A rapid assessment of drinking water quality in informal settlements after a cholera outbreak in Nairobi, Kenya

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ABSTRACT

Populations living in informal settlements with inadequate water and sanitation infrastructure are at risk of epidemic disease. In 2010, we conducted 398 household surveys in two informal settlements in Nairobi, Kenya with isolated cholera cases. We tested source and household water for free chlorine residual (FCR) and *Escherichia coli* in approximately 200 households. International guidelines are ≥0.5 mg/L FCR at source, ≥0.2 mg/L at household, and <1 *E. coli*/100 mL. In these two settlements, 82% and 38% of water sources met FCR guidelines; and 7% and 8% were contaminated with *E. coli*, respectively. In household stored water, 82% and 35% met FCR guidelines and 11% and 32% were contaminated with *E. coli*, respectively. Source water FCR ≥0.5 mg/L ($p = 0.003$) and reported purchase of a household water treatment product ($p = 0.002$) were associated with increases in likelihood that household stored water had ≥0.2 mg/L FCR, which was associated with a lower likelihood of *E. coli* contamination ($p < 0.001$). These results challenge the assumption that water quality in informal settlements is universally poor and the route of disease transmission, and highlight that providing centralized water with ≥0.5 mg/L FCR or (if not feasible) household water treatment technologies reduces the risk of waterborne cholera transmission in informal settlements.

Key words | cholera, *E. coli*, informal settlements, water quality, water treatment

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INTRODUCTION

In 2009, for the first time in recorded history, the urban population exceeded the rural population globally (UNDESA/PD 2010; United Nations 2011). This trend continues, and by 2020, an estimated 54% of the world's population will live in urban areas (United Nations 2011). Urban growth is occurring primarily in developing countries; from 2010 to 2020, the urban growth rate in developing countries is projected to be 2.21% annually compared with 0.61% in developed countries (United Nations 2011).

Many new urban residents in developing countries move into unplanned informal settlements, or slums, defined as 'heavily populated urban area(s) characterized by substandard housing and squalor' (United Nations 2003). Currently, over 1.2 billion people live in informal settlements worldwide (UNSD 2012).

Informal settlements often have inadequate or non-existent infrastructure (Knudsen & Slooff 1992; United Nations 2003, 2011; de Snyder *et al.* 2011; Zulu *et al.* 2011; Patel & Burkle 2012; Katukiza *et al.* 2012); many residents live there illegally or unofficially and therefore do not benefit from government utility services, such as treated water supply, sewage, drainage, and garbage collection (Kimani-Murage & Ngindu 2007). In addition, high population densities make adequate separation of water supply and sewage difficult, leading to contamination (Kimani-Murage & Ngindu 2007). Water may also be contaminated after collection during transport and storage within the home (Ahmed *et al.* 1998).

Populations in informal settlements with inadequate water and sanitation infrastructure are at risk of epidemic disease, such as cholera. Waterborne cholera epidemics decimated the cities of Asia, Europe, and the Americas in the mid-19th century, and remain a persistent threat to cities in developing countries where population density and access to safe drinking water, sanitation, and hygiene are sub-optimal (Barua 1992; Azman *et al.* 2012). Cholera is caused by ingestion of the toxigenic bacterium *Vibrio cholerae* serogroup O1 or O139, most commonly via fecally contaminated food or water. Approximately, 10–20% of cholera cases result in severe illness, and without proper treatment, death by dehydration can occur within a few hours (WHO 2014b).

Epidemic cholera has virtually been eliminated from industrialized nations, largely as the result of centralized piped water and sanitation systems. However, cholera persists in developing nations (WHO 2012). In 1970, the seventh pandemic reached Sub-Saharan Africa, where it continues today. Between 1970 and 2005, Sub-Saharan African populations experienced exponential growth in cholera cases (176,849–758,866) and a relatively steady death rate (Gaffga *et al.* 2007).

To prevent cholera, the World Health Organization (WHO) recommends ensuring safe drinking water, proper hygiene, and adequate sanitation (WHO 2014a). Safe drinking water can be obtained from centralized sources or through use of household water treatment and safe storage (HWTS) options (WHO 2014a). The recommendations for free chlorine residual (FCR) in drinking water in centralized systems and in household treated and stored water during a cholera outbreak are $\geq$0.5 mg/L and 0.2–2.0 mg/L, respectively (WHO 2011). The United Nations Children's Fund (UNICEF) cholera toolkit divides the sources further, recommending 1.0 mg/L in systems with standpipes (UNICEF 2013). Recommended source FCR levels outside times of outbreaks are $\geq$0.2 mg/L (WHO 2011).

Nairobi, the capital city of Kenya, has between 100 and 150 informal settlements, mostly along the city's outskirts (Pamoja Trust 2006; Kenya OpenData 2009), with the exact number of settlements being difficult to define due to variation in boundary definitions and census methods. According to the 2009 census data, the settlements in the Nairobi province and district had populations ranging from 246 to 140,321, land areas from 0.06 to 123 km^2, and population densities from 135 to 119,055 people per square kilometer (Kenya OpenData 2009). The municipal water supply system in Nairobi is managed by the Nairobi Water and Sewerage Company (NaWaSCo); however, NaWaSCo water has limited reach to residents living in informal settlements (Macharia 2012). Some informal settlement residents rely on water purchased from largely unregulated kiosks at fluctuating prices (Patinkin 2013). While this water source is often from the municipal water supply system, it is potentially compromised by illegal tapping, pipe breakage due to old, rusty, or unreliable pipes, cross-contamination from sewer lines and intrusion of contaminants when positive pressure is not maintained throughout the system (Macharia 2012).

Cholera has been reported in Kenya every year since 1971 (WHO 2010). The largest outbreak occurred from 1997 to 1999, with 26,901 cases and 1,362 deaths (WHO 2010, Mutonga *et al.* 2013). About 1,000 cases per year were reported from 2000 to 2007 (Mutonga *et al.* 2013). In 2009, Kenya reported 11,769 cases of cholera, with 274 deaths in all 8 provinces, including the province containing the informal settlements of Nairobi (Mutonga *et al.* 2013).

The goal of this study was to identify which water and sanitation interventions could prevent future cholera outbreaks in informal settlements around Nairobi by: (1) examining the microbiological quality of source and stored household drinking water in two informal settlements in Nairobi recently affected by cholera outbreaks; and (2) assessing water treatment practices at the municipal and household level in these two informal settlements.

METHODS

Informal settlement selection

Two informal settlements were selected for study inclusion based on the following criteria: (1) oral reports of cholera cases to the Ministry of Public Health and Sanitation (MoPHS) by late 2009; and (2) sufficient security within the settlement to allow staff access to resident households. This investigation was part of a public health disease outbreak investigation and did not meet the definition of research under 45 CFR 46.102 (d) and therefore did not require formal Institutional Review Board review. The surveys were completed in January and February 2010.

Household selection

We superimposed grid squares sized 50×50 m over satellite images of the settlements, acquired from the US National Geospatial Intelligence Agency, to obtain a random sample of sources and households throughout the selected settlements, spaced so that each square contained at least one operational water source. Then, a random sample of 100 grid squares in each settlement was generated out of the 228 total squares in Korogocho and 342 in Mukuru. Maps were created using these grid coordinates and satellite images, and used by village guides, who spun a bottle at the central point of the grid square to randomly select two households within the grid. Surveys were completed at both households, and source and household water samples were collected from one of the households, selected by a coin flip. This sampling strategy was designed around the constraint of a maximum microbiological sampling and testing capacity of 600 samples.

Survey

The survey consisted of questions on household demographics, diarrhea prevalence, water source types, storage, and treatment practices; questions on sanitation and hygiene behaviors; knowledge of HWTS options; and household observations including visual verification of the water storage containers and any available water treatment products. Surveys were translated into Swahili and back translated to ensure accuracy. Ten local enumerators were hired and trained in survey administration and water sampling procedures.

Water quality testing

Source and household water samples collected from the selected households were analyzed for FCR, total chlorine residual (TCR), and microbiological water quality.

Enumerators were trained to measure FCR and TCR using Hach® ColorWheel test kits (Loveland, CO, USA) at each surveyed household selected for water testing and at the water source for that household.

Samples for microbiological analysis were collected by enumerators in sterile sample bottles, labeled, stored on ice, and transported to the laboratory for processing within 6 hours of collection. Laboratory tests were conducted at the Centers for Disease Control and Prevention/Kenya Medical Research Institute laboratory in Nairobi, Kenya by trained study staff. Each water sample was tested using Colilert® (Idexx Co., Westbrook, ME, USA) Quanti–Tray® test kits to obtain most probable number (MPN) estimates for total coliforms and *Escherichia coli*. All standard procedures for microbiological testing were met, including testing 10% of samples in duplicate to ensure quality control. To characterize the result repeatability, we conducted selective repeat sampling on a subset of water sources that were negative for total coliform and *E. coli* contamination on initial water quality testing.

Statistical analysis

Survey and water quality data were entered into Microsoft Access and Microsoft Excel (Redmond, WA, USA), cleaned, and exported into Stata 13.0 (College Station, TX, USA) for analysis. T-tests and chi-squared analysis were performed to test for differences between samples grouped by FCR presence, absence of *E. coli*, source and household samples, and between settlement samples in normally distributed data. Normality was checked with histograms, and in cases of non-normal data, Wilcoxon rank-sum tests were performed and medians reported. FCR and *E. coli* variables were also categorized based on WHO standards for water in a cholera setting. Continuous data were reviewed and there was no loss of relevant information by creating categories, such as FCR cutoffs. Variables tested for association included those seen in previous studies to be associated with water quality outcomes.

RESULTS

Site selection

The informal settlements Mukuru kwa Njenga (henceforth referred to as Mukuru) and Korogocho were chosen for study inclusion. Mukuru and Korogocho are located to the north-east of Nairobi and are the third and fourth largest informal settlements of the city. Both lack optimally functioning water and sewage systems.

Korogocho settlement

Based on information from local contacts, Korogocho is home to between 150,000 and 200,000 people living in a 1.5 km^2 area near Nairobi's largest dump. Twenty-nine cases of cholera were reported to the MoPHS in the Korogocho settlement, with illness onset dates ranging from June–December 2009. Ten cases (34.5%) were in females. The median patient age was 5 (range <1–79 years). Stool cultures from 18 (81.8%) of 22 patients yielded *Vibrio cholerae*. One patient died, leading to a case fatality rate (CFR) of 3.4%.

Mukuru settlement

Mukuru houses over 100,000 people according to local contacts. Forty-three cases of cholera were reported in the Mukuru settlement, with illness onset dates ranging from October–November 2009. Patient median age was 14 years (range 0.2–49 years); 20 (46.5%) patients were female. Stool cultures from 14 (60.9%) of 23 patients yielded *Vibrio cholerae*. No deaths were reported.

The numbers above likely represent under-reporting of actual cholera cases and deaths, as active case finding was not conducted (Shikanga *et al.* 2009).

Survey results

We completed 398 household surveys in the two informal settlements in January and February of 2010 (Table 1). No households declined to participate in the study. The average age of respondents was 29.5 years, and over half of respondents (68%) had completed primary school. Most respondents (89%) self-reported literacy (ability to read and write) and most households (59%) had children under 5 years old. There were, however, significant differences between the two informal settlements. The respondents of Korogocho were on average less educated (8 vs. 9 years of school, $p < 0.001$). In addition, 16% of respondents in Korogocho self-reported their household had at least one member with cholera compared to 2% in Mukuru ($p < 0.001$).

Standpipes were the most frequently reported source of drinking water in both settlements, particularly in Korogocho (99 vs. 78%, $p < 0.001$) (Table 2). Respondents in Mukuru also reported using water vendor, water tanker and borehole sources. Fewer Korogocho respondents reported paying for their water (90 vs. 99%, $p < 0.001$). The vast majority of respondents (99.8%) reported living within 500 m of their source; however, the median walking distance in Korogocho was 5 m and in Mukuru 10 m ($p < 0.001$). In addition, the median cost for 20 L of water was

Table 1 | Study population characteristics, Korogocho and Mukuru informal settlements, Nairobi, February 2010

	Korogocho	Mukuru	*p*-value	Total
Number of households surveyed	198	200	–	398
Number (%) female respondents ($n = 398$)	166 (83.8)	171 (86)	0.645	337 (85)
Mean respondent age in years (range) ($n = 397$)	31.1 (13–85)	27.9 (13–53)	0.004	29.5 (13–85)
Number (%) able to read and write ($n = 398$)	170 (86)	183 (92)	0.076	353 (89)
Number (%) of highest education level ($n = 397$)				
No education ($n = 43$)	28 (14)	15 (8)	0.033	43 (11)
Some primary ($n = 85$)	58 (29)	27 (14)	< 0.001	85 (21)
Completed primary ($n = 119$)	56 (28)	63 (32)	0.483	119 (30)
Some secondary ($n = 52$)	23 (12)	29 (15)	0.393	52 (13)
Completed secondary ($n = 83$)	27 (14)	56 (28)	< 0.001	83 (21)
College or university ($n = 15$)	6 (3)	9 (5)	0.441	15 (4)
Mean (range) years in school ($n = 385$)	7.9 (0–19)	9.4 (0–19)	< 0.001	8.7 (0–19)
Median (range) people in household ($n = 398$)	4 (1–52)	4 (1–21)	0.120	4.3 (1–52)
Number (%) children under 5 in HH ($n = 396$)	116 (59)	117 (59)	0.986	233 (59)
Number (%) of households who had cholera ($n = 384$)	31 (16)	4 (2)	< 0.001	35 (9)
Median (range) persons per HH who had cholera ($n = 37$)	0 (1–3)	0 (1–2)	< 0.001	1.3 (1–3)

If data are not normally distributed, median values were reported and Wilcoxon rank-sum test performed.

2 Kenyan shillings ($0.02) in Korogocho and 5 Kenyan shillings ($0.06) in Mukuru ($p < 0.001$). Water was available two-thirds of the day in Korogocho and over half the day in Mukuru ($p = 0.002$), and almost all days of the week in both settlements. Respondents reported collecting water an average of two times per day.

Fewer households in Korogocho reported storing water in their homes (93 vs. 98%, $p = 0.023$). Half (50%) of the storage containers were 2-L Jerry cans, slightly more in Mukuru ($p = 0.038$), with the remainder consisting of 5-L Jerry cans and super drums, which ranged in volume from 50 to 200 L. Overall, 66% of containers had narrow mouths and 79% were covered. Fewer containers were covered in Korogocho than Mukuru ($p < 0.001$).

Compared to Korogocho, in Mukuru almost twice as many respondents reported treating their water (58 vs. 28%, $p < 0.001$), and three times as many reported purchasing treatments (23 vs. 7%, $p < 0.001$) such as the socially marketed, commercially available, liquid chlorine HWTS solution WaterGuard. Overall, 38% of respondents in Mukuru reported receiving free products (almost exclusively Aquatabs brand chlorine tablets) since September 2009. In Korogocho, only 7% had received any water treatment product. The most frequently reported HWTS product donor was the MoPHS (61%). Most (89%) households reported receiving instructions during free product distributions, and approximately a third (28%) saw a demonstration.

Compared to only 10% in Korogocho, 35% of households in Mukuru reported treating their water on the day of the survey ($p < 0.001$). Most households that reported treatment in Korogocho reported boiling; in Mukuru, 55% reported boiling and 42% reported chlorinating.

Almost all households reported using a latrine (90%), of which 96% were shared with other households (Table 2). The median distance from the household to a latrine or toilet was 5 m. Over a quarter (28%) of latrines charged a fee, with a median cost of 3 Kenyan shillings ($0.04) per use. Most households self-reported washing hands with soap and water (94%), though only a fifth (21%) had hand-washing stations and only a quarter of households (24%) had soap at the time of the survey visit.

Water quality

In Korogocho, 27% and 15% of source water samples were contaminated with total coliforms at ≥ 1 and > 10 MPN/100 mL,

Table 2 | Selected water survey results, Korogocho and Mukuru informal settlements, Nairobi, February 2010

	Korogocho ($n = 198$)	Mukuru ($n = 200$)	p-value	Total
Drinking water sources				
Drinking water sources ($n = 398$)				
Public taps/standpipes, n (%)	196 (99)	151 (78)	< 0.001	347 (87)
Water vendor, n (%)	2 (1)	15 (8)	0.001	17 (4)
Water tanker, n (%)	–	22 (11)	< 0.001	22 (6)
Borehole, n (%)	–	12 (6)	< 0.001	12 (3)
Median (range) distance to source in meters ($n = 398$)	5 (1–800)	10 (1–400)	< 0.001	16.6 (1–800)
Mean (%) reported paying for water ($n = 366$)	149 (90)	198 (99)	< 0.001	347 (95)
Median (range) minutes round trip to source ($n = 397$)	5 (1–42)	5 (1–30)	0.285	6.1 (1–42)
Median (range) hours per day water is available ($n = 398$)	16 (2–24)	12 (2–24)	0.002	15.6 (2–24)
Water storage practices				
Mean (%) reported storing water ($n = 396$)	183 (93)	196 (98)	0.023	379 (96)
Narrow-mouthed container ($n = 392$)	128 (66)	132 (67)	0.886	260 (66)
Covered storage container ($n = 390$)	136 (70)	171 (87)	< 0.001	307 (79)
Storage container ($n = 353$)				
20-L jerry can	78 (45)	99 (55)	0.038	177 (50)
5-L jerry can	28 (16)	28 (16)	0.984	56 (16)
Super drum (50–200 L)	33 (19)	26 (14)	0.313	59 (17)
Water treatment practices				
Number (%) reported treating day of study ($n = 267$)	10 (10)	58 (35)	< 0.001	68 (25)
Number (%) reported treating water ($n = 396$)	54 (28)	115 (58)	< 0.001	169 (43)
How often drinking water is treated in HH ($n = 173$)				
Always/sometimes	51 (91)	114 (97)	0.122	165 (95)
Number (%) who purchased treatment since September 2009 ($n = 390$)	14 (7)	46 (23)	< 0.001	60 (15)
Number (%) given treatment since September 2009 ($n = 382$)	14 (7)	73 (38)	< 0.001	87 (23)
Latrines and hygiene				
Disposal of feces – number (%) ($n = 397$)				
Latrine	174 (88)	184 (92)	0.133	358 (90)
Flush toilet	24 (12)	13 (7)	0.056	37 (9)
Median (range) distance in meters to latrine or toilet ($n = 390$)	5 (0–75)	5 (0–200)	0.081	10.3 (0–200)
Number (%) of HH with handwashing stations present ($n = 393$)	42 (22)	39 (20)	0.652	81 (21)
Number (%) of HH with soap present ($n = 363$)	40 (24)	50 (26)	0.732	90 (25)
Number (%) of HH that share latrines	183 (94)	194 (98)	0.038	377 (96)

If data are not normally distributed, median values were reported and Wilcoxon rank-sum performed.

respectively; with an overall geometric mean of 1.3 MPN/100 mL (Table 3, Figure 1(a)). All water quality results including percentage contamination, geometric means of MPN, and chlorine residual medians and ranges are presented in Table 3. In addition, 7–1% of source water samples were contaminated with *E. coli* at ≥1 and >10 MPN/100 mL (Figure 1(b)), with an overall geometric mean of 0.6 MPN/100 mL. The median source water sample FCR was 0.6 mg/L (range 0.0–0.9); and median TCR was 0.7 mg/L (range 0.1–1.2). WHO guidelines for source water FCR levels during a cholera outbreak (≥0.5 mg/L) were met in 82% of the sources.

Table 3 | Water quality of source and stored household water in Korogocho and Mukuru informal settlements, Nairobi, February 2010

	% (*n*)		**Geometric mean MPN (95% CI)**		**Median free chlorine[a] (range)**		**Median total chlorine (range)**	
Settlement	**Korogocho**	**Mukuru**	**Korogocho**	**Mukuru**	**Korogocho**	**Mukuru**	**Korogocho**	**Mukuru**
Source waters								
Total coliform contamination[b] ($n = 96$, 97- Korogocho, Mukuru)	26 (27)	32 (33)	1.3 (0.9–2.0)	1.7 (1.1–2.7)	0.6 (0.0–0.9)	0.4 (0.0–0.8)	0.7 (0.1–1.2)	0.5 (0.0–1.0)
Public tap/standpipe ($n = 92$, 75)	23 (25)	19 (25)	1.2 (0.8–1.7)	1.7 (0.9–3.0)	0.6 (0.1–0.9)	0.4 (0.0–0.8)	0.7 (0.3–1.2)	0.6 (0.0–1.0)
Storage tank ($n = 3$, 1)	2 (67)	0	13.4	0.5	0.1 (0.0–0.9)	0.4	0.2 (0.1–1.0)	0.5
Water tanker ($n = 1$, 14)	1 (100)	8 (57)	90.9	1.5 (0.7–3.2)	0.5	0.3 (0.0–0.7)	0.7	0.5 (0.0–0.8)
Borehole ($n = 0$, 6)	–	4 (57)	–	2.9 (0.2–51.4)	–	0.0 (0.0–0.1)	–	0.0 (0.0–0.1)
Water vendor ($n = 0$, 1)	–	1 (100)	–	3.1	–	0.5	–	0.7
E. coli contamination[b] ($n = 96$, 98)	7 (7)	8 (8)	0.6 (0.5–0.7)	0.7 (0.5–0.9)	0.6 (0.0–0.9)	0.4 (0.0–0.8)	0.7 (0.1–1.2)	0.5 (0.0–1.0)
Public tap/standpipe ($n = 92$, 75)	5 (5)	7 (9)	0.6 (0.5–0.7)	0.7 (0.5–0.9)	0.6 (0.1–0.9)	0.4 (0.0–0.8)	0.7 (0.3–1.2)	0.6 (0.0–1.0)
Storage tank ($n = 3$, 1)	1 (33)	0	1.6 (0.0–257.3)	0.5	0.1 (0.0–0.9)	0.4	0.2 (0.1–1.0)	0.5
Water tanker ($n = 1$, 14)	1 (100)	0	1	0.5	0.5	0.3 (0.0–0.7)	0.7	0.5 (0.0–0.8)
Borehole ($n = 0$, 7)	–	1 (14)	–	1.1 (0.2–7.4)	–	0.0 (0.0–0.1)	–	0.0 (0.0–0.1)
Water vendor ($n = 0$, 1)	–	0	–	–	–	0.5	–	0.7
Household waters								
Total coliform contamination ($n = 96$, 97)	56 (58)	66 (67)	6.4 (3.4–11.8)	21.9 (11.0–43.5)	0.3 (0.0–1.5)	0.0 (0–1.6)	0.4 (0.0–1.8)	0.1 (0.0–2.5)
Narrow-mouthed container ($n = 61$, 67)	31 (51)	46 (69)	5.1 (2.3–11.2)	19.3 (8.6–43.2)	0.3 (0.0–0.8)	0.1 (0–1.5)	0.4 (0.0–0.9)	0.2 (0.0–2.0)
Covered container ($n = 69$, 78)	42 (61)	54 (68)	7.1 (3.4–15.0)	23.0 (10.8–49.0)	0.3 (0.0–1.5)	0.0 (0–1.6)	0.4 (0.0–1.8)	0.1 (0.0–2.5)
20-L jerry can ($n = 36$, 51)	20 (56)	36 (71)	4.2 (1.6–10.8)	12.6 (5.3–30.0)	0.4 (0.0–0.8)	0.1 (0–1.6)	0.5 (0.0–0.9)	0.2 (0.0–1.7)
5-L jerry can ($n = 12$, 13)	10 (83)	8 (62)	32.8 (3.7–289.8)	38.6 (3.8–390.6)	0.3 (0.0–0.7)	0.1 (0–0.9)	0.4 (0.0–0.9)	0.2 (0.0–1.1)
Super drum (50–200 L) ($n = 18$, 11)	11 (61)	6 (55)	7.1 (1.7–30.0)	40.7 (2.3–718.8)	0.1 (0.0–1.5)	0.0 (0.0–1.5)	0.3 (0.0–1.8)	0.1 (0.0–2.5)
E. coli contamination ($n = 96$, 97)	11 (11)	31 (32)	0.7 (0.5–0.8)	1.3 (0.9–1.8)	0.3 (0.0–1.5)	0.0 (0–1.6)	0.4 (0.0–1.8)	0.1 (0.0–2.5)
Narrow-mouthed container ($n = 61$, 67)	5 (8)	19 (28)	0.6 (0.5–0.8)	1.3 (0.8–2.2)	0.3 (0.0–0.8)	0.1 (0–1.5)	0.4 (0.0–0.9)	0.2 (0.0–2.0)
Covered container ($n = 69$, 78)	9 (13)	25 (32)	0.7 (0.5–1.0)	1.2 (0.8–1.7)	0.3 (0.0–1.5)	0.0 (0–1.6)	0.4 (0.0–1.8)	0.1 (0.0–2.5)
20-L jerry can ($n = 36$, 51)	4 (11)	13 (25)	0.8 (0.5–1.4)	0.9 (0.7–1.3)	0.4 (0.0–0.8)	0.1 (0–1.6)	0.5 (0.0–0.9)	0.2 (0.0–1.7)
5-L jerry can ($n = 12$, 13)	1 (8)	3 (23)	0.5 (0.5–0.6)	1.7 (0.4–7.4)	0.3 (0.0–0.7)	0.1 (0–0.9)	0.4 (0.0–0.9)	0.2 (0.0–1.1)
Super drum (50–200L) ($n = 18$, 11)	5 (28)	5 (45)	0.9 (0.5–1.6)	2.8 (0.5–15.8)	0.1 (0.0–1.5)	0.0 (0.0–1.5)	0.3 (0.0–1.8)	0.1 (0.0–2.5)

[a]The recommendations for FCR in drinking water in centralized systems and HWTS during a cholera outbreak are 1.0 mg/L and 0.2 mg/L–2.0 mg/L, respectively.
[b]Contamination was defined as any value greater than ≥1 cfu/100 mL. Percentages are based on all samples and not just those with contamination.

Total coliforms in Korogocho were found in household water samples at ≥1 and >10 MPN/100 mL in 58% and 36%, respectively (Figure 1(c)); with an overall geometric mean of 6.4 MPN/100 mL *E. coli* was found at ≥1 and >10 MPN/100 mL in 11 and 5% of household samples (Figure 1(d)), with an overall geometric mean of 0.7 MPN/100 mL. The median household water FCR was 0.3 mg/L (range 0.0–1.5 mg/L) and median TCR was 0.4 mg/L (range 0.0–1.8). WHO guidelines for stored water FCR levels during a cholera outbreak (≥0.2 mg/L) were met in 82% of the households.

In Mukuru, 33% and 15% of all source water samples had total coliform contamination at ≥1 MPN/100 mL and >10 MPN/100 mL, respectively (Figure 1(a)); with geometric means of 1.7 MPN/100 mL *E. coli* was found in 8% of samples at ≥1 MPN/100 mL and 5% of samples at >10 MPN/100 mL (Figure 1(b)), with a geometric mean of 0.7 MPN/100 mL. The median source water sample FCR was 0.4 mg/L (range 0.0–0.8); and median TCR was 0.5 mg/L (0.0–1.0). WHO guidelines for source water FCR levels during a cholera outbreak (≥0.5 mg/L) were met in 38% of the sources.

Among household water samples in Mukuru 67% were contaminated with total coliform ≥1 MPN/100 mL; 55% were contaminated with total coliform >10 MPN/100 mL (Figure 1(c)); 32% were contaminated with *E. coli* ≥1 MPN/100 mL; and 11% were contaminated with *E. coli* >10 MPN/100 mL (Figure 1(d)). The median FCR and TCR were 0.0 mg/L (range 0–1.5) and 0.1 mg/L (range 0.0–2.5), respectively. WHO guidelines for stored water FCR levels during a cholera outbreak (≥0.2 mg/L) were met in 35% of the households.

Across both settlements, source, and household waters, total coliform and *E. coli* presence was statistically significantly higher when FCR was <0.2 mg/L compared to ≥0.2 mg/L ($p < 0.001$ for all comparisons, Figure 2(a)–(h)).

All 20 sources with *E. coli* <1 MPN/100 mL that were retested in Korogocho were confirmed as <1 MPN/100 mL. In Mukuru, 50 (94%) of the 53 sources that were retested were confirmed as <1 MPN/100 mL; 2 (4%) had <10 MPN/100 mL and 1 (2%) had <100 MPN/100 mL.

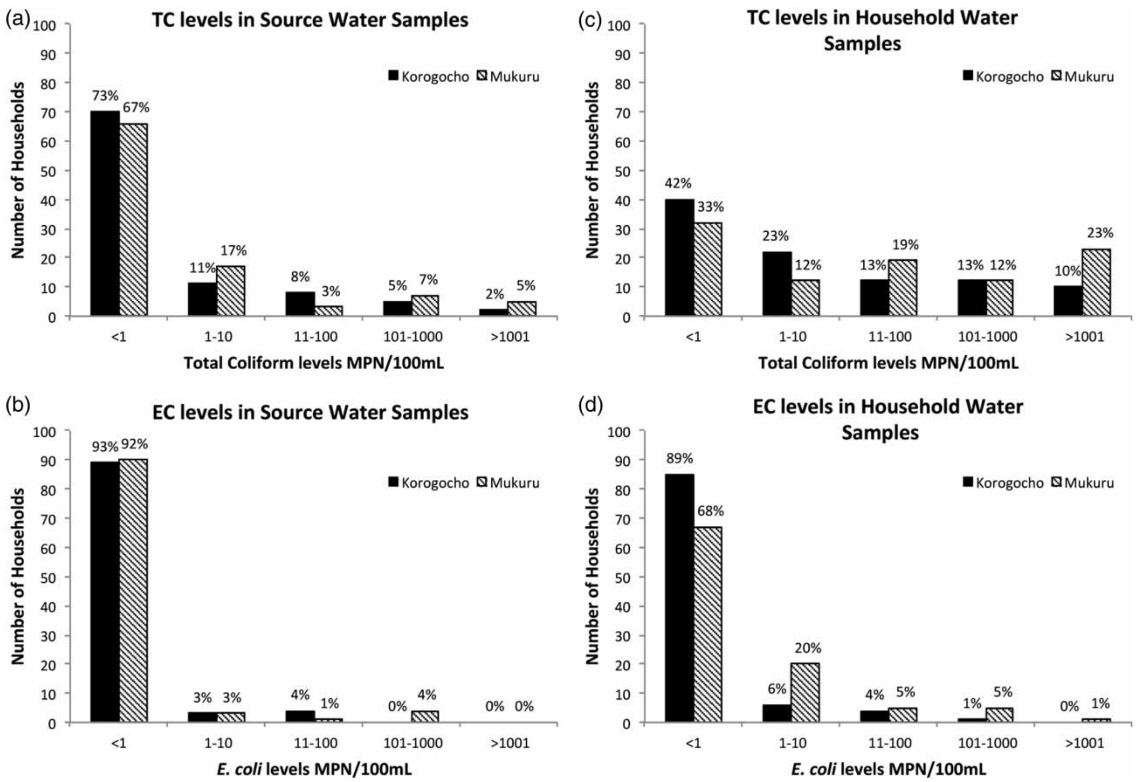

Figure 1 | Total coliform and *E. coli* levels in source and household water samples.

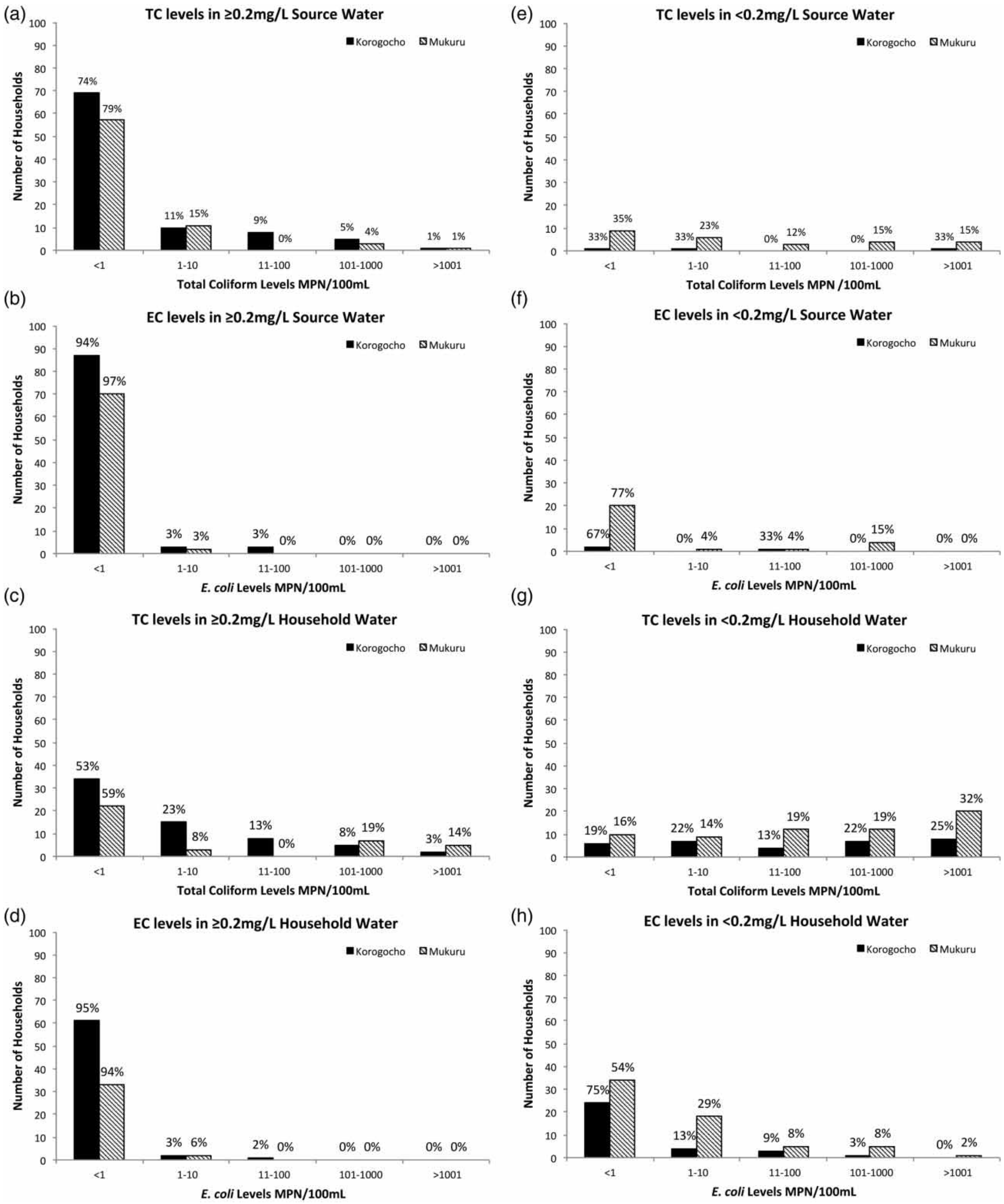

Figure 2 | Total coliform and *E. coli* levels in source and household waters that had FCR levels of ≥ and <0.2 mg/L.

Summary of statistical analysis

Overall, more source waters in Korogocho had FCR ≥0.5 mg/L than source waters in Mukuru (82 vs. 38%, $p < 0.001$). In addition, standpipes in both settlements were more likely to have a FCR ≥0.5 mg/L compared to other sources (66 vs. 23%, $p < 0.001$). Similarly, household waters in Korogocho were more likely to have a FCR ≥0.2 mg/L than household waters in Mukuru (66 vs. 35%, $p < 0.001$).

Household stored waters were more likely to have FCR $\geq$0.2 mg/L when their source water FCR was $\geq$0.5 mg/L (68 vs. 32%, $p = 0.003$). In addition, more household stored waters had FCR $\geq$0.2 mg/L if the household reported purchasing a water treatment method since September 2009 (80 vs. 47%, $p = 0.002$).

Household waters with FCR $\geq$0.2 mg/L were less likely to have *E. coli* contamination than household waters with FCR of <0.2 mg/L (5 vs. 39%, $p < 0.001$).

DISCUSSION

In early 2010, we evaluated demographics, water knowledge, attitude, and practices, and household and source water quality in Korogocho and Mukuru informal settlements after cholera cases were confirmed in these settlements in late 2009. With varying levels of success, the city was able to maintain FCR close to WHO guidelines (but not UNICEF guidelines) in water sources used by the majority of the population in both settlements during a period of cholera risk. Despite, the occurrence of several confirmed cases, no major outbreaks were detected. Households whose water sources met the WHO chlorination guidelines for standpipes during a period of cholera risk (FCR $\geq$0.5 mg/L) were more likely to have stored household drinking water that met WHO chlorination guidelines (FCR $\geq$0.2 mg/L). Consequently, *E. coli*, a marker for fecal contamination, was less likely to be detected in stored household drinking water that met WHO FCR guidelines.

The protective effect of adequately chlorinated source water was evident even in Korogocho settlement, despite less favorable social and environmental circumstances. Korogocho had a larger population of older residents with less education, and higher reported rates of cholera. Household water practices in Korogocho were less ideal, as there were fewer covered containers and less reported water treatment. However, residents of Korogocho had better access to improved water sources: water sources were closer; there were more public taps/standpipes; more hours of access to water; fewer paid for water and the cost of water was less; fewer reported storing water; and, the source water was more likely to have $\geq$0.5 mg/L FCR compared to Mukuru. In addition, Korogocho residents did not have to share latrines as frequently as in Mukuru and the latrines were closer to their homes. Unofficially, it was noticed that Korogocho had far fewer illegal connections to the water supply than in Mukuru, which could have contributed to higher FCR in Korogocho.

While the water quality data are consistent, the cholera data are conflicting. In the survey, Korogocho residents' reported cholera rate is eight times the rate reported in Mukuru (Table 1). However, from the official cholera reports, Mukuru had a rate 2.6 times that of Korogocho: 43/100,000 estimated residents compared to Korogocho at 29/175,000 estimated residents. The discrepancy between these data sets highlights the potential disparities between official surveillance, self-reporting, and actual number of cases. As a result, we cannot definitively differentiate cholera attack rates between the two settlements or include those in analysis.

Our results challenge the assumption that water supply and water quality in informal settlements are universally poor. Overall, >90% of Korogocho and Makuru residents had sources with *E. coli* levels in compliance (<1 MPN/100 mL) with WHO guideline values and over 95% met WHO guidelines for low-risk water (<10 MPN/100 mL). Given the recent cholera outbreak in the country, it is possible that higher than normal FCR levels were maintained in municipal sources in reaction to the outbreak. Total coliform levels rose significantly from source to stored water, but overall contamination levels for *E. coli,* even at the household level, remained low. The observation of total coliform presence, even in the presence of FCR, is consistent with other experiences. The health implications of higher total coliform levels are not entirely known, although especially in tropical areas, environmental bacteria exist in most untreated waters; the presence of total coliforms in treated water can suggest regrowth (WHO 2011).

Reported purchase of HWTS options was also associated with water with sufficient FCR, but this method reached a smaller number of households than centralized source chlorination. HWTS methods have been shown to be effective in small populations in areas with little infrastructure (Harshfield *et al.* 2012). For families that do not have adequately chlorinated water sources, HWTS is a helpful complementary precaution.

Although this work was done after the outbreak, the water quality results presented herein, and the relatively low numbers of cholera cases in these two informal settlements, suggest water might not have been a dominant route of cholera transmission. Alternative transmission vectors, such as contaminated food, including foods and beverages prepared by street vendors, could have played a greater role, as documented in Guatemala (Koo *et al.* 1996). In addition, sub-optimal sanitation and hygiene measures may have also contributed to low-level cholera transmission. Other studies have identified additional risk factors for cholera in African cities, such as proximity to a landfill in Kumasi, Ghana (Osei & Duker 2008), and low elevation in Harare, Zimbabwe (Luque Fernandez *et al.* 2012).

Several other settlements in Nairobi also met study inclusion criteria, but we were unable to conduct investigations there. Thus, our results should not be interpreted as representative of all informal settlements in Nairobi, Kenya. In addition, our results are limited by small sample size in subcategories of water sampling (such as microbiological results from specific types of water sources) that preclude further statistical analysis. We were also not able to collect data at the peak of the outbreak, which could have led to better knowledge of associations between cholera and water quality. Lastly, although the intent was to obtain a random sample, the inclusion of two households in each geographic grid for sampling leads to the possibility of intra-cluster correlation. However, the cluster size was only two, and therefore any design effect would likely be small. We were unable to adjust for this potential design effect in our analysis because, for ethical reasons, data were not kept at the field level on which house was associated with which cluster. Thus the p-values presented herein might be slightly overestimated.

E. coli in household drinking water has been shown to be reflective of fecal contamination (Gruber *et al.* 2014). The WHO guidelines for drinking water quality show that the fecal bacteria *E. coli* and *V. cholerae* are equally intolerant to chlorine treatment, although this depends on the strain of *Vibrio*. The rugose strain of *Vibrio* requires a higher dose of chlorine for a longer period of time to become inactivated compared to the smooth strain and *E. coli*. Nevertheless, once treated, the inactivation for both species is >99.99% (WHO 2011), supporting chlorine as a water treatment of choice for *E. coli* and *Vibrio* contaminations. It has not yet been shown that *E. coli* is an effective indicator bacteria for *Vibrio*, and therefore it cannot reliably be used in order to assess *V. cholerae* contamination. However, as *E. coli* is an indicator for fecal contamination, by definition it can be useful for identifying water sources at risk for other contaminants. In a cholera outbreak, understanding which water sources are fecally contaminated can help direct resources and treatment. It is thus recommended that future water quality studies obtain both microbial contamination as well as residual chlorine data in order to better understand the association between chlorine treatments and clean water and that research is completed to investigate the potential relationship between *E. coli* and *V. cholerae* in the environment.

It is clear from our results that the risk of water contamination and subsequent disease transmission was reduced with sufficient source water chlorination. When the integrity of the distribution system can be assured, centralized water treatment is an effective means to ensure microbiologically safe water for populations living in informal settlements. Household water treatment is a useful adjunct where distribution system integrity is compromised and for populations who depend on unchlorinated or inadequately chlorinated drinking water sources. Based on our results, we recommend following the WHO guidelines for chlorination of water sources to a minimum of 0.5 mg/L in a cholera emergency, and providing supplemental HWTS technologies only when this is not possible or when a significant proportion of the population relies on untreated water sources.

CONFLICT OF INTEREST

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention.

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