Urban Water Services in Fragile States: An Analysis of Drinking Water Sources and Quality in Port Harcourt, Nigeria, and Monrovia, Liberia

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Abstract. Establishing and maintaining public water services in fragile states is a significant development challenge. In anticipation of water infrastructure investments, this study compares drinking water sources and quality between Port Harcourt, Nigeria, and Monrovia, Liberia, two cities recovering from political and economic instability. In both cities, access to piped water is low, and residents rely on a range of other private and public water sources. In Port Harcourt, geographic points for sampling were randomly selected and stratified by population density, whereas in Monrovia, locations for sampling were selected from a current inventory of public water sources. In Port Harcourt, the sampling frame demonstrated extensive reliance on private boreholes and a preference, in both planned and unplanned settlements, for drinking bottled and sachet water. In Monrovia, sample collection focused on public sources (predominantly shallow dug wells). In Port Harcourt, fecal indicator bacteria (FIB) were detected in 25% of sources ($N = 566$), though concentrations were low. In Monrovia, 57% of sources contained FIB and 22% of sources had nitrate levels that exceeded standards ($N = 204$). In Monrovia, the convenience of piped water may promote acceptance of the associated water tariffs. However, in Port Harcourt, the high prevalence of self-supply and bottled and sachet drinking water suggests that the consumer's willingness to pay for ongoing municipal water supply improvements may be determined by service reliability and perceptions of water quality.

INTRODUCTION

Residents of fragile and conflict-affected states (FCAS), which are more susceptible to violence due to lack of capacity to mediate conflicts, are less likely to have access to safe drinking water than those in stable developing countries.¹ In sub-Saharan Africa, where many fragile states are located, barely one-third of urban citizens have access to piped water supply connections in their dwellings or yards,² and those with piped water may still experience unreliable, poor quality service.³ Most households rely on public standpipes and non-piped water supplies, such as hand-dug wells, boreholes, springs, and water vendors.² The risk of contamination of these water sources by pathogens and harmful chemicals is high due to increasing population densities, lack of adequate sanitation infrastructure, and poor construction.^{4–6}

Robust data on existing water services and water quality are necessary for guiding infrastructure development and management priorities in FCAS. Limited information is generally available regarding the prevalence of different types of water sources and the risks these sources pose to consumer health. Though many non-piped water sources fall within the World Health Organization (WHO)/United Nations Children's Emergency Fund (UNICEF) Joint Monitoring Program (JMP) classification of an improved source, recent studies have questioned whether improved sources, by definition, provide water that is microbiologically safe^{7,8}; others have asked if the risks to water quality among non-piped improved sources are higher in urban than rural areas.⁹

This study analyzes drinking water sources and water quality in two cities—Port Harcourt, Nigeria, and Monrovia, Liberia—that are recovering from political and economic instability that probably contributed to degradation of their public water infrastructure. Of the roughly 190 km of piped

water distribution network that was installed in Port Harcourt in the 1950s, less than 10 km remained functional by 2013.¹⁰ In the 2010 Demographic and Health Survey in Nigeria, 85% of households within the Port Harcourt municipality reported using borehole water as their primary water source.¹¹ In greater Monrovia in 2011, the piped network was estimated to reach less than 5% of the population^{12,13} and half of households reported using water from dug wells.¹⁴ One study of drinking water quality in Port Harcourt focused on commercial sachet water¹⁵; other available water quality data from the city were either limited to surface waters, that are generally not used for drinking, or aggregated with data from the rest of Rivers State, Nigeria.^{16–19} Publicly available data on water quality in Monrovia, which has a history of cholera outbreaks, have been restricted to studies of the informal settlement of West Point.^{20–23}

Both cities have planned or ongoing investments in municipal water infrastructure. In Port Harcourt, the Urban Water Sector Reform and Port Harcourt Water Supply and Sanitation Project and Urban Water Sector Reform Projects (2014–2019) include support from the African Development Bank and the World Bank to rehabilitate and expand the public piped water supply and construct sanitation infrastructure.²⁴ Regulatory reforms include the creation of the Rivers State Water Services Regulatory Commission to oversee the quality of water service provision.^{25,26} In Monrovia, the Liberia Water, Sanitation, and Hygiene (WASH) Sector Investment plan for 2012 to 2017 includes the rehabilitation and extension of the distribution system, the expansion of treatment plant capacity, and a limited focus on non-piped sources (protecting and chlorinating wells).¹³ Our research objective was to generate representative information on drinking water sources and water quality in both cities to inform water management policies and infrastructure priorities. Different sampling strategies, accounting for the differing use of public and private sources in each city, were used to assess water quality: sampling in Monrovia was focused on public sources whereas sampling in Port Harcourt was focused on private and commercial sources.

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MATERIALS AND METHODS

Port Harcourt, Nigeria. *Study site.* Port Harcourt, occupying an area of 300 km² with 2.2 million inhabitants, is located in the Niger Delta region of Rivers State, Nigeria (Figure 1).²⁷ Mean annual rainfall in Port Harcourt is 2,311 mm, with a dry season occurring from November to March and a rainy season from April to October.²⁸ Nigeria's 2010 Poverty Profile reports that half of the households in the study area earn less than US\$1 per day.²⁹ Since Port Harcourt lies within a major oil-producing zone, petroleum contamination is a water quality concern. This risk is exacerbated by illicit tapping ("bunkering") of oil pipelines, which can release significant amounts of crude oil into the environment.³⁰

Port Harcourt is underlain by a thick sequence of unconsolidated deposits of gravels, sand, silts, and clays. The coastal geology in and around Port Harcourt is characterized by quaternary sediments that range from 40 to 150 m in thickness with alternating layers of sand and silt/clay. The Benin Formation underlies the Quaternary Age deposits with thicknesses that are up to 2 km.³¹ Most wells in Port Harcourt are hand-drilled boreholes, a common practice on the Nigerian coastline, enabled by the geologic conditions.³² Reported well depths range up to 60 m for private boreholes, 60–130 m for medium-sized private, industrial, and municipal boreholes, and > 130 m for a more limited number of industrial and municipal boreholes.¹⁰

During the study period (November 2013–February 2014), 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.

Sampling strategy: stratified random geographic sampling. For infrastructure planning purposes, Port Harcourt was divided into 17 hydraulic zones by an engineering firm.^{27,33} We first allocated a number of water sample collection points to each of the 17 zones in proportion to estimated zonal populations, totaling to 400 points (the number of points was determined based on available resources). Using ArcGIS (Esri, Redlands, CA), we then randomly assigned these points to locations within each zone (zone populations, areas,

and sampling frequencies are described in Supplemental Table 3.1). Half of the sampling points in each zone were assigned to unplanned settlements to ensure that these areas were adequately represented; we identified unplanned settlements by manually digitizing contiguous areas of densely packed small structures visible from high-resolution satellite imagery available through Google Earth Pro (Google Inc., Mountain View, CA; Supplemental Text 1, Supplemental Figure 1.1 and 1.2). Other studies have also used satellite imagery to map unplanned settlements based on density, as well as building characteristics, access networks, and settlement locations.^{34–37}

Sample collection and analysis. 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 (Supplemental Text 1). At each location, water samples were collected from the sources identified for drinking, cooking, and/or washing (if separate). As a result, a range of water sources were sampled, including taps, household storage containers, commercial water sachets, and bottled water. Samples from commercial packaged water were collected from unopened sachets or bottles if respondents had them available. If the respondent did not have unopened packages available, the sampling team purchased the same brand of water that the respondents reported using from a nearby shop. In cases where water was stored on-site, all samples were taken from the storage containers to assess quality from water stored before consumption. We managed map and field data with the Fulcrum mobile phone application (Spatial Networks Inc., DE).

Before collecting samples from taps, the sample collectors flame-sterilized or swabbed faucets with alcohol and flushed for a few minutes. Samples from hand-dug open wells (without pumps) were obtained from the container used by the respondent for drawing water. Sample collectors also took photographs of 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

FIGURE 1. Port Harcourt and Monrovia study areas. Each point represents a location where a water sample was collected.

PHWC for processing within 6 hours of collection. Thermotolerant coliforms, pH, electrical conductivity (EC), turbidity, nitrate, fluoride, arsenic, and refined oil concentrations were measured using a Potalab[®] test kit and a Macro 900 meter (Palintest Ltd., Gateshead, United Kingdom). Refined oils, measured with a probe and the Macro 900 meter (lower detection limit 0.1 mg/L), provide a bulk measurement of petroleum hydrocarbons that are highly sensitive to volatile organic compounds such as benzene, toluene, ethyl benzene, and xylene. To enumerate thermotolerant coliforms, the Potalab test kit membrane filtration apparatus was used to filter 100-mL water samples through a 0.45- μ m filter that was subsequently incubated with lauryl sulfate broth at 44°C to select for the growth of thermotolerant coliform bacteria. Equipment for analyzing physical parameters was calibrated regularly and field replicates and blank samples were tested daily.

Monrovia, Liberia. *Study site.* Greater Monrovia experienced a growth in population from approximately 400,000 people in 1998 to nearly 1 million in 2008.³⁸ Liberia has a tropical monsoon climate and an average annual precipitation of 5,100 mm, with a dry season from November to April and a rainy season from May to October.³⁹ In 2011, per capita gross domestic product (GDP) was US\$278.⁴⁰ Monrovia lies along the Cape Mesurado peninsula, between the Atlantic Ocean and the Mesurado River, whose mouth forms a large natural harbor. Greater Monrovia extends north of Cape Mesurado into Montserrado County where the St. Paul River forms the city's northern boundary (Figure 1). The geology in the greater Monrovia area is characterized by the Paynesville Sandstone series of Paleozoic–Mesozoic age (upper weathered zone and deeper, more competent zones), diabase bedrock in the eastern parts of the city, and unconsolidated sandy formations in coastal areas. Groundwater levels are shallow, ranging from less than 1 m in coastal areas to a few meters below ground further inland. Hand-dug wells are shallow (up to 10-m depths) and completed 1–2 m below the top of the water table. Boreholes (drilled wells) are in the 50–100 m depth range.

During the study period in September 2011, the Liberia Water and Sewer Company (LWSC) supplied treated surface water, abstracted from the St. Paul River at the White Plains intake, through a piped network.

Sampling strategy: water source inventory. The Water Point Mapping Project, implemented by the World Bank Water and Sanitation Program and partners, mapped water supplies throughout Liberia in 2010–2011, including more than 1,000 water points in Monrovia. The resulting inventory included protected hand-dug wells fitted with hand pumps, drilled wells (boreholes) fitted with hand pumps, kiosks supplied by vendors from groundwater or municipal water, and standpipes supplied by the LWSC.⁴¹ We used ArcGIS to randomly select 204 water points for sampling (the total number of points was determined by available resources). Selection was stratified by source type to reflect the water sources in the inventory with additional points added to ensure representation from areas of the city prone to cholera outbreaks (Supplemental Text 3.2). We added 18 unprotected hand-dug wells to the sampling frame from locations near sampled protected wells. These were not included in the Water Point Mapping Project inventory but represent a widespread source of drinking water, particularly in dense, low-lying networks such as West Point and Clara Town.

Sample collection and analysis. Before collecting samples, hand pump outlets were flame-sterilized or swabbed with alcohol and flushed for a few minutes. Samples from hand-dug open wells (without pumps) were obtained using Teflon bailers. Water samples were collected for bacteriological analysis in sterile containers with sodium thiosulfate and transported on ice to a field laboratory. Sample collectors photographed sources not included in the Water Point Mapping Project and documented well head and site conditions (well apron, pedestal, general condition of pumps, drainage systems, proximity to latrines, land use).

Laboratory teams measured EC, pH, temperature, and *Escherichia coli* contamination on-site. *Escherichia coli* bacteria were quantified as most probable numbers (MPN) by adding Colilert[®] growth medium (IDEXX Laboratories Inc., Westbrook, ME) to 100-mL water samples and incubating them at 35°C in IDEXX Quanti-Trays[®] (IDEXX Laboratories Inc.). After incubation, compartments that fluoresced under ultraviolet light were counted as positive for *E. coli*. Samples for chemical analysis were packed in coolers with ice and transported to The University of the Free State's laboratory in Bloemfontein, South Africa, for analysis. Equipment for analyzing physical parameters was calibrated regularly and field replicates and blank samples were tested daily.

Research approvals. The water quality analysis in Port Harcourt was approved by the Rivers State Ministry of Water Resources and Rural Development (RSMWRRD) and data collection was restricted to water sampling from residences, business, and public agencies by staff members of the PHWC and RSMWRRD acting in their official capacity. Respondents at each location were informed of the nature of the study, and those agreeing to participate gave verbal consent to the sample collection. The water quality analysis in Monrovia was approved by LWSC and was restricted to sampling public sources of drinking water supplies.

Data analysis. We used sanitary inspection data to classify all groundwater sources according to the definitions used by the WHO/UNICEF JMP as “improved” or “unimproved” water supplies. Boreholes and protected dug wells are improved and unprotected dug wells are unimproved (protected wells are defined as having a lining/casing extending above the ground surface, functioning drainage, and a protective well cover).⁴²

Fecal indicator bacteria (FIB; thermotolerant coliforms in Port Harcourt and *E. coli* in Monrovia) concentrations of > 100 colony-forming units (CFU)/100 mL or > 100 MPN/100 mL were considered too numerous to count. The upper detection limit was used in cases where a sample exceeded the detection limit; statistical tests involving samples that were above the detection limit were performed on their rank values. Log transformations for FIB data used a value of $\log_{10}(x + 1)$. A conservative factor of 0.64 was used to convert from EC to total dissolved solids (TDS).⁴³ Visual display and data analysis were carried out using the ArcGIS 10 (Esri, Redlands, CA) and R (R Core Team, Vienna, Austria, 2014) software packages.

RESULTS

Port Harcourt. *Water sources.* In Port Harcourt, we collected 637 water samples from 386 locations. Most of these sampling locations were households (73%) and small businesses (18%), with the remaining locations (< 10%)

including places of worship, schools, government offices, and hospitals ($N = 383$; data unavailable for three locations). If respondents reported using multiple sources, we collected separate samples of drinking and cooking/washing water. At 244 locations, we collected two samples because the respondents used different water sources for drinking than for cooking/washing. At the remaining 139 locations, we collected one sample because the same water source was used for all three purposes.

Of the 637 water samples, 55% came from boreholes, 32% from commercial sachet water, 6% from vended water (water collected from groundwater sources and sold from hand carts in plastic jerry cans), 5% from commercial bottled water, and < 1% from open dug wells and the PHWC piped network ($N = 636$; source information for one sample was missing). The majority (70%) of the sampled boreholes were privately owned, 27% were commercial, and 2% were government owned ($N = 351$).

Water quality. We only detected significant contamination by FIB: 25% of the samples tested for thermotolerant coliforms had > 0 CFU/100 mL, the Nigerian Drinking Water Standard (NDWS) ($N = 579$; Table 1). FIB concentrations, however, were low, with only 5% of samples exceeding 100 CFU/100 mL ($N = 579$). Nitrate and fluoride concentrations were low, with fewer than 2% of samples exceeding the detection limits of > 40 mg/L and > 1 mg/L, respectively ($N = 625$ and $N = 623$). No samples had detectable concentrations of arsenic ($N = 347$) or refined oils ($N = 410$), and only 1% of the samples contained TDS concentrations greater than the NDWS guideline of 500 mg/L. In most of the samples (90%), turbidity was < 1 nephelometric turbidity unit (NTU) ($N = 629$). The pH of most samples was < 6.5 (89%, $N = 629$). Though low pH is not a health risk, it can accelerate infrastructure corrosion (e.g., well casings, pumps, pipes, etc.), which affects taste.

Fecal contamination was highest in unprotected open wells, although the sample size was very small (five wells; Figure 2). Sachet water showed fewer samples positive for thermotolerant coliforms (15%, $N = 186$) than bottled (26%, $N = 27$), borehole (29%, $N = 322$), or vended water (33%, $N = 36$), with concentrations significantly lower in sachet than borehole water ($P \leq 0.01$, pairwise Wilcoxon rank sum test; Figure 2). Of the borehole samples, 72% tested for FIB were taken from elevated tanks ($N = 317$); these samples had significantly lower thermotolerant coliform contamina-

tion than water stored in drums and buckets ($P \leq 0.01$, Wilcoxon rank sum) (Supplemental Figure 3.1 describes storage containers and associated FIB contamination).

Water use. The majority (67%) of residents used a different source of water for drinking than for cooking or washing, though almost all (96%) reported using the same water source for cooking and washing ($N = 384$; Figure 3). Water used for drinking was of significantly better microbial quality than water used for cooking and washing, and median values of pH, TDS, fluoride, and nitrate were also lower in drinking water than in cooking and washing water (Table 2). These data reflect the fact that many respondents who used borehole or vended water for domestic purposes drank sachet or bottled water. Notably, a similar percentage of residents in unplanned and planned settlements drank sachet water (58% in unplanned versus 53% in planned).

Spatial patterns. Nitrate, TDS, and fluoride concentrations in boreholes were lower in hydraulic zones located at the periphery of the city (zones 1–8 and 14–17, Supplemental Figure 3.2) compared with zones in the center of the city (zones 9–13, Supplemental Figure 3.2) ($P \leq 0.01$, Wilcoxon rank sum) (Figure 4; data not shown for fluoride). We did not find spatial patterns of fecal contamination ($P = 0.09$, Wilcoxon rank sum; Supplemental Figure 3.2) or any significant relationships between fecal contamination and population density (Supplemental Text 2). Within the first 2 km from the waterfront, TDS concentrations were slightly higher in groundwater samples collected closer to the estuaries compared with those collected further away, suggesting limited intrusion of saline estuarine water into nearby wells (Figure 4 and Supplemental Figure 3.3). We did not detect significant differences in water quality between samples collected from drinking water or water used for any purpose from unplanned settlements compared with those from planned settlements ($P = 0.43$ and $P = 0.94$, respectively, Wilcoxon rank sum).

Monrovia. **Water sources.** The water samples in Monrovia were collected from 204 public water points. Of these sources, 91% were supplied with untreated groundwater and included protected hand-dug wells fitted with hand pumps (72%), unprotected hand-dug open wells without hand pumps (open wells; 9%), and boreholes with hand pumps (9%) ($N = 204$). Treated surface water was provided through the LWSC piped distribution network taps and below ground reservoir vaults (3% of sources), with the remaining samples (6%) from kiosks supplied by groundwater or LWSC surface water.

TABLE 1
Summary statistics for measured water quality parameters in Port Harcourt and Monrovia

	Port Harcourt				Monrovia			
	<i>n</i>	Median (range)	NDWS	% ES	<i>n</i>	Median (range)	LWQS	% ES
FIB*/100 mL	579	0 (0 to > 100)	< 1	25%	204	1 (< 1 to > 100)	< 1	57%
pH	629	5.1 (3.5 to 9.7)	6.5 to 8.5	89%	204	5.9 (4.2 to 8.9)	6.5 to 8.0	82%
TDS (mg/L)	629	26 (1 to 714)	< 500	1%	204	107 (15 to 1,015)	< 500†	3%
Turbidity (NTU)	629	1 (0 to 42)	< 5	1%	—	—	—	—
Arsenic (ug/L)	347	< 2 (< 2 to < 2)	< 10	0%	204	< 6 (< 6 to 44)	< 50	0%
Fluoride (mg/L)	622	0.08 (< 0.01 to > 1)	< 1.5	1.5%	204	< 0.01 (< 0.01 to 0.21)	< 1.5	0%
Nitrate (mg/L)	625	4.12 (< 0.01 to > 40)	< 50	50%	204	< 0.05 (< 0.05 to 358.59)	< 40	22%
Refined oil (mg/L)	410	0 (0 to 0)	< 0.007	0%	—	—	—	—

ES = exceeding the standards; FIB = fecal indicator bacteria; LWQS = Liberian Class 1 Water Quality Standards; NDWS = Nigerian drinking water standards; NTU = nephelometric turbidity unit; TDS = total dissolved solids.

The statistics show sample size (*n*), median and range, NDWS and LWQS, and percent of samples exceeding standards (ES).

*FIB were thermotolerant coliforms in Port Harcourt and *Escherichia coli* in Monrovia.

†TDS standard based on WHO guideline.

FIGURE 2. Fecal indicator bacteria (FIB) contamination in Port Harcourt and Monrovia. FIB contamination is shown as the percentage of samples in categories of < 1, 1–10, 11–100, > 100 colony-forming units (CFU) or most probable number (MPN)/100 mL and ordered by the geometric mean concentration of FIB in each source type. Most dug wells with a hand pump were considered protected, whereas open wells lacked a functioning hand pump and were unprotected.

Because of the definition of the sampling frame, all sources were either in communal or institutional settings.

Water quality. The proportion of samples that tested positive for fecal contamination in Monrovia was high: 57% of the samples had ≥ 1 MPN/100 mL *E. coli* and 19% had concentrations ≥ 100 MPN/100 mL ($N = 204$; Table 1). In addition, 22% of the samples exceeded the Liberian standard for nitrate of 40 mg/L ($N = 204$; Table 1). No samples exceeded the standard for fluoride levels and most samples (97%, $N = 204$) had low TDS concentrations (< 500 mg/L). The pH was low (< 6.5) in 80% of samples. Other parameters tested but not presented here are available in Uhl and others, 2012.⁴⁴

Drilled boreholes contained the lowest level of *E. coli* contamination (44%, $N = 18$), followed by protected hand-dug wells fitted with a hand pump (52%, $N = 147$) and kiosks (71%, $N = 14$; Figure 2). All of the open wells (100%, $N = 18$) had detectable *E. coli*, with concentrations significantly higher than in any other source ($P \leq 0.01$, pairwise Wilcoxon rank sum). Nitrate concentrations were higher in shallow

groundwater sources (median: 37 mg/L in open wells and 21 mg/L in protected hand-dug wells with hand pumps) compared with boreholes, which access deeper groundwater (median: 8 mg/L), and piped water (median: < 1 mg/L; Supplemental Figure 3.4).

Spatial patterns. To examine intra-urban differences, we defined three sections of Monrovia based on geography and population density: urban, semi-urban, and peri-urban (Supplemental Figure 3.5), with 71%, 14%, and 15% of sampled sources located in these areas, respectively ($N = 204$; neighborhoods are displayed in Supplemental Figure 3.5). The majority of water sources in peri-urban areas (80%, $N = 145$) and semi-urban areas (75%, $N = 28$) were protected hand-dug wells fitted with a hand pump, whereas in urban areas, sample sources were spread between kiosks (39%), protected hand-dug wells with hand pumps (26%), open wells (19%), and piped water (16%, $N = 31$). Overall, there were no significant spatial trends in *E. coli*, nitrate, or TDS when pooling all groundwater source types ($P > 0.05$ for all comparisons, pairwise Wilcoxon rank sum; Figure 4) except for fluoride, which was higher in urban areas than semi- or peri-urban areas ($P \leq 0.01$ and $P = 0.04$, respectively, Wilcoxon rank sum). Shallow groundwater sources in urban and semi-urban areas had higher nitrate, fluoride, and TDS concentrations than those located in peri-urban areas ($P < 0.05$ for all comparisons, pairwise Wilcoxon rank sum; Figure 4 and Supplemental Figure 3.5). Nitrate and fluoride concentrations were higher in unplanned than in planned settlements ($P = 0.03$ and $P = 0.02$, respectively, Wilcoxon rank sum); however, because only 10% of the samples were collected from water sources in unplanned settlements, these results are limited by small sample size.

Groundwater quality in both cities. To evaluate water quality differences in similar sources, we compared untreated groundwater between Port Harcourt and Monrovia. The majority of sampled groundwater sources were drilled boreholes in Port Harcourt whereas most in Monrovia were shallow hand-dug wells (Figure 2). Boreholes accounted for 89% of the 363 groundwater sources in Port Harcourt tested for

FIGURE 3. Use of water sources for drinking, cooking, and washing in Port Harcourt. The coded bars represent the percentage of respondents in Port Harcourt that reported using each source of water for drinking, cooking, and washing.

TABLE 2
Quality of water sources for drinking and washing in Port Harcourt

	Drinking		Cooking		<i>P</i> value
	<i>n</i>	Median (range)	<i>n</i>	Median (range)	
Arsenic (mg/L)	203	0 (0 to 0)	217	0 (0 to 0)	
Fecal coliform (CFU/100 mL)	346	0 (0 to > 100)†	357	0 (0 to > 100)†	< 0.01**
Fluoride (mg/L)	365	0.06 (0 to > 1)	385	0.09 (0 to > 1)	0.03*
Nitrate (mg/L)	367	3.4 (0.01 to 19.3)	385	5 (0 to > 40)	< 0.01**
pH	372	5.6 (3.7 to 6.3)	383	4.6 (2.5 to 4.2)	< 0.01**
Refined oil (mg/L)	242	0 (0 to 0)	249	0 (0 to 0)	
TDS (mg/L)	372	20 (3.2 to 713.6)	383	45 (0.7 to 713.6)	< 0.01**
Turbidity (NTU)	372	0.5 (0.8 to 3.4)	383	0.5 (0.1 to 41.7)	0.858

CFU colony-forming units; NTU = nephelometric turbidity unit; TDS = total dissolved solids.

The statistics show the sample size (*n*) median values, and ranges of water quality parameters of the water sources used primarily for drinking or cooking/washing. Some samples may be included in both drinking and cooking water quality data sets if used for both purposes. *P* value represents significance testing using Wilcoxon rank sum test. ** *P* < 0.01; * *P* < 0.05.

† In drinking water, 21% of samples drinking water had > 0 CFU/100 mL and 2% of samples had > 100 CFU/100 mL, compared with 29% and 6% in cooking water, respectively.

FIB and only 10% of the 183 groundwater sources tested in Monrovia, whereas shallow dug wells accounted for 1% of sampled groundwater source in Port Harcourt and the majority of sources tested (90%) in Monrovia. Overall, groundwater sources were less contaminated by FIB and nitrate in Port Harcourt than in Monrovia, based on both the percentage of

contaminated sources and their contamination levels (Wilcoxon rank sum, *P* ≤ 0.01; Figures 2 and 4). Boreholes in Port Harcourt had lower concentrations of FIB than boreholes in Monrovia (*P* ≤ 0.01, Wilcoxon rank sum); hand-dug open wells could not be compared because only five wells were sampled in Port Harcourt.

FIGURE 4. Groundwater quality in Port Harcourt (left) and Monrovia (right). The maps display sampling points of groundwater sources in Port Harcourt and Monrovia. The colors represent concentrations of nitrate (NO_3^- ; top row) and total dissolved solids (TDS; bottom row).

In Monrovia, one-third (33%, $N = 110$) of dug wells with hand pumps were unimproved whereas the remaining dug wells were improved (67%, $N = 110$). Overall, improved sources in Port Harcourt had lower concentrations of FIB and nitrate than improved sources in Monrovia: FIB were detected in 22% of improved sources in Port Harcourt ($N = 317$) compared with 36% of those in Monrovia ($N = 91$), and nitrate exceeded 40 mg/L in only 2% of sources in Port Harcourt ($N = 348$) compared with 22% in Monrovia ($N = 90$; Figure 5).

DISCUSSION

Summary of main results. The random selection of water sources in Port Harcourt identified low access to treated piped water, forcing residents to rely on multiple alternative water sources (Figure 2). One-quarter of samples exceeded Nigerian regulatory limits for FIB, though concentrations were low (Table 1). Most residents differentiated between sources for drinking and domestic purposes, indicating an awareness of the importance of water quality: sachet and bottled water were commonly used for drinking and had lower overall levels of contamination (Figure 3 and Table 2). Water quality did not differ significantly between planned and unplanned settlements, and the only spatial variations identified were in levels of nitrate, which were lower at the periphery of the city, and TDS concentrations, which were higher near the waterfront along the Bonny River (Figure 4).

In Monrovia, the sampling framework selected for public water sources, which included hand-dug wells fitted with hand pumps, unprotected open wells, boreholes, kiosks, and LWSC supplied water (Figure 2). This method resulted in the exclusion of sachet and bottled water, though at the time of the study these sources were not prevalent. FIB were found in the majority of tested sources and nitrate levels exceeded regulatory standards in 22% of tested sources (Table 1). Nitrate and TDS concentrations were lower in peri-urban than semi-urban and urban areas (Figure 4 and Supplemental Figure 3.5).

Differences in water quality between Port Harcourt and Monrovia. Though comparisons of groundwater quality showed significantly higher levels of FIB and nitrate in Monrovia than in Port Harcourt (Figures 2 and 5), the com-

position of groundwater sources sampled in the two cities was markedly different, with boreholes constituting the majority of sources in Port Harcourt compared with shallow dug wells in Monrovia. Nevertheless, restricting the groundwater quality comparisons to improved sources in the two cities continued to indicate higher levels of FIB and nitrate contamination in Monrovia than Port Harcourt. This can be explained by the features of boreholes, which generally provide more protection from seepage contamination due to screening below the top of the groundwater table and completion at depths of tens of meters. In contrast, shallow hand-dug wells are completed a few meters below the top of the shallow groundwater table and are vulnerable to impacts from pollution sources such as pit latrines, septic tank drain fields, contaminated drainage ways, and waste disposal. As a result, the aggregated groundwater data from Monrovia includes a greater proportion of samples taken from sources that were more likely to be compromised by fecal contamination due to the nature of their construction and depths of the water table, though many of these contaminated sources in Monrovia are classified as improved sources according to the JMP definition.

In dense urban settings that lack centralized sewage collection, it is well documented that unimproved pit latrines and poorly maintained septic tanks can lead to significant groundwater contamination: latrines and septic tanks that are in close proximity to water points can contribute to both microbiological and nitrate contamination.^{45,46} In both Port Harcourt and Monrovia, sanitation services are inadequate: Port Harcourt has no wastewater or fecal sludge treatment system, and most households rely on septic tanks or pit latrines, or practice open defecation. In Liberia, 70% of the urban population use unimproved sanitation facilities or practice open defecation.^{29,47} Given the similar sanitation conditions in both cities, the less frequent and lower levels of fecal and nitrate contamination in groundwater sources from Port Harcourt merit further investigation (Figure 5).

The differences in fecal contamination between the two cities may have been even more pronounced than we measured: *E. coli*, the indicator species used to detect fecal contamination in Monrovia, represents a subset of the multiple species that comprise thermotolerant coliforms, that was the indicator used in Port Harcourt. It is possible that testing for thermotolerant coliforms instead of *E. coli* in Monrovia

FIGURE 5. Fecal indicator bacteria (FIB) and nitrate concentrations in groundwater sources in Port Harcourt and Monrovia. All groundwater sources include protected and unprotected hand-dug wells, boreholes, and vended water. Improved groundwater sources include boreholes and protected hand-dug wells. Box and whisker plots show the median, lower and upper quartiles, and outliers.

would have identified an even greater number of contaminated samples. Moreover, in Port Harcourt, most samples were obtained from water that had been stored in elevated tanks or in households, whereas in Monrovia, samples were collected directly from water sources, before collection and storage by households. Microbial water quality tends to degrade during collection and storage; therefore, by the time consumers drank water from the sources tested in Monrovia, *E. coli* concentrations had likely increased.⁴⁸ Although the sampling strategy in Port Harcourt was designed to emphasize collection of samples from unplanned settlements, we observed similar water quality within the same source types in both planned and unplanned settlements.

We used different sampling strategies in each city. Stratified geographic random sampling in Port Harcourt focused on the respondent and was appropriate for this context, which had many private, on-plot water sources. This method allowed us to 1) collect data on water source type prevalence in a setting with little prior information (e.g., we were able to quantify use of commercial packaged water), 2) document use of different water sources for different purposes, and 3) collect samples from contexts outside of households, such as businesses and schools. Limitations of this method include the potential to undersample in densely populated areas or buildings. We stratified sampling by zonal populations to reduce this limitation; however, this required documented population data. Our use of satellite data to identify informal settlements suggests that similar techniques could be used to determine population densities. Sampling based on a water source inventory, as applied in Monrovia, was appropriate for sampling public supplies and allowed us to select water sources in proportion to source prevalence. However, inventories may be constrained to certain source types or be incomplete (e.g., the inventory in Monrovia did not include unprotected hand-dug wells, though they were common) and the method excludes private, on-plot sources and packaged water. Future studies should compare the results of sampling using the two methods in the same area.

Notably, we did not detect refined oils in any samples from Port Harcourt. It is possible this was due to the analytical method: concentrations may have been too low (< 0.1 mg/L) for the probe to detect, or the low molecular weight hydrocarbons detected by the instrument may have been biodegraded or removed from solution (via evaporation or partitioning onto soil or sediment particles) as they traveled laterally through the subsurface. Though bunkering of oil is widespread in the region, these activities do not likely occur inside the Port Harcourt metropolitan area. This conclusion is consistent with results from measurements of a stream in the southwest of Port Harcourt that measured low concentrations (< 1 mg/L) of oil and grease.¹⁷

There are several limitations to our comparisons. Seasonal variation may explain some of the observed differences in fecal contamination between the two cities: in Port Harcourt, the study was conducted during the dry season, when fecal contamination of water sources is likely to be lower, and the sampling period in Monrovia took place during the rainy season, when contamination levels are likely to be higher. Previous studies have found that water quality is influenced by weather; microbial water quality, particularly in groundwater sources, usually deteriorates when it rains.^{49,50} Samples collected from boreholes in Port Harcourt during the rainy

season were more frequently contaminated with thermo-tolerant coliforms than those from the dry season (rainy: 38%, $N = 355$; dry: 29%, $N = 322$); however, the rainy season FIB contamination levels remained lower than those observed among groundwater sources in Monrovia.⁵¹ Future studies of urban water quality, particularly of groundwater sources, should account for seasonality in the sampling strategy. Source ownership may also affect water quality: the majority of the sampled sources in Port Harcourt were private whereas all in Monrovia were communal. However, we did not find differences in water quality between commercial, public, or private household boreholes in Port Harcourt (Supplemental Figure 3.6). In a 2011 nationally representative household survey in greater Monrovia, only 10% of households reported using water from on-premises wells, suggesting most households use shared sources.¹⁴

Implications for regulation and investment. The high prevalence of commercial bottled and sachet drinking water may be placing a disproportionate economic burden on poor households: sachet drinking water cost US\$0.03–0.06/500 mL in Port Harcourt at the time of the study and US\$0.11–0.16/300–500 mL in Monrovia at the time of publication. Sachet water was used to similar degrees in planned and unplanned communities in Port Harcourt; therefore, the poor in unplanned settlements are dedicating a higher proportion of their income to purchase what they perceive to be safer drinking water. This inequity is often noted as a consequence of limited public water infrastructure in developing country settings.⁵² Furthermore, 15% of sachet samples and 26% of bottled water samples in Port Harcourt tested were contaminated with FIB (Figure 2). In areas with high demand for these sources, regulation of their quality is an important consideration.

Research from Morocco suggests that the time savings and reductions in social stresses associated with increased water quantity and ease of access promoted high willingness to pay for household water connections, even in areas where public taps with good quality water already existed.⁵³ In Monrovia, surveys indicate that consumers are unsatisfied with their current services and have expressed demand for reliable piped water services.⁴⁸ The recent Ebola outbreak led to temporary closure of some public or shared wells due to rumors of water supply poisoning.^{54–56} These findings suggest that in settings with limited on-site water supplies, consumers may accept the tariff costs associated with obtaining household-level connections.

In Port Harcourt, however, there is extensive reliance on private, self-supply of groundwater. In this context, the consumer's willingness to pay for water services delivered by the ongoing investment in municipal infrastructure improvements may be low. High quality drinking water is one incentive that could increase demand for municipal water services; however, municipal utilities in developing economies are generally not attentive to monitoring and communicating the quality of their water supplies, thereby, promoting reliance on sachet and bottled water marketed as safe. In Ghana, for example, households continue to purchase sachet drinking water, despite the availability of piped water.⁵⁷ Without adequate attention to service quality and raising consumer awareness, infrastructure improvements accompanied by higher tariffs may significantly increase the financial burden of poor households that continue to purchase commercial bottled and sachet water.

Received October 20, 2015. Accepted for publication March 8, 2016.

Published online April 25, 2016.

Note: Supplemental information, table, and figures appear at www.ajtmh.org.

Acknowledgments: The Water and Sanitation Program (WSP) of the World Bank provided funding for these studies. We are grateful for the cooperation and support of the Honorable Commissioner of Water Resources and Rural Development for Rivers State, Nigeria, Patricia Simon-Hart, her special assistant Judith Martyns-Yellowe, the acting MD of PHWC, Engineer Martin Mmeo, and the hard work of field and laboratory staff in Port Harcourt: Frank Derek Ucheowaji, Isaac Edward, Monica Nwofor, Queen Amachree, Damilola Omolayo, Agolia Ngiataba, Henrietha Fortune, Dennis Miller, Bele Akanibo, Giadom Nenubari, Amadi Kenneth, Njunjima Njunbemere, Williams ThankGod, Livewell Ezeagonye, Adaye Braide, Peter Bagadam, and Abraham Elumele. We also acknowledge input from CMAP in Port Harcourt. In addition, we would like to acknowledge the University of the Free State, EDEN Preferred Water Services, and, in Liberia, Abdul Koroma, Joseph Collins, Sheikh Koroma, Thomas Targbwe, and the many individuals who look after the local water points and assisted the field teams.

Financial support: This research was supported by independent consulting contracts from the Water and Sanitation Program of the World Bank (<http://www.wsp.org>) to The Aquaya Institute and Uhl and Associates, Inc. The consulting contracts supported contributions by Emily Kumpel, Jeff Albert, Rachel Peletz, Vincent Uhl, Ashish Daw, and Ranjiv Khush to the study design, data collection and analysis, and manuscript preparation.

Disclosure: Dominick de Waal, Maximilian Hirn, and Alexander Danilenko 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.

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