling several diseases such as diarrhoea, schistosomiasis, trachoma, and soil-transmitted helminths (World Health Organization 2023). Recognizing the importance of safe drinking water to life and well-being, the United Nations declared it a fundamental human right; this is in the realization that clean drinking water is critical to achieving all human rights (United Nations General Assembly 2010). This is further affirmed by the Sustainable Development Goals (SDG), the sixth of which aims to ensure access to water and sanitation for all the world's population by 2030. Seven out of the eight targets of SDG 6 are water related, with target 6.1 particularly advocating for equitable and universal access to safe and affordable drinking water for all (The Global Goals 2023). Unfortunately, a significant proportion of the world's population can still not achieve these targets. As of 2020, only 30% of the African population had access to safely managed drinking water (World Health Organization & United Nations Children Fund 2021). This and other social, economic, cultural, and humanitarian factors continue to sustain the high incidence of diarrhoeal diseases such as cholera on the continent (Ajayi & Smith 2019).

Cholera is an acute diarrheal infection, which is acquired through the ingestion of water or food that are contaminated by a bacterium known as *Vibrio cholerae* (Clemens *et al.* 2017). The seventh cholera pandemic reached the shores of Africa in 1971 and has spread rapidly on the continent and is now endemic in several countries, including Malawi (Ali *et al.* 2015). Since 1998, the country has experienced yearly seasonal epidemics during the rainy season in the southern parts, which are flood-prone (Msyamboza *et al.* 2014). On 3 March 2022, through its Ministry of Health, the country declared a cholera epidemic following confirmation of a case in the Machinga district in the southern parts of the country (World Health Organization 2022a, 2022b). The epidemic occurred against the backdrop of tropical Storm Ana and Cyclone Gombe, which hit the country's southern parts in 2022 and resulted in massive flooding and population displacement (World Health Organization 2022a, 2022b). This epidemic proved to be one of the longest and deadliest in the history of cholera in the country. As of 16 July 2023, the country had recorded 58,941 cases and 1766 deaths in all its 28 districts, with a case fatality ratio of 3% (World Health Organization 2023). The urban districts of Lilongwe, Blantyre, and Mangochi, on Lake Malawi's shores, accounted for more than 50% of the cases. The epidemic was further worsened by tropical Cyclone Freddy, which hit the central and southern parts of the country in March 2023. The country, with the support of its national and international partners, instituted wide-ranging epidemic response interventions, including the establishment of cholera treatment centres to manage the cases, implementation of emergency Water, Sanitation and Hygiene (WASH) interventions, including water quality testing, monitoring, and surveillance, and cholera Risk Communication and Community Engagement (RCCE) in all the affected districts.

Anecdotal evidence indicated that contaminated water played a major role in the propagation of the epidemic. Available literature also indicated that a sizable percentage of the Malawian population obtains their drinking water from sources which could be potentially contaminated. Mumba *et al.* (2021) estimated that 60% of the population has inadequate access to safe drinking water, while Mkandawire & Banda (2009) show that 21, 37, 16, and 26% of the Malawian population, respectively, use piped water, boreholes, rivers and lakes, and unprotected wells. While these studies have previously documented the status of the quality of drinking water in Malawi, a recent literature search showed no empirical data on drinking water quality during the cholera epidemic. Such empirical data are critical for the planning, implementation, monitoring, supervision, and evaluation of cholera epidemic control interventions, particularly the WASH and RCCE components (Blanton *et al.* 2015). This study, therefore, sought to establish the situation of drinking water quality in Malawi to provide empirical information for evidence-based decision-making, planning, implementation, and evaluation of the preparedness and response interventions during the current and future cholera epidemics in the country.

2. METHODS

2.1. Study design and setting

We conducted a cross-sectional study to assess drinking water quality in 17 cholera-affected Malawi districts from February to April 2023. Malawi, a country in southeastern Africa, borders Tanzania to the north and northeast, Mozambique to the east, south and southwest, and Zambia to the west. In 2021, the country's population was estimated at 19.4 million people. Administratively, it is divided into three regions, northern, central, and southern regions, which are subdivided into 28 districts. Seven of the districts are located on the shores of Lake Malawi, while one district is an island on the Lake. It is one of the least developed countries globally, with an estimated 85% of the population living in rural areas. The country's main water sources are surface water, such as lakes, rivers, and streams, and underground water, such as boreholes and shallow wells. Only 24.2% of the population has access to safely managed sanitation services. About half (50.7%) of the Malawian population is estimated to fall below the poverty line; this rises to 56.6% in rural areas. Life expectancy at birth is 65.6 years as of 2019. The southern and central regions of the country are prone to tropical storms and cyclones which often result in flooding, population displacement, and epidemics of waterborne infections.

2.2. Data collection

2.2.1. Water sampling method

Seventeen of the 28 districts of the country were enrolled in the study. The selection criteria were districts with large cholera caseloads and affected by tropical cyclone Freddy, mostly in the country's central and southern regions during the study period. In each district, the data collection teams visited the major cholera treatment centres to assess the cholera line lists to determine where the cholera caseloads were large. In each locality, a purposive sampling method was used to select households, water kiosks, boreholes, and wells from where samples of drinking water were collected. The definitions of various water sources in Malawi are described in Box 1. Attempts were made to sample all and, if not possible, as many drinking water sources in the selected locality as possible.

2.2.2. Water collection and testing procedure

Three research teams, each comprising five persons, namely, a water chemist, water microbiologist, water quality technician, health surveillance assistant and driver, collected the water samples and data. The Ministry of Health, Ministry of Water and Sanitation, and WHO WASH experts trained the teams on sample collection techniques, calibration, and use of the equipment and recording of the data before the study. The team conducted pilot tests in Lilongwe in households and water sources not included in the study to familiarize themselves with the equipment, water sampling, and testing and data collection procedures. The first team covered Nkhotakota, Salima, Mchinji, Machinga, Mangochi, Balaka, and Neno districts. The second team surveyed Lilongwe, Dedza, Ntcheu, Zomba, Phalombe, and Mulanje, while the third covered Nsanje, Chikwawa, Blantyre, and Thyolo districts. In each locality, the research team collected the water samples from various points where the population collected their drinking water: boreholes, shallow wells, municipal water systems, water kiosks, and drinking storage containers in homes. The data collection team collected approximately 200 ml of water at each sample collection site using the sterilized glass collection vessels or bags included in the testing kit. The water samples were tested for eight water quality parameters, namely, pH, temperature, turbidity, total dissolved substances (TDS), free residual chlorine

Box 1 | Definition of drinking water sources in Malawi

Water source	Definition
Household	This is water stored in containers (jerry cans, drums, pots, etc.) at home for household drinking purposes. These are expected to be chlorinated. This is particularly so given the stage of the cholera epidemic and ongoing distribution of chlorine tablets as part of the emergency water and sanitation interventions.
Borehole	This is a narrow shaft, which is drilled into the ground, with a case and sealed. Water from this source is not expected to be chlorinated but should be free of contamination.
Water board tap stand	This is a piped water tap which is situated in households or compounds. Water from this source is piped by the water board, a government entity mandated to provide clean, safe drinking water to the population of Malawi, and is expected to be chlorinated.
Shallow unprotected well	This is a hand-dug well which is shallow, largely without a case and sealed cover. Water from this source is not expected to be chlorinated and are highly prone to contamination due to it unprotected nature.
Water kiosk	This is a kiosk/vendor that sells water to individuals who do not have water tap stands in their households. Like water board tap stands, water from this source is piped by the water board and is expected to be chlorinated.
Water truck	This is a mobile water tanker that provides drinking water to households. Depending on where the water was fetched, it may or may not be chlorinated.
Unprotected spring	This is unprotected surface water that naturally flows from underground water sources due to gravity or pressure. This water source is not expected to contain chlorine; due to its unprotected nature, it highly prone to contamination.

(FRC), electricity conductivity (EC), thermotolerant coliform (TTC), and *Escherichia coli*. The acceptable ranges and levels for these parameters are outlined in Table 1.

All tests except TTC and *E. coli* counts were conducted onsite to avoid cross-contamination. The tests were performed using the various modules of the Aquasafe® WSL25 Pro water testing kit. pH was measured with Hanna HI9125 digital pH/ORP meter. EC and TDS were measured with a rugged, waterproof, handheld Hanna HI99300 digital EC/TDS meter. Turbidity was measured with a handheld Hanna HI98703 field meter, while FRC was measured with Lovibond MD100T. TTC was measured with a Membrane Filtration kit (M EZFITBASE1), while *E. coli* count was done with the same equipment but using chromogenic *E. coli* agar. For TTC and *E. coli* counts, 100 ml of the water sample was passed through water filter papers which were then put into a sterilized petri dish containing transport media and labelled. In locations where the water filter papers could not be transported to the laboratory within 2–4 h, they were incubated in the field using millipore mobile incubators, while the other samples were transported to the National Central Water Laboratory for incubation. In the laboratory, the filtered water samples were incubated between 36 and 44 °C for 18–24 h. The filtrates in Millipore Petri dishes were then taken out, and the colonies were read using a magnifying glass. TTC colonies have a pinkish colour, while *E. coli* colonies have a greenish-to-bluish colour on the filter paper. The counting of the TTC and *E. coli* colonies on each filter paper was stopped when the count reached 100. The results were entered into forms with 16 variables: name of compound, district, area, date and time of sample collection and testing, type of water source, and the eight water quality parameters.

2.3. Data analyses

A clerk entered the data into Microsoft Excel. The Microsoft Excel database was regularly reviewed by a supervisor to ensure the completeness of the data. A data manager cleaned and exported the data from Microsoft Excel to Stata version 15 (College Station, TX, USA) and R (version 4.2.2) on R Studio (version 2022.12.0-353) where all the analyses were conducted. Continuous variables were summarized as medians and interquartile range (IQR), and categorical variables as proportions. We conducted between-group comparisons using a chi-square or Fisher's exact test whenever the expected frequencies were less than 5. We conducted three separate univariable logistic regression analyses. The dependent variable was either TTC positive or negative, *E. coli* positive or negative, or both TTC or *E. coli* positive or negative. For each of the regression models, the independent variable was the water source (household versus non-household). The results are presented in the form of odds ratios (ORs) and their corresponding 95% confidence intervals (CIs). These ORs represent the risk of contamination of household water sources with TTC, *E. coli*, or either of the two. We also tested the correlation between the presence of FRC and the presence of TTC and *E. coli* in the water source. For all statistical tests, two-tailed $p < 0.05$ was considered statistically significant. We presented the analysed data as tables and figures.

3. RESULTS AND DISCUSSION

We analysed 633 records. Figure 1 presents the distribution of the records according to the type of water source showing that 60.8% of the water samples were collected from households. Table 2 presents the distribution of these water sources

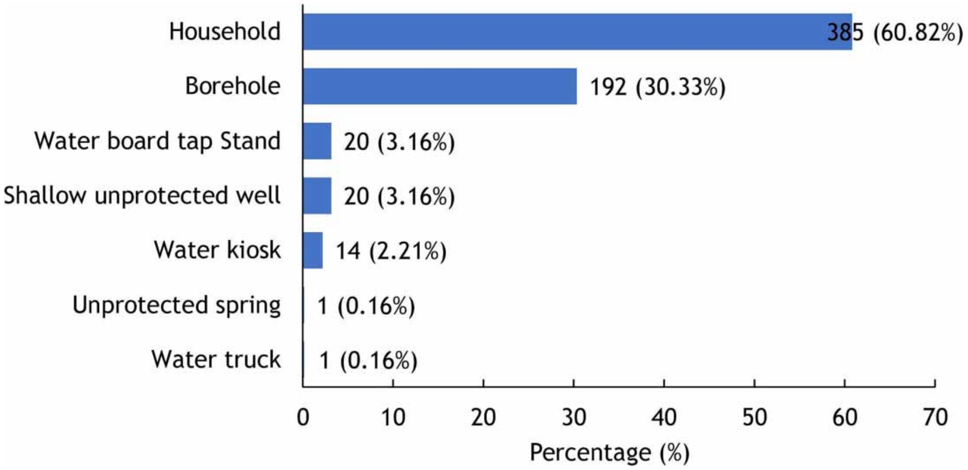

Figure 1 | Distribution of drinking water sources by type in Malawi – February to May 2023.

Table 2 | Distribution of water samples by place and drinking water sources in Malawi – February to May 2023

		Drinking water sources (%)				
	N	**Borehole**	**Household**	**Shallow unprotected well**	**Water board tap Stand**	**Water kiosk/truck and unprotected spring**
District *(N = 633)*						
Balaka	40	13 (32.5)	26 (65.0)	0 (0.0)	1 (2.5)	0 (0)
Blantyre	27	6 (22.2)	18 (66.7)	0 (0.0)	1 (3.7)	2 (7.4)
Chikwawa	39	9 (23.1)	25 (64.1)	0 (0.0)	5 (12.8)	0 (0.0)
Dedza	40	10 (25.0)	28 (70.0)	2 (5.0)	0 (0.0)	0 (0.0)
Lilongwe	50	6 (12.0)	27 (54.0)	8 (16.0)	1 (2.0)	8 (16.0)
Machinga	41	16 (39.0)	23 (56.1)	1 (2.4)	1 (2.4)	0 (0.0)
Mangochi	40	16 (40.0)	23 (57.5)	0 (0.0)	1 (2.5)	0 (0.0)
Mchinji	40	12 (30.0)	22 (55.0)	3 (7.5)	3 (7.5)	0 (0.0)
Mulanje	31	7 (22.6)	23 (74.2)	0 (0.0)	1 (3.2)	0 (0.0)
Neno	40	18 (45.0)	22 (55.0)	0 (0.0)	0 (0.0)	0 (0.0)
Nkhotakota	40	17 (42.5)	22 (55.0)	1 (2.5)	0 (0.0)	0 (0.0)
Nsanje	40	16 (40.0)	22 (55.0)	0 (0.0)	1 (2.5)	1 (2.5)
Ntcheu	42	11 (26.2)	28 (66.6)	1 (2.4)	1 (2.4)	1 (2.4)
Phalombe	39	11 (28.2)	25 (64.1)	0 (0.0)	3 (7.7)	0 (0.0)
Salima	30	9 (30.0)	16 (53.3)	2 (6.7)	1 (3.3)	2 (6.7)
Thyolo	14	4 (28.6)	8 (57.1)	1 (7.1)	0 (0.0)	1 (7.1)
Zomba	40	11 (27.5)	27 (67.5)	1 (2.5)	0 (0.0)	1 (2.5)

according to the districts with Lilongwe district being the most represented with 50 water samples (7.9%). Table 3 shows the median and IQR of the physicochemical and microbiological parameters of drinking water by the district in Malawi. The median counts/100 ml for TTC was 98 (IQR: 4–100) and that for *E. coli* was 0 (IQR: 0–9). For the physicochemical parameters, the median value of the water turbidity in nephelometric turbidity units (NTU) was 1.61 (IQR: 0.79–3.47), FRC was 0 mg/l (IQR: 0–0.2), pH was 7.08 (IQR: 6.61–7.46), conductivity was 755 mg/l (IQR: 275–1275), TDS was 419 mg/l (IQR: 157–762), and temperature was 26.5 °C (IQR: 24.7–28.3). Table 3 also shows that the drinking water in all (except one) districts was contaminated by TTC, while six of the districts had their drinking water sources contaminated by *E. coli*. The turbidity of the water samples in almost all the districts was outside the acceptable national and international (WHO) limits.

For *E. coli* and TTC, the percentage of contaminated drinking water sources was significantly higher in shallow unprotected wells (80.0% for *E. coli* and 95.0% for TTC) and in households (55.8% for *E. coli* and 86.0% for TTC). For the physicochemical parameters, the percentage of the abnormal rate was significantly higher in shallow unprotected wells for the turbidity (95.0%) and pH (35.0%), while 90.9% of the household water samples had sub-optimal FRC. A total of 66.4% of all the water samples had NTU of above 1, which is the nationally acceptable limit for Malawi. When computed using an NTU limit of 5, which is acceptable in emergency situations, the result was 16.8%. A total of 87.6% of the water samples that were expected to have FRC had sub-optimal levels of the chemical which is below the Malawi acceptable level of 0.2 mg/l. When a cutoff of 0.5 mg/l of FRC, which is acceptable during cholera epidemics, was used, only 12.3% of the water samples had the required dosage of chlorine, which is expected during a cholera epidemic (Table 4). Overall, the proportion of water contaminated with *E. coli* was 45.5% (95% CI, 41.64–49.41). The proportion of water contaminated with TTC was significantly higher, i.e., 80.3% (95% CI, 76.96–83.18; $p < 0.000$) (Table 4).

Figure 2 presents the association between the household's water source and the contamination by *E. coli*, TTC, and the contamination by *E. coli* or TTC. Logistic regression showed a significant association between all *E. coli* or TTC contamination and the household's water source. Household water has three times more risk of being contaminated by *E. coli* and two and a half times more risk of being contaminated by TTC.

Table 3 | Median and interquartile range of physicochemical and microbiological parameters of drinking water in Malawi – February to May 2023

	Physicochemical and microbiological parameters of drinking water							
	NTU	**PH**	**FRC**	**EC**	**TDS**	**Temp**	**TTC**	***E. coli***
District *(N = 633)*								
Balaka	0.825 (0.59–1.455)	7.035 (6.76–7.28)	0.09 (0.09–0.1)	148h2.5 (1255–2360)	889.5 (763–1416)	26.85 (25.95–27.7)	87.5 (11.5–100)	0.5 (0–8)
Blantyre	1.51 (0.9–2.74)	6.73 (6.49–7.79)	0 (0–0.2)	396 (113.9–730)	198 (58–363)	25.4 (24–27)	100 (23–100)	0 (0–35)
Chikwawa	0.65 (0.5–1.23)	7.61 (6.96–7.91)	0 (0–0)	1047 (714–1073)	530 (352–624)	30.5 (29.6–31.4)	100 (79–100)	0 (0–0)
Dedza	2.44 (1.04–4.91)	7.135 (6.905–7.455)	0 (0–0.34)	604 (412–1065)	347 (242–557.5)	26.5 (23.35–27.7)	100 (17.5–100)	1.5 (0–37.5)
Lilongwe	3.525 (2.38–7.07)	7.21 (6.73–7.53)	0.24 (0.08–0.39)	239.5 (218–1173)	141.5 (130–702)	24.55 (24.1–25.2)	90 (0–100)	1 (0–52)
Machinga	1.27 (0.82–4.98)	7.63 (6.74–8.01)	1.5 (1.5–1.5)	642 (371–904)	385 (223–542)	27 (26.3–27.7)	100 (9–100)	4 (0–20)
Mangochi	1.415 (0.975–2.775)	7.1 (6.875–7.275)	0 (0–0)	1473 (1167–1809)	884 (700–1085)	28.3 (26.55–28.8)	34.5 (4–100)	0.5 (0–5)
Mchinji	1.55 (0.815–5.5)	5.66 (5.375–5.85)	0.6 (0.09–0.6)	169.5 (128–204)	101.5 (77–122)	25 (23.9–25.65)	30.5 (0–100)	2.5 (0–14)
Mulanje	1.92 (0.87–4.13)	6.67 (6.39–7.11)	0 (0–0.39)	254 (111–380)	152 (67–228)	22.7 (22.6–22.8)	100 (18–100)	1 (0–3)
Neno	1.37 (0.835–1.945)	7.145 (6.875–7.375)	3 (3–3)	1478 (976.5–1996)	887 (586–1197.5)	28 (27–29.7)	3 (0–65)	0 (0–1.5)
Nkhotakota	1.365 (0.62–29.75)	6.355 (6.01–6.505)	–	259 (167–433)	155.5 (100.5–260.5)	28.65 (28–29.4)	100 (19.5–100)	0 (0–2)
Nsanje	0.665 (0.41–1.09)	7.3 (6.9–7.61)	0 (0–0)	681 (563.5–1032)	350 (289–516.5)	28.25 (27.05–29.65)	94 (14.5–100	0 (0–0)
Ntcheu	3.045 (1.72–5.99)	7.415 (7.11–7.68)	0 (0–0.37)	1075.5 (794–1286)	645.5 (476–772)	27.1 (25.7–27.9)	100 (20–100	2.5 (0–13)
Phalombe	2.01 (1.37–4.05)	7.22 (6.97–7.46)	0 (0–0)	801 (548–1104)	481 (329–662)	25.1 (24.4–26.1)	100 (40–100)	3 (0–8)
Salima	0.76 (0.51–1.91)	6.445 (6.23–6.67)	0 (0–0.1)	761 (497–928)	458 (298–567)	27.15 (26.7–28.4)	0 (0–1)	0 (0–40)
Thyolo	0.98 (0.68–1.3)	6.045 (5.43–6.4)	0 (0–0)	200.5 (147–215)	101 (74–108)	26.1 (24.5–27.7)	100 (7–100)	0 (0–0)
Zomba	3.05 (2.465–4.4)	7.425 (7.285–7.575)	0 (0–0.115)	1367.5 (412.5–2000)	809.5 (217.5–1200.5)	24.6 (24.3–24.9)	100 (4–100)	0.5 (0–10.5)

Table 4 | Percentage of drinking water samples that did not meet water quality standards as defined in Table 1 in Malawi–February to May 2023

		% of samples that did not meet water quality standards				
	N	**NTU**	**FRC**	**PH**	**TTC**	***E. coli***
Drinking water source		$p < 0.000$	$p < 0.000$	$p = 0.025$	$p < 0.000$	$p < 0.000$
Borehole	192	48.4	–	28.1	72.4	26.0
Household	385	73.0	90.9	18.7	86.0	55.8
Shallow unprotected well	20	95.0	–	35.0	95.0	80.0
Water board tap stand	20	65.0	63.2	20.0	70.0	20.0
Water kiosk[a]	14	93.3	61.5	7.1	21.4	21.4
Water truck[a]	1	100.0	100.0	0.0	100.0	0.0
Unprotected spring[a]	1	100.0	–	0.0	100.0	0.0
Total	*366*	*66.4*	*87.6*	*21.8*	*80.3*	*45.5*

[a] Less than 20 observations in this group.

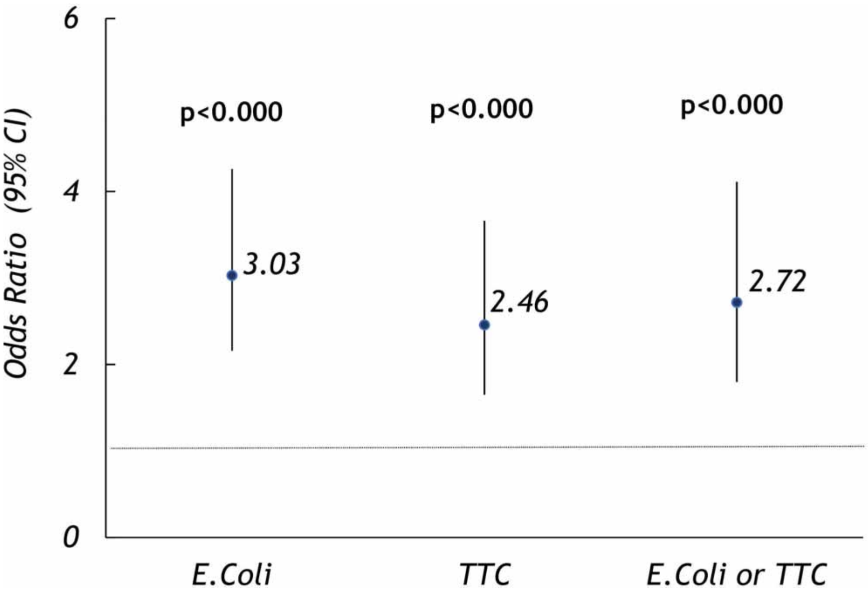

Figure 2 | The association between the household's water source and the contamination by *E. coli*, TTC, and the contamination by *E. coli* or TTC.

The associations between the presence of FRC and *E. coli*, TTC, and both *E. coli* and TTC are presented in Figure 3. This analysis shows that water sources with FRC below the acceptable limits are more likely to be contaminated by TTC, *E. coli*, or both (OR, 2.36 (95% CI, 1.12–5.00) for *E. coli*; OR, 2.92 (95% CI, 1.35–6.29) for TTC; OR, 3.75 (95% CI, 1.72–8.19) for both *E. coli* and TTC).

Our study shows that most of the drinking water sources in Malawi were contaminated with TTC and *E. coli*, turbid, and lacked the required dosage of chlorine to render water safe for drinking in the context of a cholera epidemic. Our results also confirmed that regardless of the type of contamination, drinking water sources at the household level were more likely to be contaminated than all other types of water sources in Malawi, suggesting ongoing contamination at the household level. These findings confirm the anecdotal evidence that the prolonged cholera epidemic in Malawi could have been due to widespread contamination of drinking water sources.

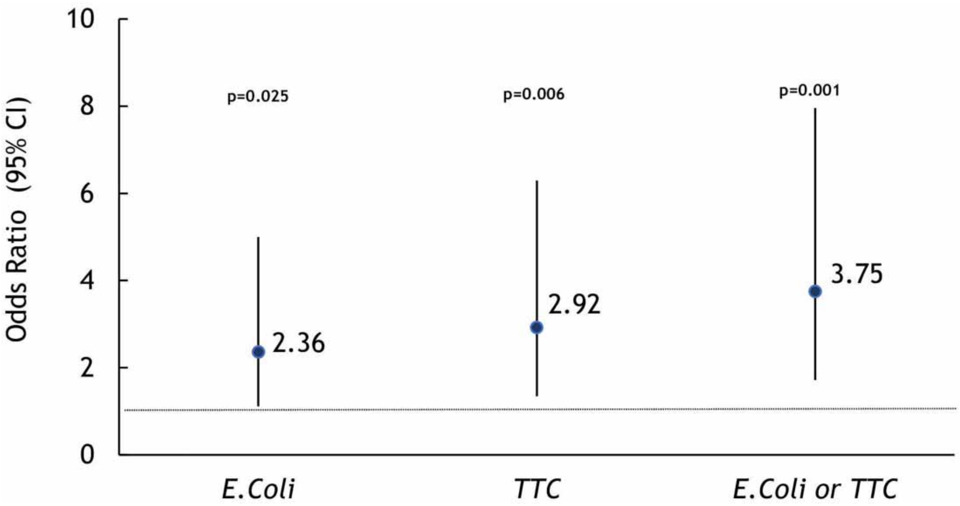

Figure 3 | The association between FRC values that did not meet national standards as defined in Table 1 and contamination by *E. coli*, TTC, and both *E. coli* and TTC.

The fact that most drinking water sources were contaminated cast doubt on the effectiveness of the ongoing WASH and RCCE interventions which commenced implementation almost a year before the study. We posit that these interventions are ineffective due to a few reasons. First, while intensive RCCE interventions were implemented in the country, our observations showed that the messages did not adequately communicate the technicalities involved in the safe handling and storage of household water and hand hygiene. Second, Malawi's high poverty level may be a hindrance to households' compliance with the conditions required to purify and safely store household water. Observations during the study period showed that even when communities were aware of water purification and storage practices, lack of resources often hinder their ability to adopt such practices. Third, the mass water chlorination which was ongoing at the time of the study may have been inadequate in terms of its coverage, intensity, and methodology; this is corroborated by the sub-optimal FRC levels in most drinking water sources in the study area.

Chlorine is a commonly used agent for microbiological quality control of drinking water in water distribution systems. FRC is required in sufficient quantities in drinking water to guarantee its safety throughout the water chain by inhibiting microbiological growth (World Health Organization 2013). The effectiveness of chlorine depends on the water's turbidity level, storage method, and pH of the water. Storage of water away from direct sunlight (i.e., in shaded areas) and in tightly sealed water containers reduces the chances of chlorine evaporation (Rosalam *et al.* 2007). In addition, FRC optimally disinfects water at a pH of 6.8–7.2 (World Health Organization 2013). In an everyday context, the acceptable level for FRC is 0.2 mg/l. However, during a threat or epidemic of cholera, the acceptable limit is increased to 0.5 mg/l (World Health Organization 1993). A significant percentage of the water samples in this study had sub-optimal FRC when subjected to the standard acceptable limits, while only about 12.5% of the water samples met the acceptable level of FRC for an epidemic. This may have contributed to the widespread contamination of household drinking water reported in this study. This observation is supported by the finding that water samples with sub-optimal FRC were more likely to be contaminated, which underscores the importance of intensive, effective, and sustained water chlorination during cholera epidemics. These findings may be due to a few reasons. First, there may have been inadequate chlorination from the waterworks and at the household level. Second, the drinking water sources in the country are largely from untreated sources that are likely to be contaminated, such as boreholes, shallow wells, and other unprotected water sources (Mkandawire & Banda 2009). Third, this finding could have been due to how the water is stored and handled at home. Our observations showed that most household drinking water is stored in open buckets, water drums, and uncovered jerry cans, which could have facilitated rapid evaporation of FRC where present.

The finding that most household drinking water was contaminated is corroborated by other studies (Clasen & Bastable 2003; Copeland *et al.* 2009). This finding is not surprising given the fact that a significant amount of the drinking water sources sampled in this study were contaminated. However, it is of significant concern for controlling the current epidemic as the household, which should be at the centre of the cholera epidemic prevention and control efforts, perpetuates it. We attribute this to two main reasons. First, the sub-optimal level of FRC observed in the majority of drinking water indicates the ineffectiveness of the ongoing chlorination efforts. The second plausible reason could be due to poor storage and handling of household drinking. Several studies have described the factors associated with household water contamination (Gasana *et al.* 2002; Quick *et al.* 2002; Oswald *et al.* 2007). These include the type and design of the storage vessels, the method of drawing drinking water from the storage vessels, the pattern of use of the drinking vessels and water storage conditions. Our observations showed that a combination of these three factors could have also contributed to the contamination of household drinking water.

The high level of TTC may also be associated with the abnormal levels of turbidity and temperature of the water found in this study. Turbidity influences safe drinking water in two ways. First, turbid water provides a suitable medium for pathogens to survive, and second, it reduces the effectiveness of chlorine as a water disinfectant (Kelley *et al.* 2014; Bwire *et al.* 2020). The higher dosage of chlorine, which is required for turbid water, could increase the cost of chlorination and result in chlorine odour and taste in the water, a situation that may result in the rejection of such water. The median turbidity of 1.61 NTU reported in this study is higher than acceptable national and international (WHO) limits but falls within the acceptable limits for emergency situations. Moreover, the turbidity of more than 60% and more than 16.8% of all the water samples were, respectively, above the nationally and internationally acceptable limits, pointing to a critical problem with water turbidity in Malawi. This could contribute to an increased risk of water contamination in the study area. Water temperature also contributes to the quality of drinking water. Temperatures above 17 °C have been demonstrated to be favourable for the survival of pathogens in water (Bwire *et al.* 2020). The median temperature of 26.5 °C, reported in this study, could have contributed to the widespread contamination of the water sources.

Unsurprisingly, many of the unprotected wells and boreholes were contaminated with TTC and *E. coli* given that several studies have documented the risk associated with the consumption of untreated boreholes and well water (O'Dwyer 2015; Taonameso *et al.* 2019; Masindi & Foteinis 2021). However, the process leading to this contamination in the Malawian context requires further elucidation as to whether this is through seepage through the walls, contamination by humans, or surface sewage water (Graham & Polizzotto 2013).

The findings of this study should be interpreted within the context of three limitations. First, the study was conducted in the districts that had active transmission of cholera; thus, its findings may not reflect the situation in the districts that were not reporting cases of the disease at the time of the study. Second, this is a cross-sectional study which tested only one sample from the water sources. The collection of several water samples at various times would have been more representative and shed light on the variations in water quality over time. Nevertheless, we believe that the study's large sample size has compensated for these limitations. Third, most of the water samples were collected from households (stored water), and we could not link contaminated household drinking water to their sources of collection to understand the exact point and mode of contamination. This limitation is, however, mitigated by the fact that most of the drinking water sources in the study were contaminated.

4. CONCLUSION

This study demonstrated widespread contamination of drinking water during a cholera epidemic in Malawi, which may be the plausible reason for the protracted nature of the epidemic. The fact that most of the drinking water at the household level was contaminated supports this conclusion. The high level of household water contamination is likely due to ineffective chlorination, poor personal and household hygiene and poor water collection, transportation, storage, and consumption practices. The widespread turbidity and sub-optimal FRC found in this study could have also contributed to the widespread contamination of the drinking water. Addressing the root causes of this widespread contamination of drinking water sources will play a critical role in breaking the transmission chain of the current epidemic and preventing future ones in Malawi and other African countries.

On the basis of our findings, we propose five key recommendations. First, ongoing surveillance and analyses of drinking water's physicochemical and microbiological parameters and rapid sanitary surveys should be implemented during cholera epidemics. The data from the surveillance system should be used to define the variations in water quality over time. Furthermore, the data should be used to plan, implement, monitor, and evaluate evidence-based WASH and RCCE interventions, particularly those aimed at ensuring safe drinking water. To ensure sustainability, the water quality surveillance should be integrated into the Integrated Disease Surveillance and Response (IDSR) system in cholera-endemic settings. Second, we recommend intensive promotion of sustained and effective hand washing and chlorination of household and other drinking water sources as part of RCCE/WASH interventions to prevent and control the current and future outbreaks. Third, focused RCCE interventions that communicate the technicalities associated with safe handling, storage, and consumption of drinking water in simple language should be implemented to address the widespread contamination of household water during the current epidemic. These interventions should include anthropological methods to understand the local practices fuelling contamination. Fourth, further epidemiological studies are required to identify the other risk factors associated with this protracted epidemic. Finally, we call on the Government of Malawi and its health and WASH partners to implement comprehensive and long-term interventions to strengthen the water and sanitation policies, institutions, and systems in Malawi towards the attainment of the SDGs water targets in the country. This in our view is the key strategy for effective and sustainable prevention and control of cholera and other diarrhoeal diseases in the country in the long term.

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.

REFERENCES

Ajayi, A. & Smith, S. I. 2019 Recurrent cholera epidemics in Africa: Which way forward? A literature review. *Infection* **47** (3), 341–349. doi: 10.1007/s15010-018-1186-5.

Ali, M., Nelson, A. R., Lopez, A. L. & Sack, D. A. 2015 Updated global burden of cholera in endemic countries. *PLOS Neglected Tropical Diseases* **9** (6), e0003832. doi: 10.1371/journal.pntd.0003832.

Blanton, E., Wilhelm, N., O'Reilly, C., Muhonja, E., Karoki, S., Ope, M., Langat, D., Omolo, J., Wamola, N., Oundo, J., Hoekstra, R., Ayers, T., De Cock, K., Breiman, R., Mintz, E. & Lantagne, D. 2015 A rapid assessment of drinking water quality in informal settlements after a cholera outbreak in Nairobi, Kenya. *Journal of Water and Health* **13** (3), 714–725. https://doi.org/10.2166/wh.2014.173.

Bos, R., Alves, D., Latorre, C., Macleod, N., Payen, G., Roaf, V. & Rouse, M. 2016 *Manual on the Human Rights to Safe Drinking Water and Sanitation for Practitioners*. IWA Publishing, London.

Bwire, G., Sack, D. A., Kagirita, A., Obala, T., Debes, A. K., Ram, M., Komakech, H., George, C. M. & Orach, C. G. 2020 The quality of drinking and domestic water from the surface water sources (lakes, rivers, irrigation canals and ponds) and springs in cholera prone communities of Uganda: An analysis of vital physicochemical parameters. *BMC Public Health* **20** (1), 1128. https://doi.org/10.1186/s12889-020-09186-3.

Clasen, T. F. & Bastable, A. 2003 Faecal contamination of drinking water during collection and household storage: The need to extend protection to the point of use. *Journal of Water and Health* **1** (3), 109–1115.

Clemens, J. D., Nair, G. B., Ahmed, T., Qadri, F. & Holmgren, J. 2017 Cholera. *Lancet* **390** (10101), 1539–1549. doi: 10.1016/S0140-6736(17)30559-7.

Copeland, C. C., Beers, B. B., Thompson, M. R., Fitzgerald, R. P., Barrett, L. J., Sevilleja, J. E., Alencar, S., Lima, A. A. & Guerrant, R. L. 2009 Faecal contamination of drinking water in a Brazilian shanty town: Importance of household storage and new human faecal marker testing. *Journal of Water and Health* **7** (2), 324–331. https://doi.org/10.2166/wh.2009.081.

De Zuane, J. 1997 *Handbook of Drinking Water Quality*. John Wiley & Sons, New York.

Gasana, J., Morin, J., Ndikuyeze, A. & Kamoso, P. 2002 Impact of water supply and sanitation on diarrheal morbidity among young children in the socioeconomic and cultural context of Rwanda (Africa). *Environmental research* **90** (2), 76–88. doi: 10.1006/enrs.2002.4394.

Graham, J. P. & Polizzotto, M. L. 2013 Pit latrines and their impacts on groundwater quality: A systematic review. *Environmental Health Perspectives* **121** (5), 521–530. doi: 10.1289/ehp.1206028.

Howard, G., Bartram, J., Williams, A., Overbo, A., Fuente, D. & Geere, J. 2020 Domestic water quantity, service level and health. In: *Domestic Water Quantity, Service Level and Health (who.int)*, 2nd edn (Howard, G., Bartram, J., Williams, A., Overbo, A., Fuente, D. & Geere, J., eds.). World Health Organization, Geneva.

Kelley, C. D., Krolick, A., Brunner, L., Burklund, A., Kahn, D., Ball, W. P. & Weber-Shirk, M. 2014 An affordable open-source turbidimeter. *Sensors (Basel, Switzerland)* **14** (4), 7142–7155. https://doi.org/10.3390/s140407142.

Malawi Standards Board. 2013 *Drinking water specification (ICS13.030.40 - MS 214: 2013) 2nd edition*. Malawi Standards Board, Blantyre. https://mbsmw.org/wp-content/uploads/2017/10/2017-Malawi-Standards-Catalogue.pdf.

Masindi, V. & Foteinis, S. 2021 Groundwater contamination in sub-Saharan Africa: Implications for groundwater protection in developing countries. *Cleaner Engineering and Technology* **2**, 100038. https://doi.org/10.1016/j.clet.2020.100038.

Mkandawire, T. & Banda, E. 2009 Assessment of drinking water quality of Mtopwa village in Bangwe Township, Blantyre. *Desalination* **248** (1–3), 557–561.

Msyamboza, K. P., Kagoli, M., M'bang'ombe, M., Chipeta, S. & Masuku, H. D. 2014 Cholera outbreaks in Malawi in 1998–2012: Social and cultural challenges in prevention and control. *Journal of Infection in Developing countries* **8** (6), 720–726. doi: 10.3855/jidc.3506.

Mumba, M., Kilingo, F. M. & Yongji, Z. 2021 Water availability. Quality and treatment methods in Malawi: A review. *International Journal of Scientific and Research Publications* **11**, 6. doi: 10.29322/IJSRP.11.06.2021.p11472.

O'Dwyer, J. 2015 *Microbiological Contamination of Private Water Wells in the Midwest Region of Ireland: Investigation of Water Quality, Public Awareness and the Application of Logistic Regression in Contaminant Modelling. Thesis*, University of Limerick. https://hdl.handle.net/10344/4652 (accessed 31 August 2023).

Oswald, W. E., Lescano, A. G., Bern, C., Calderon, M. M., Cabrera, L. & Gilman, R. H. 2007 Fecal contamination of drinking water within peri-urban households, Lima, Peru. *The American Journal of Tropical Medicine and Hygiene* **77** (4), 699–704.

Quick, R. E., Kimura, A., Thevos, A., Tembo, M., Shamputa, I., Hutwagner, L. & Mintz, E. 2002 Diarrhea prevention through household-level water disinfection and safe storage in Zambia. *The American Journal of Tropical Medicine and Hygiene* **66** (5), 584–589. doi: 10.4269/ajtmh.2002.66.584.

Rosalam, H. J., Sarbatly, K. & Duduku, K. 2007 Free chlorine residual content within the drinking water distribution system. *International Journal of Physical Sciences* **2** (8), 196–201. https://doi.org/10.5897/IJPS.9000265.

Taonameso, S., Mudau, L. S., Traoré, A. N. & Potgieter, N. 2019 Borehole water: A potential health risk to rural communities in South Africa. *Water Supply* **19** (1), 128–136. https://doi.org/10.2166/ws.2018.030.

The Global Goals. 2023 Goal 6: Clean water and sanitation. Goal 6: Clean water and sanitation – The Global Goals.

United Nations General Assembly. 2010 Resolution 64/292: The human right to water and sanitation. UNITED.

WHO/UNICEF. 2021 *Progress on Household Drinking Water, Sanitation and Hygiene 2000–2020: Five Years Into the SDGs. Progress on Household Drinking Water, Sanitation and Hygiene, 2000–2020: Five Years Into the SDGs – UNICEF DATA*.

World Health Organization. 1993 Guidelines for cholera control. 924154449X.pdf (who.int).

World Health Organization. 2013 Measuring chlorine level in water supplies. Available from: who-tn-11-measuring-chlorine-levels-in-water-supplies.pdf (accessed 16 June 2023).

World Health Organization. 2020 Water, Sanitation and Hygiene (WASH). Water, sanitation and hygiene (WASH) (who.int).

World Health Organization. 2022a Disease outbreak news: Cholera – Malawi (who.int).

World Health Organization. 2022b Tropical storms, flooding and cholera: Malawi faces cholera emergency amidst severe climate events. Tropical storms, flooding and Cholera: Malawi faces cholera emergency amidst severe climate events | WHO | Regional Office for Africa.

World Health Organization. 2023 Weekly Regional Cholera Bulletin: 17 July 2023. AFRO Cholera Bulletin.21_Final.pdf (who.int) (accessed 2 August 2023).

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