Seasonal Variation in Drinking and Domestic Water Sources and Quality in Port Harcourt, Nigeria

Emily Kumpel,^{1*} Alicea Cock-Esteb,¹ Michel Duret,² Dominick de Waal,³ and Ranjiv Khush⁴

¹Aquaya Institute, Nairobi, Kenya; ²Water and Sanitation Program, World Bank, Abuja, Nigeria; ³Water and Sanitation Program, World Bank, London, United Kingdom; ⁴Aquaya Institute, Larkspur, California

Abstract. We compared dry and rainy season water sources and their quality in the urban region of Port Harcourt, Nigeria. Representative sampling indicated that municipal water supplies represent < 1% of the water sources. Residents rely on privately constructed and maintained boreholes that are supplemented by commercially packaged bottled and sachet drinking water. Contamination by thermotolerant coliforms increased from 21% of drinking water sources in the dry season to 42% of drinking water sources in the rainy season ($N = 356$ and $N = 397$). The most significant increase was in sachet water, which showed the lowest frequencies of contamination in the dry season compared with other sources (15%, $N = 186$) but the highest frequencies during the rainy season (59%, $N = 76$). Only half as many respondents reported drinking sachet water in the rainy season as in the dry season. Respondents primarily used flush or pour-flush toilets connected to septic tanks (85%, $N = 399$). The remainder relied on pit latrines and hanging (pier) latrines that drained into surface waters. We found significant associations between fecal contamination in boreholes and the nearby presence of hanging latrines. Sanitary surveys of boreholes showed that more than half were well-constructed, and we did not identify associations between structural or site deficiencies and microbial water quality. The deterioration of drinking water quality during the rainy season is a serious public health risk for both untreated groundwater and commercially packaged water, highlighting a need to address gaps in monitoring and quality control.

INTRODUCTION

In many African cities, access to piped water is low, with average coverage reported as 63% across the continent.¹ In the most populous African country, Nigeria, average piped water coverage was 41% among the 36 utilities reporting in the International Benchmarking Network for Water and Sanitation Utilities (IBNET) database in 2013.² In the absence of piped water infrastructure, residents rely on alternative sources, including groundwater and commercial packaged water. In dense urban settings that lack sewerage, groundwater is vulnerable to contamination by pit latrines, poorly maintained septic systems, and other sources of pollution.^{3–5} Consumption of commercial packaged water has grown markedly in Africa, and studies of water quality have shown they often have lower levels of fecal contamination than other sources.^{6–9}

In a previous study of water sources and water quality in the urban region of Port Harcourt, Nigeria, we found that < 1% of the population had access to piped water.¹⁰ Despite the lack of a centralized sewage collection or treatment system, 71% of the borehole samples and 85% of sachet water samples did not display any detectable fecal contamination.¹⁰ In addition, we did not observe any spatial patterns of water quality contaminants.¹⁰ Although sanitation and other sources of pollution can affect water quality, the effects of nearby sanitation facilities and other factors (e.g., well construction and maintenance, other sources of pollution) vary in different contexts.^{3–5,11–13} However, we collected these data during the dry season. Previous research indicates that drinking water quality is influenced by changing weather patterns, with microbial water quality usually deteriorating in the rainy season.^{14,15} In general, high levels of precipitation raise the groundwater table and increase susceptibility to pollution.¹⁶ Furthermore, little is known about the seasonality of packaged water, as previous studies have been cross-sectional.^{6,14,17}

Our objectives were to compare drinking and domestic water sources and water quality in Port Harcourt between the dry and rainy seasons, specifically evaluating the effects of flooding, rain, and higher water tables on water quality and investigating the influences of sanitation, drainage, and land use on groundwater quality. Given the high prevalence of on-site sanitation systems, identifying patterns in contamination could be helpful for identifying potential hazards and mitigating risks to water quality in non-piped water sources in the Port Harcourt region.

METHODS

Study site. The urban region of Port Harcourt, located in Rivers State, Nigeria, has a population of approximately 2.2 million. The dry season is from November to March and the rainy season is from April to October. During the study period (2013–2015), the Port Harcourt Water Corporation (PHWC) supplied treated and untreated groundwater from elevated tanks and pumping stations at the Rumuola and Moscow well fields through approximately 10 km of functional piped network.

The dominant geological formation in the study area is the Benin Formation, generally comprised of highly permeable sands. Data from an area 50 km north of Port Harcourt documented a multilayered aquifer system with varying degrees of confinement.¹⁸ Boreholes are often hand-augered in this region due to the nature of the soil¹⁹; aquifers tapped by hand-augering are unconfined, which are more susceptible to shallow contaminants.¹⁸

Data collection. We collected water source and water quality data during a dry season (November 2013–February 2014) and a rainy season (July–September 2015). Our analysis of the dry season data was previously published.¹⁰ We developed our sampling framework by first allocating a total of 400 sampling locations across the 17 hydraulic zones of the city in proportion to estimated zonal populations²⁰ and then used ArcGIS (ESRI, Redlands, CA) to randomly assign

*Address correspondence to Emily Kumpel, Aquaya Institute, P.O. Box 21862, Nairobi 00505, Kenya. E-mail: ekumpel@umass.edu

sampling locations within each zone (Supplemental Figure 1). We reassigned half of the sampling locations in each zone to unplanned settlements (identified by densely packed small structures visible from high-resolution satellite imagery available through Google Earth Pro [Google Inc., Mountain View, CA]) to ensure that these areas were adequately represented. The full details of the sampling strategy are described in Kumpel and others.¹⁰

Sample collection teams navigated to the selected locations, identified the structure closest to each location (home, office, place of worship, etc.), and asked occupants to identify their water sources. At each location, they collected water samples from sources used for drinking, cooking, and/or washing (if different). In most cases, water was stored on-site and samples were collected from the storage vessels (e.g., elevated tanks for borehole water, jerrycans for vended water). We managed map and field data with the Fulcrum mobile phone application (Fulcrum Mobile Solutions, LLC, St. Petersburg, FL). We hypothesized that dispersed risk factors might be associated with water quality and, therefore, included some of these variables in the second round; during the rainy season, sample collectors also conducted a short survey about sanitation, land use, and sanitary inspection of boreholes (the latter was adapted from the World Health Organization Drinking Water Quality Guidelines²¹) (Table 1).

Sample collectors flushed taps for a few minutes before collecting samples. They obtained samples from hand-dug open wells (without pumps) with the container regularly used for drawing water. Sample collectors also photographed commercial water sachets, bottles, and storage tanks. Water samples were collected in sterile 1.0-L Whirl-Pak collection bags (Nasco, Modesto, CA) (those for chlorinated water contained sodium thiosulfate to neutralize chlorine) and transported on ice to laboratory facilities at the PHWC for processing within 6 hours of collection.

During both the dry and rainy seasons, we tested water samples for the presence of thermotolerant coliform (TTC) bacteria, nitrate, refined oils, pH, total dissolved solids (TDS), and turbidity. During the dry season, we also tested for fluoride in all samples and arsenic in a subset of samples. During the rainy season, we excluded fluoride and arsenic assays, but we included measurements of iron, *Escherichia coli* bacteria, and total coliform bacteria in all samples and measurements of aluminum, nickel, and zinc in a subset of samples (approximately half of the samples every day). We tested for metal contaminants using Palintest Photometer reagents

(Palintest Ltd, Gateshead, United Kingdom). We used the membrane filtration method to quantify bacterial indicator species. To detect TTC, we incubated filters with lauryl sulfate media (Palintest Ltd.) at 44°C. To detect *E. coli* and total coliforms, we incubated filters with m-ColiBlue24 media (Hach Co., Loveland, CO) at 37°C.

We measured daily rainfall values using a rain gauge (All Weather Rain Gauge; Productive Alternatives Inc., Fergus Falls, MN) installed at the PHWC office in the Rumuola neighborhood of Port Harcourt. Measurements were taken at the same time every morning (half of rainfall measured on Monday morning was apportioned to Saturday and half to Sunday).

We submitted the study protocol for ethical review by the independent Western Institutional Review Board (WIRB) in the United States (Olympia, WA). The WIRB exempted the protocol from full review under the guidance of 45 CFR §46.101(b)(2) of the Common Rule in the United States.

Data analysis. We extrapolated monthly rainfall by taking the average measured daily precipitation for observed days and applying this to unobserved days in the month. We considered total coliform, TTC, and *E. coli* concentrations of ≥ 100 colony-forming units (CFU)/100 mL as too numerous to count. We used the upper detection limit figure in cases where a sample exceeded the detection limit; statistical tests were performed on their rank values (Wilcoxon rank sum) with significance at the $P < 0.05$ level. We reported median values or the upper detection limit for nitrate (the upper detection limits were > 20 or > 80 mg/L, depending on the season). Comparisons between sanitary and land use factors were performed for factors with > 10 observations in the group. We used a value of $\log_{10}(x + 1)$ for log transformations of indicator bacteria. We used a factor of 0.64 to convert from electrical conductivity to TDS.²² We used R (R Core Team, 2016) and ArcGIS 10 (ESRI) to analyze and visualize data.

RESULTS

Respondents and water sources. The proportions of sampling locations were similar in both seasons (Supplemental Table 1): three-quarters were households (73%, $N = 380$, in the dry season and 74%, $N = 399$, in the rainy season), and slightly more businesses were sampled in the dry season than the rainy season (18%, $N = 380$, compared with 12%, $N = 399$). The remaining sampling locations included

TABLE 1

Observations of sanitation facilities, land use, and sanitary conditions at all sampling locations recorded by sample collectors, and observations for the sanitary survey conducted at boreholes

Observations of activities near water point	Sanitary survey of boreholes Yes means a risk factor is present
Sanitation facility in this compound	Lack of superstructure covering borehole
Destination of fecal waste	Latrine or sewerage < 20 m
Sanitation facilities used by neighbors	Sources of pollution < 10 , 10–20, or 20–30 m
Nearby drainage infrastructure	Uncapped well < 20 m
Drain overflowed in the last 1 week	Inadequate fencing
Height of floodwater in the last week/month	Surface surrounding pump sloped
Nearby industry, local refinery, agriculture, market, laundry, recycling, or major construction	Permeable surface surrounding pump
Solid waste visible nearby	Surface surrounding pump flooded
Solid waste disposal method and location	Well seal broken and/or dirty
Domestic animals < 10 m from water source	Pump broken/leakage to ground
Rain in previous 1, 2, or 5 days	Well casing below the maximum flood levels

Adapted from the World Health Organization Drinking Water Quality Guidelines.

FIGURE 1. Percent of respondents reporting use of a water source for drinking, cooking, and washing purposes in the dry (d) and rainy (r) seasons.

government offices or public agencies, places of worship, schools, hospitals, and farms, or open land (Supplemental Table 1). In the rainy season, 88% of boreholes were reportedly owned by respondents, their landlord, or their compound, 8% were public facilities, and 2% belonged to neighbors or commercial establishments ($N = 352$) (data not shown).

In the dry season, we collected 636 water samples from 383 locations: 136 respondents used only one water source and 247 used at least two different water sources (some used three different water sources).¹⁰ In the rainy season, we collected 486 water samples from 399 locations: 312 respondents used only one source of water and 87 used two different sources of water.

During the dry season, 54% of respondents reported drinking sachet water and 10% of respondents reported drinking bottled water ($N = 383$), whereas during the rainy season, use of sachet and bottled water dropped by more than half to 20% and 4%, respectively ($N = 399$) (Figure 1). Conversely, more respondents reported drinking borehole water in the rainy season than in the dry season. Overall, more respondents reported using multiple sources in the dry season due to the greater consumption of commercial packaged water during the dry than the rainy season. Almost all respondents in both study rounds used the same source of water for both cooking and washing (Figure 1).

Seasonal comparisons of water quality. We recorded 474.1 mm of precipitation with the rain gauge between July 10 and September 5, 2015, representing over 50 days of precipitation (of 58 possible days) (Supplemental Table 2, Supplemental Figure 2). Rainfall data reported by other sources suggest that the number of days with rain that we recorded

in July and August 2015 matched average figures for Port Harcourt, though the amounts of precipitation we recorded were lower than in previous years (Supplemental Table 2).

The quality of drinking water sources or water used for any purpose was worse in the rainy season than in the dry season with respect to most of the tested parameters (Tables 2 and 3, Supplemental Table 3). In the dry season, 20.5% of the water sources used for drinking were positive for TTC, which was lower than the 24.5% observed across water sources used for all purposes (drinking, cooking, or washing) ($N = 346$ and 579 , respectively). In the rainy season, the percentage of drinking water sources contaminated with TTC increased to 42.3% ($N = 397$), and the percentage of all water sources contaminated with TTC increased to 41.7% ($N = 482$) (Table 2, Supplemental Table 3). Surprisingly, sachet water samples, which showed the lowest frequencies of TTC contamination during the dry season (14.5% positive for TTC, $N = 186$), showed the highest frequencies of contamination during the rainy season (59.2% positive for TTC, $N = 76$) (Figure 2). Similarly, frequencies and concentrations of TTC in samples from boreholes were significantly higher during the rainy season than the dry season (38% and 29% were positive for TTC and the geometric means were 1.8 and 1.0 CFU/100 mL, respectively) ($P < 0.01$, Wilcoxon rank sum) (Figure 2). There were no significant differences between seasons with respect to TTC concentrations in samples from bottled water, and there were too few samples from open wells or piped systems to test for differences.

Although turbidity and TDS concentrations were significantly higher in the rainy than the dry season ($P < 0.01$, Wilcoxon rank sum); few samples exceeded Nigerian Drinking Water Quality Standards (NDWQS) in either season (Table 2). pH did not change between seasons, with most samples below the NDWQS recommended range of 6.5–8.5 (Table 2).

We only detected elevated nitrate concentrations in the rainy season (Table 3). We did not detect significant arsenic or fluoride contamination (tested only during the first round). However, 83.2% ($N = 185$) of drinking water samples tested during the second round had aluminum concentrations that exceeded the NDWQS of 0.2 mg/L, and 61.6% ($N = 211$) and 69.6% ($N = 391$) of samples tested for nickel and iron had concentrations exceeding the NDWQS (> 0.02 mg/L and > 0.3 mg/L, respectively) (Table 3). Less than 1% of samples exceeded NDWQS for zinc ($N = 229$). We did not detect refined oils in water samples collected from Port Harcourt in either season (Table 3).

TABLE 2
Microbial, physical, and chemical parameters of water quality in water sources used for drinking

Water quality parameters	NDWQS	Dry					Rainy				
		<i>n</i>	Median	min	max	% ES	<i>n</i>	Median	min	max	% ES
Thermotolerant coliform (CFU/100 mL)	0	346	0.6*	< 1	> 100	20.5	397	2.2*	< 1	> 100	42.3
Total coliform (CFU/100 mL)	< 10			Not tested			387	4*	< 1	> 100	36.1
<i>Escherichia coli</i> (CFU/100 mL)	0			Not tested			399	0.6*	< 1	> 100	21.4
Turbidity (NTU)	< 5	372	0.5	0.1	3.4	0	384	0.6	0.1	99.5	1
TDS (mg/L)	< 500†	372	20.2	3.1	713.6	0.5	384	50.1	0.2	1,176.3	2.6
pH	6.5–8.5	372	5.6	3.7	9.7	83.1	327	5.5	3.6	7.6	83.8

% ES = % of samples exceeding NDWQS; CFU = colony-forming units; NDWQS = Nigerian Drinking Water Quality Standards; NTU = nephelometric turbidity unit; TDS = total dissolved solids. Water quality measurements for drinking water sources and comparisons with the NDWQS including the sample size (*n*), median, minimum (min), maximum (max), and % ES in dry and rainy seasons.

* Geometric mean.

† TDS standard based on World Health Organization guideline.

TABLE 3
Chemical and metal parameters of water quality in water sources used for drinking

Water quality parameters	NDWQS	Dry					Rainy				
		n	Median	min	max	% ES	n	Median	min	max	% ES
Fluoride (mg/L)	< 1.5	365	0.1	0	> 1	—			Not tested		
Nitrate (mg/L)	< 50	367	3.4	0	> 40	—	300	> 20	0	> 80	—
Refined oil (mg/L)	0	242	0	0	0	0	268	—	0	0	0
Aluminum (mg/L)	< 0.2			Not tested			185	0.8	0	5.1	83.2
Iron (mg/L)	< 0.3			Not tested			391	0.7	0	50	69.6
Nickel (mg/L)	< 0.02			Not tested			211	0	0	4	61.6
Zinc (mg/L)	< 3			Not tested			229	0.1	0	4.6	0.9
Arsenic (mg/L)	< 0.01	203	0	0	0	0			Not tested		

% ES = % of samples exceeding NDWQS; NDWQS = Nigerian Drinking Water Quality Standards. Water quality measurements for drinking water sources and comparisons with the NDWQS including the sample size (n), median, minimum (min), maximum (max), and % ES in dry and rainy seasons.

Spatial patterns. Although both the frequency of occurrence and concentrations of TTC were higher in water samples taken during the rainy season than the dry season, there were no distinct spatial patterns of TTC contamination in either season, based on comparisons of hydraulic zones at the periphery to the city (zones 1–8 and 14–17; zones shown in Supplemental Figure 3) with those in the center (zones 9–13) ($P = 0.06$, $P = 0.23$, $P = 0.65$ for total coliform, TTC, and *E. coli*, respectively, Wilcoxon rank sum) (Supplemental Figure 3). TDS concentrations were slightly, though significantly, lower in borehole samples collected from zones at the periphery of the city (zones 1–8 and 14–17) compared with zones in the center of the city (zones 9–13) ($P < 0.01$, Wilcoxon rank sum). There were no significant differences in any other parameters between areas of the city ($P > 0.05$, Wilcoxon rank sum) (Supplemental Figure 3).

Comparisons of microbial indicators. In the rainy season, we tested water samples in parallel for three bacterial indicators of microbial water quality: total coliforms, TTC (a subset of total coliforms), and *E. coli* (a subset of TTC). As expected, the frequency and concentrations of total coliform contamination were highest across all source types, followed by TTC and then *E. coli* (Figure 3). We found the highest concentrations of total coliforms in sachet water samples, with a geometric mean value of 13.3 CFU/100 mL: 72% of samples from sachets were positive for total coliform, with 41% of those samples containing concentrations ≥ 100 CFU/100 mL ($N = 74$) (Figure 3).

Escherichia coli is a more specific indicator of fecal contamination than the large group of TTC species. Notably, 24% of sachet water samples were positive for *E. coli*, including 5% at high concentrations of > 100 CFU/100 mL ($N = 76$) (Figure 3). Nineteen percent of samples from boreholes were positive for *E. coli*, including 3% at concentrations of > 100 CFU/100 mL ($N = 354$) (Figure 3).

Sachet water. Among the 284 sachet water samples collected from both seasons, we identified 83 different brands of sachet water (we could not identify the brands for 16 samples). We collected between one and 26 samples per brand. Of these 83 brands, 55 were found in only a single hydrological zone, whereas the remaining brands were found in at most five zones, suggesting that sachets were produced by small-scale, local entrepreneurs. Samples from 14 of the 18 brands that were represented in both seasons were more frequently contaminated with TTC during the rainy season (Figure 4), and TTC levels among these samples were often the same or higher in the rainy than in the dry season (Supplemental Figure 4). Samples from two brands did not contain detectable TTC contamination in either season, and samples from two brands were more frequently contaminated with TTC in the dry season (Figure 4).

Boreholes. Most of the sampled boreholes where enumerators were able to conduct a sanitary survey in the rainy season (169 of 358 boreholes) complied with good sanitary construction and maintenance practices: more than 83% had an intact well seal, had a well casing above floodwaters, did

FIGURE 2. Percent of samples from dry (d) and rainy (r) seasons in all source types with thermotolerant coliform (TTC) concentrations of < 1 , 1–10, 11–100, and > 100 colony-forming units (CFU)/100 mL.

FIGURE 3. Comparisons of fecal indicator bacterial (FIB) contamination by source type during the rainy season: (A) total coliform, (B) thermotolerant coliform, and (C) *Escherichia coli* at concentrations of < 1, 1–10, 11–100, and > 100 colony-forming units (CFU)/100 mL.

not have an uncapped well within 20 m, sloped surfaces, eroded surroundings, or a broken pump, and did not experience flooding near the pump ($N = 169$) (Table 4). However, we frequently observed potential sources of pollution, including latrines, septic tanks, surface waters, and solid waste near boreholes (Table 4). Most lacked a fence or superstructure; however, since they were largely located in compounds, this may not pose a risk (Table 4). Almost half (47%) of the sampled boreholes had a permeable surface near the pump. None of the sanitary factors showed a significant association with indicator bacteria concentrations, although the similarity of sanitary conditions across many boreholes, which included good sanitary construction but poor sanitary conditions and unconfined sandy soils, limited our ability to identify associations ($P > 0.05$, Wilcoxon rank sum) (Table 4).

Sanitation facilities and water quality. Sample collectors recorded sanitation facilities at all sampling locations. Among surveyed respondents, 90.5% had flush or pour-flush toilets (93% of which drained to septic tanks and the

remainder of which drained to rivers), 5.3% had hanging latrines that drained to the river or open drains, and 1.8% had pit latrines ($N = 398$; one respondent did not answer). Septic tanks were emptied manually or by trucks or were allowed to leach underground. As expected, hanging latrines were concentrated in waterfront areas in zones 9, 11, and 17 (Figure 5A), as were instances of fecal waste emptying to the river (Figure 5B). Respondents who reported having no facilities were located in zones near the periphery of the city (1 and 4) or near the river waterfronts (9, 11, and 12) (Figure 5A).

We observed significantly higher concentrations of indicator bacteria (total coliform, TTC, *E. coli*) and nitrate in boreholes located near hanging/pier toilets compared with those located near flush/pour-flush toilets (Table 5). Statistical comparisons of other types of sanitation (pit latrines, lack of facilities) or fecal waste management (open drain or pit) were not possible due to small sample sizes. We also detected significantly higher concentrations of total coliforms in water samples taken from locations with open, unlined drains or

FIGURE 4. Percent of samples positive for thermotolerant coliform in the 18 brands of sachet water (labeled A–R) that were tested in both the dry and rainy seasons. Paired bars represent values from the dry and rainy seasons for each brand.

TABLE 4
Results from the sanitary survey of boreholes

Feature	No Yes Could not observe		
	%		
Lack superstructure	15	84	1
Lack fence	16	83	1
Any pollution			
< 10 m	43	57	0
< 20 m	30	70	0
< 30 m	38	62	0
Latrine septic or surface water < 20 m	31	69	0
Surface permeable	51	47	2
Well seal cracked	83	5	11
Backfill eroded	86	11	2
Well casing below floodwaters	86	7	7
Uncapped well < 20 m	89	10	1
Surface sloped	92	6	2
Pump broken	95	4	1
Flooded around pump	96	2	2

"Yes" means there is a hazard present; "No" means the hazard is not present. $N = 169$ for all observations. No relationships produced statistically significant differences in total coliform, thermotolerant coliform, or *Escherichia coli* for those with at least 10 observations in each group (Wilcoxon rank sum).

without drains compared with locations with underground drains (sewers), and we detected higher concentrations of TTC in borehole samples collected from locations with covered drains compared with underground drains (Table 5). We did not detect significant differences in microbial indicator bacteria, nitrate, and turbidity concentrations among samples collected from boreholes differentiated by other sanitary factors, including population density, drainage overflows, and recent flooding (Table 5).

We also collected information on solid waste and land uses near sampled locations. The only land use indicators associated with significantly higher microbial indicator bacteria concentrations in boreholes were the presence of solid waste nearby ($P < 0.01$) or signs of animal presence, including any type of animal or livestock ($P < 0.05$), which were positively associated with total coliform contamination (Supplemental Table 4).

DISCUSSION

Seasonality of water sources and quality. We identified significant changes between the dry and rainy seasons in water sources used by respondents: fewer respondents reported drinking sachet and bottled water in the rainy season than in the dry season, although cooking and washing water sources did not change with season (Figure 1). The consistency in use of cooking and washing water sources between seasons suggests that seasonal source switching in Port Harcourt is not due to changes in water availability (e.g., boreholes drying up), which has been reported from other regions of west Africa.²³ Instead, the fluctuations in sachet and bottled water consumption between the dry and rainy seasons suggest that drinking water choice may be related to convenience, outside temperatures, or perceptions of water quality. Average temperatures between 2001 and 2010 ranged from 22.4°C to 32.0°C in the dry season and 21.5°C to 29.1°C in the rainy seasons²⁴; the slightly warmer dry season may promote demand for cooler and more convenient sachet and bottled water.

We also observed significant deterioration in water quality in all source types from the dry to the rainy seasons (Figure 2, Tables 2 and 3). This finding is consistent with a recently published systematic review of water quality which showed that several types of water sources, including boreholes, suffered from greater contamination during the rainy seasons.¹⁴ The significant increases in both the frequency and concentrations of microbial contamination in sachet water in the rainy season (which is consistent for total coliforms, TTC, and *E. coli*) is particularly concerning (Figures 2 and 4). It is possible that treatment is inadequate at manufacturing plants during both seasons, but that the source water quality (likely from boreholes) is worse in the rainy season. In addition, greater exposure to sunlight while sachets are carried in buckets or stored in the open during the dry season may contribute to ultraviolet disinfection.¹⁷ During the dry season, we were able to verify a registration

FIGURE 5. Sanitation facilities reported by respondents at sampling locations throughout the city as (A) type of sanitation infrastructure used by households and (B) where fecal matter was disposed to.

TABLE 5

Geometric mean values of water quality parameters and the sample size for water samples collected from boreholes for sanitary conditions

Variable	Total coliform	TTC	<i>Escherichia coli</i>	Nitrate
	Geometric mean (no. of samples reporting this factor)			
Sanitation of respondent: type				
Flush/pour flush (Ref)	2.6 (319)	1.7 (332)	0.5 (331)	18.0 (241)
Hanging/pier	12.1 (16)**	6.6 (16)*	2.4 (16)**	26.2 (16)**
Pit latrine	2.9 (4)	1.5 (4)	0 (4)	14.6 (3)
None	0.4 (2)	1 (2)	0 (2)	29.5 (2)
Fecal management				
Septic tank (<i>n</i> = Ref)	2.6 (302)	1.7 (315)	0.5 (314)	18.3 (227)
Pit	4.7 (3)	2.4 (3)	0 (3)	14.8 (1)
Open drains	6.4 (6)	2.4 (6)	1.7 (6)	28 (6)
River	6.4 (28)*	3.7 (28)	1.2 (28)	17.8 (26)
Neighbor's sanitation				
Flush/pour flush (Ref)	2.8 (306)	1.7 (317)	0.5 (317)	18.5 (233)
Hanging/pier	9.7 (20)**	4.7 (20)	1.6 (20)	20.9 (20)
Pit latrine	0.6 (9)	2.2 (10)	0 (9)	11.1 (4)
Open defecation	0.3 (3)	3 (3)	0 (3)	34.7 (3)
Population density				
Low (Ref)	2.1 (65)	2.4 (67)	0.6 (67)	17.6 (49)
Medium	2.9 (190)	1.9 (197)	0.6 (197)	19.5 (146)
High	3.5 (87)	1.3 (91)	0.5 (90)	16.9 (68)
Drainage				
Underground drains (Ref)	1 (29)	0.9 (30)	0.4 (30)	17.3 (22)
Covered drains	2.6 (26)	3.5 (28)*	0.3 (28)	16.9 (18)
Open lined	2.6 (138)	1.8 (141)	0.5 (141)	17.1 (104)
Open unlined	4.8 (18)*	1.5 (19)	0.7 (19)	17.8 (13)
None	3.7 (131)*	1.9 (137)	0.6 (136)	20.6 (106)
Drainage overflowed				
No (Ref)	2.2 (223)	1.7 (227)	0.6 (227)	18.3 (165)
Yes	3.2 (32)	2.7 (36)	0.4 (36)	15.7 (25)
Flooding last week				
No (Ref)	2.6 (252)	1.8 (257)	0.6 (257)	18.9 (191)
Yes	3.7 (90)	1.8 (98)	0.5 (97)	17.3 (72)
Flooding last month				
No (Ref)	2.6 (249)	1.8 (254)	0.6 (254)	18.6 (188)
Yes	3.8 (93)	1.9 (101)	0.5 (100)	18.0 (75)

TTC = thermotolerant coliform. Geometric mean values of water quality parameters (total coliform, TTC, *Escherichia coli*, and nitrate) and the sample size (in parenthesis) for water samples collected from boreholes for sanitary conditions as noted by sample collectors. Significance values calculated from Wilcoxon rank-sum tests compared with the reference category (Ref) for each for those with ≥ 10 observations in a group. ** $P < 0.01$; * $P < 0.05$.

number from the Nigerian National Agency for Food and Drug Administration and Control (NAFDAC) for 66 of the 82 different brands of bottled and sachet water represented in our sample. However, the high levels of microbial contamination in sachet water samples in the rainy season indicate that NAFDAC regulations and enforcement are currently not sufficient to ensure their safety.

We detected high concentrations of aluminum, nickel, and iron in water samples (Table 3, Supplemental Table 3). High concentrations of aluminum can occur if the pH is low (51% of samples from borehole water in Port Harcourt were < 5.5), if there are also high levels of humic acids or other complexing agents (e.g., fluoride, sulfate, or industrial ligands such as ethylenediaminetetraacetic acid), or if there is poorly managed mine drainage.²⁵ Heavy metals have been found in other groundwater sources in the delta region of Nigeria due to petroleum exploration and production activities.²⁶ We cannot distinguish between the natural occurrence of these metals and their introduction by industrial activity and improper waste disposal. Exposures to elevated levels of nickel may have health consequences, and elevated aluminum, nickel, and iron levels can cause discoloration, unpleasant taste, and, in the case of iron, corrosion of pipes, well casings, and pumps.²⁷

Risk factors and water quality. During the rainy season, we did find a significant association between borehole water

quality and latrine type: microbial water quality was worse in locations with hanging/pier latrines than those with pour-flush latrines, and was worse in areas that disposed of fecal waste to rivers rather than into septic tanks. We also found a significant association between total coliform in boreholes in areas near open unlined drains or without drains nearby than those in areas near underground drainage (Table 5). We did not find significant associations between water quality and other hazards, including population density, overflow conditions, and flooding (Table 5), or between water quality and sanitary survey observations, although there were too few observations in many groups to make comparisons (Table 4). We did not examine the important role of subsurface soil in this study. Similar studies of the associations between source water quality and sanitary surveys have produced contradictory results.^{3,28,29}

In Port Harcourt, 85% of the respondents in our rainy season sampling frame ($N = 399$) used flush or pour-flush toilets connected to septic tanks, with the remainder relying on sanitation that drained into surface waters. The high prevalence of septic tanks may explain both the relatively low levels of fecal contamination that we observed in groundwater samples during the dry season and the lack of distinct spatial patterns of microbial water quality (Supplemental Figure 3). However, we did find significant associations between nearby hanging latrines and fecal contamination of boreholes

(Table 5); these latrines directly compromise local surface water quality, which can affect groundwater due to frequent flooding in areas along the riverbank. Among other water quality risk factors, we identified positive associations between total coliform levels and two factors: the presence of solid waste near boreholes and the presence of animals near boreholes (Supplemental Table 4). These associations illustrate the risks posed by the ease of contaminant transport through the porous sandy soils and are relevant for sanitary inspections conducted in areas with similarly porous soils.

Limitations. There are several limitations to this study. First, we did not obtain information regarding the soil formations to enable comparisons with water quality parameters. Second, the seasonal observations occurred in two different years, so other changes in the intervening period may have affected water source uses and water quality. Third, although we collected samples for the same locations in both seasons, we did not always collect a sample from the same respondent at each location. Therefore, our results are derived from comparisons of two cross-sectional analyses rather than from a longitudinal study. Finally, the land uses explored in this study were based on visual observations, and there may have been unobserved land uses; exploration of land use could be augmented by satellite or other data sources in future studies.

CONCLUSIONS

The deterioration of microbial drinking water quality during the rainy season and the influence of sanitation facilities on microbial water quality indicate the public health risks associated with current water sources in Port Harcourt. The striking increase in fecal contamination of sachet water during the rainy season is of particular concern. Our results also suggest several important implications for research on and monitoring of water quality in urban areas that are primarily served by non-piped water supplies. First, we found substantial seasonal changes in both water source usage and quality in Port Harcourt, demonstrating the limitations of cross-sectional studies and infrequent monitoring. Second, while sachet water is an expanding drinking water source in urban Africa, there is a need for more research on the factors that influence sachet water quality, such as the relative importance of source water, treatment processes, and packaging; our results emphasize that future studies of sachet water should ensure adequate sample sizes, geographic reach, and time scales. Third, we found that sanitation and drainage facilities indicated risk to groundwater quality, likely mediated by the unique soil and subsurface properties in Port Harcourt. Information on sanitation facilities could be used to guide monitoring and management programs to improve the cost-effectiveness of these programs. Fourth, quantifying the health risks posed by the non-piped drinking water sources in Port Harcourt will help determine the health benefits that might be achieved by upgrading the existing water and sanitation infrastructure, including the planned investment in treated, centralized piped supply. Fifth, the influence of the region's subsurface soil types on groundwater quality (including parameters such as dissolved oxygen and ammonia), and the possibility of industrial contamination, including heavy metals with serious health consequences (e.g., chromium, cadmium), merit further investigation. Finally, most regulations in urban areas focus on formal piped supplies; however, since

almost all residents of Port Harcourt were consuming non-piped water from a variety of different sources, regulatory strategies are needed to ensuring the quality of these alternative water supplies.

Received March 4, 2016. Accepted for publication September 23, 2016.

Published online November 7, 2016.

Note: Supplemental tables and figures appear at www.ajtmh.org.

Acknowledgments: We are grateful for the cooperation and support of the MD of PHWC, Kenneth Anga, the Permanent Secretary Collins Davidson, former Commissioner of Water Resources and Rural Development for Rivers State, Patricia Simon-Hart, and the assistance of Judith Martyns-Yellowe, Ala Chuku, and Engineer Martin Mmeo, and the hard work of field and laboratory staff in Port Harcourt, particularly Monica Nwafur, Queen Amachree, Bele Akanibo, Kenneth Amadi, Peter Bagadam, Gonee Barile, Adaye Braide, Chris Chinedum, Bob-Manuel Sokari Dele, Osowo Ebuta, Isaac Edward, Abraham Elumele, Charles Eniiche Emelike, Helen Abiye Evans, Livewell Ezeagonye, Henrietha Fortune, Helen G. Hosea, Bruce Clinton Itolmukua, Lulu Johnson, Amadi Kenneth, Dennis Miller, Giadom Nenubari, Agolia Aina Ngiataba, Njunjima Njunbemere, Monica Nwofor, Damilola Omolayo, Henrietta Tariah, Williams ThankGod, Frank Derek Ucheowaji, and Joseph Umah.

Financial support: This research was supported by consulting contracts from the Water and Sanitation Program of the World Bank (<http://www.wsp.org>) to The Aquaya Institute. The consulting contracts supported contributions by Emily Kumpel, Alicea Cock-Esteb, and Ranjiv Khush to the study design, data collection, and analysis, and manuscript preparation.

Disclosures: Dominick de Waal and Michel Duret are employees of the Water and Sanitation Program of the World Bank, which funded this research. The study results were not subject to any restrictions or qualifications by the World Bank.

Authors' addresses: Emily Kumpel and Alicea Cock-Esteb, Aquaya Institute, Nairobi, Kenya, E-mail: ekumpel@umass.edu and alicea@aquaya.org. Michel Duret, Water and Sanitation Program, World Bank, Abuja, Nigeria, E-mail: mduret@worldbank.org. Dominick de Waal, Water and Sanitation Program, World Bank, London, United Kingdom, E-mails: ddewaal@worldbank.org. Ranjiv Khush, Aquaya Institute, Larkspur, CA, E-mail: ranjiv@aquaya.org.

REFERENCES

1. Banerjee SG, Morella E, 2011. *Africa's Water and Sanitation Infrastructure: Access, Affordability, and Alternatives*. Washington, DC: The World Bank. <http://elibrary.worldbank.org/doi/book/10.1596/978-0-8213-8457-2>. Accessed January 22, 2016.
2. World Bank, 2016. *The International Benchmarking Network for Water and Sanitation Utilities*. Available at: ib-net.org. Accessed March 1, 2016.
3. Howard G, Pedley S, Barrett M, Nalubega M, Johal K, 2003. Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda. *Water Res* 37: 3421–3429.
4. Kulabako NR, Nalubega M, Thunvik R, 2007. Study of the impact of land use and hydrogeological settings on the shallow groundwater quality in a peri-urban area of Kampala, Uganda. *Sci Total Environ* 381: 180–199.
5. Palamuleni LG, 2002. Effect of sanitation facilities, domestic solid waste disposal and hygiene practices on water quality in Malawi's urban poor areas: a case study of South Lunzu Township in the city of Blantyre. *Phys Chem Earth Parts ABC* 27: 845–850.
6. Fisher MB, Williams AR, Jalloh MF, Saquee G, Bain RES, Bartram JK, 2015. Microbiological and chemical quality of packaged sachet water and household stored drinking water in Freetown, Sierra Leone. *PLoS One* 10: e0131772.
7. Stoler J, Ahmed H, Frimpong LA, Bello M, 2015. Presence of *Pseudomonas aeruginosa* in coliform-free sachet drinking water in Ghana. *Food Contr* 55: 242–247.

8. Stoler J, Tutu RA, Winslow K, 2015. Piped water flows but sachet consumption grows: the paradoxical drinking water landscape of an urban slum in Ashaiman, Ghana. *Habitat Int* 47: 52–60.
9. Williams AR, Bain RE, Fisher MB, Cronk R, Kelly ER, Bartram J, 2015. A systematic review and meta-analysis of fecal contamination and inadequate treatment of packaged water. *PLoS One* 10: e0140899.
10. Kumpel E, Albert J, Peletz R, de Waal D, Hirn M, Danilenko A, Uhl V, Daw A, Khush R, 2016. Urban water services in fragile states: an analysis of drinking water sources and quality in Port Harcourt, Nigeria, and Monrovia, Liberia. *Am J Trop Med Hyg* 95: 229–238.
11. Cronin A, Pedley S, Breslin N, Gibson J, 2006. Monitoring source and domestic water quality in parallel with sanitary risk identification in northern Mozambique to prioritise protection interventions. *J Water Health* 4: 333–345.
12. Graham JP, Polizzotto ML, 2013. Pit latrines and their impacts on groundwater quality: a systematic review. *Environ Health Perspect* 121: 521–530.
13. Hynds PD, Misssteart BD, Gill LW, 2012. Development of a microbial contamination susceptibility model for private domestic groundwater sources. *Water Resour Res* 48: W12504.
14. Kostyla C, Bain R, Cronk R, Bartram J, 2015. Seasonal variation of fecal contamination in drinking water sources in developing countries: a systematic review. *Sci Total Environ* 514: 333–343.
15. Levy K, Hubbard AE, Nelson KL, Eisenberg JNS, 2009. Drivers of water quality variability in northern coastal Ecuador. *Environ Sci Technol* 43: 1788–1797.
16. Driscoll FG, 1987. *Groundwater and Wells*. Saint Paul, MN: Johnson Division.
17. Stoler J, Tutu RA, Ahmed H, Frimpong LA, Bello M, 2014. Sachet water quality and brand reputation in two low-income urban communities in Greater Accra, Ghana. *Am J Trop Med Hyg* 90: 272–278.
18. Nwankwoala HO, Walter IO, 2012. Assessment of groundwater quality in shallow coastal aquifers of Okrika Island, Eastern Niger Delta, Nigeria. *Ife J Sci* 14: 297–304.
19. Danert K, Adelike D, Gesti Canuto J, 2014. *Manually Drilled Boreholes: Providing Water in Nigeria's Megacity of Lagos and beyond*. St. Gallen, Switzerland: Skat Foundation, UNICEF, and the Rural Water Supply Network.
20. Shair and Partners, 2012. *Port Harcourt Water Supply Project: Investment Plan Brief, Packages 1–5*. Port Harcourt, Nigeria: Rivers State Ministry of Water Resources and Rural Development.
21. World Health Organization, 1997. *Guidelines for Drinking Water Quality: Volume 3: Surveillance and Control of Community Supplies*, 2nd edition. Geneva, Switzerland: World Health Organization.
22. Hartler T, Rollins L, 2008. *Watersheds, Groundwater and Drinking Water: A Practical Guide*. Davis, CA: University of California Division of Agriculture and Natural Resources.
23. Stoler J, Fink G, Weeks JR, Otoo RA, Ampofo JA, Hill AG, 2012. When urban taps run dry: sachet water consumption and health effects in low income neighborhoods of Accra, Ghana. *Health Place* 18: 250–262.
24. Uko ED, Tamunobereton-Ari I, 2013. Variability of climatic parameters in Port Harcourt, Nigeria. *J Emerg Trends Eng Appl Sci* 4: 727–730.
25. Agency for Toxic Substances and Disease Registry, 2008. *Toxicological Profile for Aluminum*. Atlanta, GA: U.S. Department of Health and Human Services.
26. Asia IO, Jegede SI, Jegede DA, Ize-Iyamu OK, Akpasubi EB, 2007. The effects of petroleum exploration and production operations on the heavy metals contents of soil and groundwater in the Niger Delta. *Int J Phys Sci* 2: 271–275.
27. World Health Organization, 2011. *Drinking Water Guidelines*, 4th edition. Geneva, Switzerland: World Health Organization.
28. Mushi D, Byamukama D, Kirschner AKT, Mach RL, Brunner K, Farnleitner AH, 2012. Sanitary inspection of wells using risk-of-contamination scoring indicates a high predictive ability for bacterial faecal pollution in the peri-urban tropical lowlands of Dar es Salaam, Tanzania. *J Water Health* 10: 236.
29. Patrick JM, Murcott S, Punsalan J, 2011. Coupling microbiological testing and sanitary surveys in drinking water quality programs: results from Capiz Province, Philippines. *J Water Sanit Hyg Dev* 1: 124.