Research on Humanities and Social Sciences www.iiste.org
ISSN 2224-5766 (Paper) ISSN 2225-0484 (Online)
Vol.8, No.17, 2018

# Urban Water Services in Oromia Regional States: An Analysis of Drinking Water Sources and Quality in Bedelle, Gechi, and Dabe, Dega

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**Abstract**
Establishing and maintaining public water services in Oromia Regional states is a significant development challenge. In expectation of water infrastructure investments, this study compares drinking water sources and quality between Bedelle, Gechi, and Dabe, Dega, two towns recovering from political and economic instability. In both towns, access to piped water is low, and residents rely on a range of other private and public water sources. In Bedelle, geographic points for sampling were randomly selected and stratified by population density, whereas in Gechi, locations for sampling were selected from a current inventory of public water sources. In Bedelle, 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 Gechi, sample collection focused on public sources (predominantly shallow dug wells). In Bedelle, fecal indicator bacteria (FIB) were detected in 25% of sources ($N$ = 566), though concentrations were low. In Gechi, 57% of sources contained FIB and 22% of sources had nitrate levels that exceeded standards ($N$ = 204). In Gechi, the convenience of piped water may promote acceptance of the associated water tariffs. However, in Bedelle, 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.
**Keywords**: Analysis of Drinking Water Sources, Quality, Services

## 1. Introduction

Residents of Oromia Regional and conflict-affected states, 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 Ethiopia, where many Oromia Regional 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]

Healthy data on existing water services and water quality are necessary for guiding infrastructure development and management priorities in Oromia Regional and conflict-affected states. 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 town between Bedelle, Gechi, and Dabe, Dega that are recovering from political and economic instability that probably contributed to degradation of their public water infrastructure. Of the roughly 90 km of piped water distribution network that was installed in Bedelle in the 2001s, less than 10 km remained functional by 2015 [10]. In the 2017 Demographic and Health Survey in Bedelle, 85% of households within the Bedelle municipality reported using borehole water as their primary water source [11]. In greater Gechi in 2016, 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 Bedelle focused on commercial sachet water [15]; 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, Dabe.[16–19]. Publicly available data on water quality in Gechi, which has a history of cholera outbreaks, have been restricted to studies of the informal settlement of West Point[20–23].

Both towns have planned or ongoing investments in municipal water infrastructure. In Bedelle, the Urban Water Sector Reform and Bedelle Water Supply and Sanitation Project and Urban Water Sector Reform Projects

(2015–2020) 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 Gechi, the Dega Water, Sanitation, and Hygiene (WASH) Sector Investment plan for 2014 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 towns to inform water management policies and infrastructure priorities. Different sampling strategies, accounting for the differing use of public and private sources in each town, were used to assess water quality: sampling in Gechi was focused on public sources whereas sampling in Bedelle, was focused on private and commercial sources.

## 2. Materials and Methods

### 2.1. Study Area and Study Period

This study was conducted in Bedelle town, Gechi and Dabe, Dega during May 2018, occupying an area of 300 $km^2$ with 2 million inhabitants, is located in the Oromia Regional State, southwest [27] Mean annual rainfall in Bedelle is 2,311 mm, with a dry season occurring from November to March and a rainy season from April to October[28 ] Ethiopia 2018 Poverty Profile reports that half of the households in the study area earn less than US$1 per day[29]. Since Bedelle lies within a major coffee zone, Brewery Factorycontamination is a water quality concern. This risk is exacerbated by illicit tapping ("bunkering") ofBrewery Factory, which can release significant amounts of crude oil into the environment [30] Bedelle and Gechi study areas. Each point represents a location where a water sample was collected. Bedelle is underlain by a thick sequence of unconsolidated deposits of gravels, sand, silts, and clays. The coastal geology in and around Bedelle 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 Bedelle are hand-drilled boreholes, a common practice on the Dabe 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 2016–February 2017), the Bedelle Water Corporation (PHWC) supplied treated and untreated groundwater from elevated tanks and pumping stations at the Dabo and Tokumma Harar well fields through approximately 10 km of functional piped network.

### 2.2 Sampling strategy: stratified random geographic sampling.

For infrastructure planning purposes, Bedelle was divided into 4 hydraulic zones by an engineering firm[27,33] We first allocated a number of water sample collection points to each of the 4 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 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; 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].

### 2.3 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. 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 PHWC for processing within 6 hours of collection. Thermo tolerant coliforms, pH, electrical conductivity (EC), turbidity, nitrate, fluoride, arsenic, and refined oil concentrations were measured using a potabletest 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 thermo tolerant coliforms, the Potable test kit membrane filtration apparatus was used to filter 100-mL water samples through a 0.45-μm filter that was subsequently incubated with lauryl sulfate broth at 44°C to select for the growth of thermo tolerant coliform bacteria. Equipment for analyzing physical parameters was calibrated regularly and field replicates and blank samples were tested daily.

**2.4 Sampling strategy: water source inventory.**

The Water Point Mapping Project, implemented by the World Bank Water and Sanitation Program and partners, mapped water supplies through Dega in 2016–2018, including more than 1,000 water points in Gechi. 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. We added 10 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 Gechi Town.

**2.5 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 Laboratory in Jimma University, Ethiopia, for analysis. Equipment for analyzing physical parameters was calibrated regularly and field replicates and blank samples were tested daily.

**2.6 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; thermo tolerant coliforms in Port Harcourt and *E. coli* in Gechi) 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 10.1 (Esri, Redlands, CA) and R (R Core Team, Hawassa, Jimma, 2018) software packages.

**2.7 Ethical Consideration**

The proposal of this study was approved by Ethical Review Committee of Mettu University, College of SocialSciences and Humanities. Verbal consent was obtained from each study participants before interview. Moreover, no personal identifiers were used on data collection questionnaire and the data obtained from the study participants were kept confidentially

## 3. Resultsand Discussions

### Bedelle

**Water sources.**

In Bedelle, 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 thermo tolerant coliforms had > 0 CFU/100 mL, the Ethiopia Drinking Water Standard (NDWS) (*N* = 579; 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

**Table: 1 Summary statistics for measured water quality parameters in Bedelle and Gechi**

| | Bedelle | | | | Gechi | | | |
|---|---|---|---|---|---|---|---|---|
| | ***n*** | **Median (range)** | **NDWS** | **% ES** | ***n*** | **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 = Dabo Class 1 Water Quality Standards; NDWS = Ethiopia 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 was thermo tolerant coli forms in Bedelle and *Escherichia coli* in Gechi. †TDS standard based on WHO guideline. Fecal contamination was highest in unprotected open wells, although the sample size was very small (five wells; Sachet water showed fewer samples positive for thermo tolerant 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 Wilcox rank sum test; of the borehole samples, 72% tested for FIB were taken from elevated tanks (*N* = 317); these samples had significantly lower thermo tolerant coliform contamination than water stored in drums and buckets ($P \leq 0.01$, Wilcox rank sum) describes storage containers and associated FIB contamination). Fecal indicator bacteria (FIB) contamination in Bedelle and Gechi. 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.

**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;. 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. 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). Use of water sources for drinking, cooking, and washing in Bedelle. The coded bars represent the percentage of respondents in Bedelle that reported using each source of water for drinking, cooking, and washing.

**Table 2 Quality of water sources for drinking and washing in Bedelle**

| | **Drinking** | | **Cooking** | | ***P* value** |
|---|---|---|---|---|---|
| | ***n*** | **Median (range)** | ***n*** | **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 Wilcox 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.

**Spatial patterns**

Nitrate, TDS, and fluoride concentrations in boreholes were lower in hydraulic zones located at the periphery of the city (zones 1–4 and 1-2, compared with zones in the center of the city (zones 1-3, ($P \leq 0.01$, and Wilcox rank sum); data not shown for fluoride). We did not find spatial patterns of fecal contamination ($P = 0.09$, Wilcox rank sum; or any significant relationships between fecal contamination and population density (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. 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, Wilcox rank sum).Groundwater quality in Bedelle (left) and Gechi (right) the maps display sampling points of groundwater sources in Bedelle and Gechi. The colors represent concentrations of nitrate ($NO_3$; top row) and total dissolved solids (TDS; bottom row).

**Gechi**

**Water sources**

The water samples in Gechi 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. 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 Gechi was high: 57% of the samples had ≥ 1 MPN/100 mL *E. coli* and 19% had concentrations ≥ 100 MPN/100 mL ($N = 204$. In addition, 22% of the samples exceeded the Dabo standard for nitrate of 40 mg/L ($N = 204$. 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%, $N = 14$. 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 Wilcox 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.

**Spatial patterns**

To examine intra-urban differences, we defined three sections of Gechi based on geography and population density: urban, semi-urban, and peri-urban with 71%, 14%, and 15% of sampled sources located in these areas, respectively ($N = 204$; neighborhoods are displayed in 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 Wilcox rank sum; except for fluoride, which was higher in urban areas than semi- or peri-urban areas ($P \leq 0.01$ and $P = 0.04$, respectively, Wilcox 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 Wilcox rank sum. Nitrate and fluoride concentrations were higher in unplanned than in planned settlements ($P = 0.03$ and $P = 0.02$, respectively, Wilcox 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.

**3.1 Groundwater quality in both towns**

To evaluate water quality differences in similar sources, we compared untreated groundwater between Bedelle and Gechi. The majority of sampled groundwater sources were drilled boreholes in Bedelle whereas most in Gechi were shallow hand-dug wells. Boreholes accounted for 89% of the 363 groundwater sources in Bedelle tested for FIB and only 10% of the 183 groundwater sources tested in Gechi, whereas shallow dug wells accounted for 1% of sampled groundwater source in Bedelle and the majority of sources tested (90%) in Gechi. Overall, groundwater sources were less contaminated by FIB and nitrate in Bedelle than in Gechi, based on both the percentage of contaminated sources and their contamination levels (Wilcox rank sum, $P \leq 0.01$; Boreholes in Bedelle had lower concentrations of FIB than boreholes in Monrovia ($P \leq 0.01$, Wilcox rank sum); hand-dug open wells could not be compared because only five wells were sampled in Bedelle.

In Gechi, 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 Bedelle had lower concentrations of FIB and nitrate than improved sources in Gechi: FIB was detected in 22% of improved sources in Bedelle ($N = 317$) compared with 36% of those in Gechi ($N = 91$), and nitrate exceeded 40 mg/L in only 2% of sources in Bedelle ($N = 348$) compared with 22% in Gechi ($N = 90$. Fecal indicator bacteria (FIB) and nitrate concentrations in groundwater sources in Bedelle and Gechi 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.

**3.2 Differences in water quality between Bedelle and Gechi.**

Though comparisons of groundwater quality showed significantly higher levels of FIB and nitrate in Gechi than in Bedelle**,** the composition of groundwater sources sampled in the two cities was markedly different, with boreholes constituting the majority of sources in Bedelle compared with shallow dug wells in Gechi. Nevertheless, restricting the groundwater quality comparisons to improved sources in the two cities continued to indicate higher levels of FIB and nitrate contamination in Gechi than Bedelle. 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 Gechi 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 Gechi 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 Bedelle and Gechi, sanitation services are inadequate: Bedelle has no wastewater or fecal sludge treatment system, and most households rely on septic tanks or pit latrines, or practice open defecation. In Dega, 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 Bedelle merit further investigation.

The differences in fecal contamination between the two towns may have been even more pronounced than we measured: *E. coli*, the indicator species used to detect fecal contamination in Gechi, represents a subset of the multiple species that comprise thermo tolerant coliforms, that was the indicator used in Bedelle. It is possible that testing for thermo tolerant coliforms instead of *E. coli* in Gechi would have identified an even greater number of contaminated samples. Moreover, in Bedelle, most samples were obtained from water that had been stored in elevated tanks or in households, whereas in Gechi, 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 Bedelle 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 Bedelle 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 under sample 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 Gechi, 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 Gechi 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 Bedelle. 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 though the subsurface. Though bunkering of oil is widespread in the region, these activities do not likely occur inside the Bedelle metropolitan area. This conclusion is consistent with results from measurements of a stream in the southwest of Bedelle that measured low concentrations (< 1 mg/L) of oil and grease [47]

There are several limitations to our comparisons. Seasonal variation may explain some of the observed differences in fecal contamination between the two cities: in Bedelle, the study was conducted during the dry season, when fecal contamination of water sources is likely to be lower, and the sampling period in Gechi 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 Bedelle 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 Gechi[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 Bedelle were private whereas all in Gechi were communal. However, we did not find differences in water quality between commercial, public, or private household boreholes in Bedelle. In a 2018 nationally representative household survey in greater Gechi, only 10% of households reported using water from on-premises wells, suggesting most households use shared sources [14]

### 3.3. 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 Bedelle at the time of the study and US$0.11–0.16/300–500 mL in Gechi at the time of publication. Sachet water was used to similar degrees in planned and unplanned communities in Bedelle. 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. In areas with high demand for these sources, regulation of their quality is an important consideration.

Research from Jimma university 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 Gechi, 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 Bedelle, 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.

### 3.4 Summary of main results and discussion

The random selection of water sources in Bedelle identified low access to treated piped water, forcing residents to rely on multiple alternative water sources. One-quarter of samples exceeded Ethiopia regulatory limits for FIB, though concentrations were low. 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. 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 Daban River. In Gechi, 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. This method resulted in the exclusion of sachet and bottled water, though at the time of the study these sources were not prevalent. FIB was found in the majority of tested sources and nitrate levels exceeded regulatory standards in 22% of tested sources. Nitrate and TDS concentrations were lower in peri-urban than semi-urban and urban areas.

### References

[1]. World Bank. World Development Report 2011: Conflict, Security, and Development. Washington, DC: The World Bank; 2011

[2]. World Health Organization/UNICEF. Progress on Drinking Water and Sanitation: 2014 Update. Geneva, Switzerland: World Health Organization; 2014.

[3]. Lee EJ, Schwab KJ. Deficiencies in drinking water distribution systems in developing countries. J Water Health. 2005; 3:109–127.

[4]. Howard G, Pedley S, Barrett M, Nalubega M, Johal K. Risk factors contributing to microbiological contamination of shallow groundwater in Kampala, Uganda. Water Res. 2003; 37:3421–3429.

[5]. Kulabako NR, Nalubega M, Thunvik R. 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. 2007; 381:180–199

[6]. Massone H, Martinez D, Cionchi J, Bocanegra E. Suburban areas in developing countries and their relationship to groundwater pollution: a case study of Mar del Plata, Argentina. Environ Manage. 1998; 22:245–254.

[7]. Shaheed A, Orgill J, Montgomery MA, Jeuland MA, Brown J. Why "improved" water sources are not always safe. Bull World Health Organ. 2014; 92:283–289.

[8]. Bain R, Cronk R, Wright J, Yang H, Slaymaker T, Bartram J. Fecal contamination of drinking-water in low- and middle-income countries: a systematic review and meta-analysis. PLoS Med. 2014; 11:e1001644.

[9]. Christenson E, Bain R, Wright J, Aondoakaa S, Hossain R, Bartram J. Examining the influence of urban definition when assessing relative safety of drinking-water in Nigeria. Sci Total Environ. 2014; 2014:301–312.

[10]. African Development Bank. Environmental and Social Impact Assessment and Resettlement Action Plan. Urban Water Sector Reform and Port Harcourt Water and Sanitation Project; Tunis, Tunisia: African Development Bank Group; 2013.

[11]. National Population Commission. National Malaria Control Programmed (NMCP) Nigeria Demographic and Health Survey 2010. Nigeria: Malaria Indicator Survey (MIS); 2010. http://idhsdata.org [Dataset] ICF International [Distributors] Available at. 2010. Data extract from NGHR61FL.DTA.

[12]. Global Business Solutions, Inc. Government of Liberia Ministry of Public Works Emergency Infrastructure Project (EIP): A Corporate Audit of the Liberia Water and Sewer Corporation. Washington, DC: Global Business Solutions, Inc.; 2012.

[13]. Government of Liberia. WASH Sector Investment Plan 2012–2017. Vol 1. Monrovia, Liberia: Government of Liberia; 2013.

[14]. National Malaria Control Program, Ministry of Health and Social Welfare, Liberia Institute of Statistics and Geo-Information Services, ICF International Liberia Malaria Indicator Survey 2011. 2011. www.measuredhs.com Available at.

[15]. Akinde SB, Nwachukwu MI, Ogamba AS. Storage effects on the quality of sachet water produced within Port Harcourt Metropolis, Nigeria. Jordan J Biol Sci. 2011; 4:157–164.
[16]. Ince M, Bashir D, Oni O, Awe E, Ogbechie V, Korve K, Adeyinka M, Olufolabo A, Ofordu F, Kehinde M. Rapid Assessment of Drinking-Water Quality in the Federal Republic of Nigeria: Country Report. Geneva: Switzerland;2010. http://www.wssinfo.org/fileadmin/user_upload/resources/RADWQ_Nigeria.pdf
[17]. Obire O, Tamuno D, Wemedo S. Bacteriological water quality of Elechi Creek in Port Harcourt, Nigeria. J ApplSci Environ Manag. 2005; 9:79–84.
[18]. Ideriah T, Amachree O, Stanley H. Assessment of water quality along Amadi Creek in Port Harcourt, Nigeria. Sci Afr. 2010; 9:150–162.
[19]. Ogbuagu DH, Ayoade AA, Chukwuocha N. Spatial dynamics in physic chemistry and bacterio-and myco-plankton assemblages of Imo River in a Niger Delta community in Nigeria. Afr J Microbiol Res. 2011; 5:872–887.
[20]. Molbak K, Hojlyng N, Jepsen S. Bacterial contamination of stored water and stored food: a potential source of diarrhoeal disease in West Africa. World Med Health Policy. 1989; 102:309–316.