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Rural Ghanaian households are more likely to use alternative unimproved water sources when water from boreholes has undesirable organoleptic characteristics

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ABSTRACT

Sustainable Development Goal (SDG) 6 aims to achieve universal access to safe drinking water sources. However, the health benefits of meeting this goal will only be fully realized if improved sources are used to the exclusion of unimproved sources. Very little is known about how rural African households balance the use of improved and unimproved water sources when multiple options are present. We assessed parallel use of untreated surface water and unimproved hand-dug wells (HDWs) in the presence of boreholes (BHs) using a semi-quantitative water use survey among 750 residents of 15 rural Ghanaian communities, distributed across three BH water quality clusters: control, high salinity, and high iron. Multivariate mixed effects logistic regression models were used to assess the impact of water quality cluster on the use of BHs, HDWs, and surface water, controlling for distance to the nearest source of each type. Reported surface water use was significantly higher in the high salinity and high iron clusters than in the control cluster, especially for water-intensive activities. Respondents in the non-control clusters had approximately eight times higher odds of clothes washing with surface water ($p < 0.01$) than in the control. Respondents in the high salinity cluster also had 4.3 times higher odds of drinking surface water ($p < 0.05$). BH use was high in all clusters, but decreased substantially when distance to the nearest BH exceeded 300 m (OR = 0.17–0.25, $p < 0.001$). Water use from all sources was inversely correlated with distance, with the largest effect observed on HDW use in multivariate models (OR = 0.02, $p < 0.001$). Surface water and HDW use will likely continue despite the presence of BHs when perceived groundwater quality is poor and other water sources are in close proximity. It is essential to account for naturally-occurring but undesirable groundwater quality parameters in rural water planning to ensure that SDG 6 is met and health benefits are realized.

1. Introduction

All human populations need access to water every day. However, many communities in low-income countries face poor water quality, insufficient water quantity or inequitable distribution of water sources, unacceptable costs, and management problems (WHO & UNICEF, 2017a). Sustainable Development Goal (SDG) 6 aims to ensure universal access to safe water. Progress towards this goal is measured using indicators such as the proportion of the population using safely managed drinking water sources defined as located on premises, readily available, and free of fecal and priority chemical contamination (WHO & UNICEF, 2017b). In the absence of access to safely managed sources, people should have access to basic water services, defined as the presence of an ‘improved’ source, such as a piped water system, borehole (BH), or protected hand-dug well (HDW), with 30 min or less required for water collection and delivery to home (WHO & UNICEF, 2017b). However, the public health benefits expected from safely managed and basic water services will not materialize when their use is not exclusive

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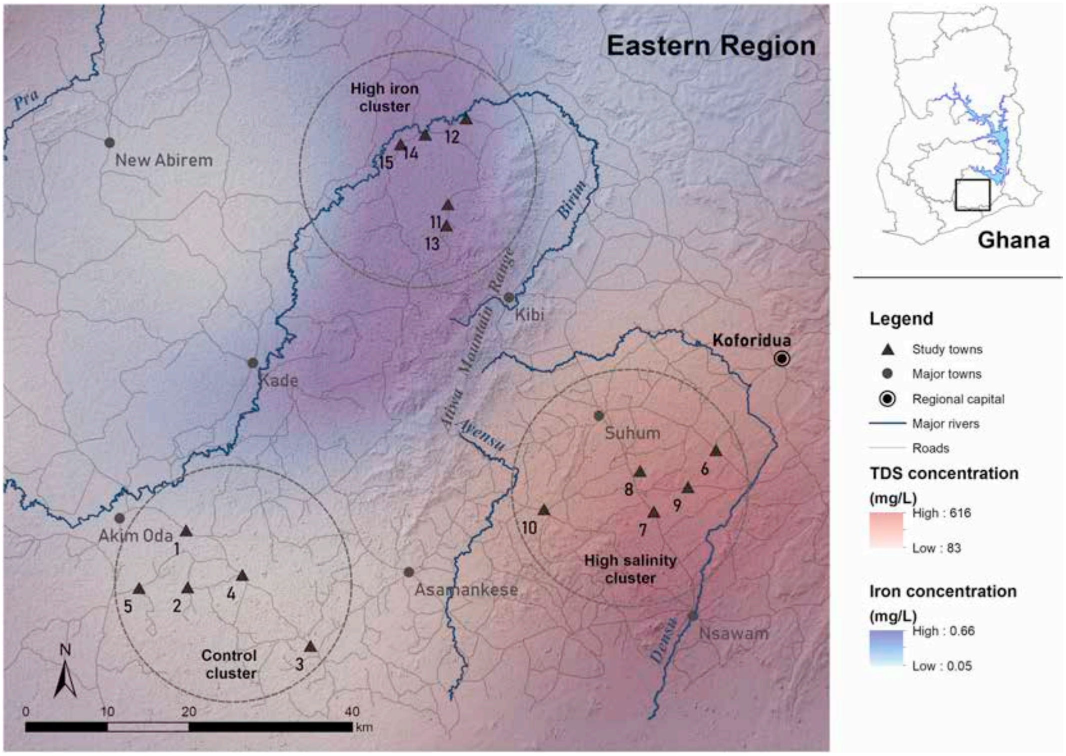

Fig. 1. Map of the study area with five communities in each of the three borehole water quality clusters indicated by large circles with dotted lines. Data sources: Major rivers layer was provided by CERSGIS, Accra, Ghana; hillshade relief was created from ASTER Global Digital Elevation Model; total dissolved solids (TDS) and iron concentrations were field collected and interpolated over the study area (Kulinkina et al., 2017b).

(Brown and Clasen, 2012; Hunter et al., 2009).

Unimproved water sources, such as unprotected HDWs and surface waterbodies, are vulnerable to contamination with waterborne pathogens, presenting a substantial risk of diarrheal disease (Osei and Stein, 2017), stunting (Darteh et al., 2014), and environmental enteropathy (Brown et al., 2013). Furthermore, reliance on surface water for bathing and washing cooking utensils and clothes can also increase the risk of schistosomiasis, a water-related disease transmitted through skin contact with surface water (Krauth et al., 2015). These health conditions are more salient in rural areas that continue to supplement their water needs with unimproved sources, despite increased global improved water coverage (WHO & UNICEF, 2017a).

There are numerous reasons that people may use unimproved water sources, such as distance to an improved source (Hopkins, 2015; Pickering and Davis, 2012), its cost (Kosinski et al., 2016; Obeng-Odoom, 2012; Stoler et al., 2015), reliability (Howard and Bartram, 2003; Hunter et al., 2009; Kulinkina et al., 2017a), queue length (Thompson et al., 2001), and perceived and actual water quality (Kulinkina et al., 2017b; Stoler et al., 2015). A previous study in 74 rural communities in the Eastern Region of Ghana showed that although most households (> 70%) had access to functional improved water sources within 300 m, they continued using alternative unimproved sources, such as unprotected HDWs and untreated surface water, in parallel (Kulinkina et al., 2017a).

Perceptions of water quality matter: studies show that people may select unimproved water sources with high levels of microbiological contamination because of their perceptions of poor water quality in the available improved sources (DeGabriele, 2002; Fuest, 2005; Kulinkina et al., 2016; Nyarko et al., 2007). At commonly occurring levels, some organoleptic properties can reduce the acceptability of improved water sources for drinking and domestic use (de Franca Doria, 2010). A second study in the Eastern Region of Ghana showed that naturally-occurring iron and salinity negatively affected perceptions of groundwater quality at levels well below the cutoffs established by the World Health Organization (WHO) and the Ghana Standards Authority (Kulinkina et al., 2017b).

Several studies have begun examining factors associated with water source selection, but gaps remain, especially when it comes to understanding parallel use of multiple sources. For example, Adams et al. (2016) reviewed the socioeconomic and demographic characteristics associated with improved water access in Ghana using the 2008 Demographic and Health Survey (DHS) data, which are nationally-representative and regularly collected. The study found that income, education and household size are significant predictors of improved water access. The DHS questionnaire asks people to report their *main* household water source for drinking and domestic use, with no information available about secondary sources (GSS & GHS, 2009). As our prior study in 74 communities suggests, characterizing access to and use of the main water source only is not sufficient to understand the water-related disease risk of rural households.

The objective of the present study was to characterize the impacts of groundwater quality in BHs on the use of alternative unimproved water sources for drinking and other domestic purposes (i.e. cooking, bathing and washing clothes). We accounted for distance to all water sources in an area where improved water source coverage is high and alternative unimproved sources are also abundant. The impact of groundwater quality on water source selection represents a substantial gap in the current understanding of water use.

2. Methods

2.1. Study design

The study was conducted in the Eastern Region of Ghana, which has a tropical climate with two rainfall peaks in June and October. We purposively selected 15 communities for the study from a larger sampling frame of 74 communities that are described in our first study in this area (Kulinkina et al., 2017a). In a second study in 55 communities,

Table 1
Summary of public water sources and households in 15 study communities.

Town ID	Population	Total mapped households	Sampled households	Functional | Total BHs	HDWs	SWAPs
Control						
1	971	216	50	2 | 2	10	1
2	1737	237	52	4 | 4	6	2
3	1574	167	47	3 | 3	6	2
4	1362	232	48	7 | 7	9	1
5	3347	327	52	4 | 8	8	1
High salinity						
6	896	170	48	1 | 2	3	3
7	975	169	45	2 | 3	5	1
8	1142	163	50	2 | 2	2	1
9	1215	160	48	2 | 4	1	4
10	3122	384	51	4 | 4	9	5
High iron						
11	1907	299	52	6 | 7	5	4
12	1708	222	50	4 | 6	9	0
13	2534	348	50	6 | 7	11	2
14	829	130	59	4 | 4	3	0
15	2829	398	48	8 | 11	7	1

water quality was measured concurrently with self-reported complaints, demonstrating that iron caused an oily sheen and an unpleasant smell, and total dissolved solids caused salty taste in BH water (Kulinkina et al., 2017b). In the same study, BH water quality data were analyzed to delineate three distinct geographical clusters water quality clusters: high iron, high salinity, and control (Fig. 1). For the present study, five communities were selected from each of the clusters. All 15 communities were rural (population < 5000), had two or more BHs, and had at least one unimproved water source, such as unprotected HDW (approximately 80% of all HDWs in the study communities were unprotected) and/or surface water access point (SWAP) (Table 1). In the study area, water from BHs is sometimes sold, but water from HDWs and surface waterbodies is always free.

We used a convenience sample to survey 750 participants in total from the 15 communities (approximately 50 individuals per community) about their perceptions of BH water quality and water use practices. This sampling approach allowed us to collect information from 250 participants in each cluster and detect a difference of 12.4% in the use of HDWs and SWAPs in high iron and high salinity cluster as compared to the control cluster with 80% statistical power ($\alpha = 0.05$). We also collected spatial data about locations of water sources and matched this data with residential locations of the survey respondents to estimate individual distances to water sources.

2.2. Data collection

2.2.1. Perceived water quality and water use

We collected data on perceived BH water quality and water use via a verbal survey in all 15 communities in the rainy season (23 May – 9 June, 2016) during all seven days of the week between the hours of 7 a.m. and 6 p.m. We administered the survey to approximately 50 adult residents aged 18+ years in each community who reported using at least one public water source. Participants were recruited based on their availability at home at the time of the survey while mapping all households in the study communities. Women were preferred respondents as they are more likely than men to fetch water and to use it for cooking, cleaning, and bathing children (Boateng et al., 2013). Data were collected by two teams, each comprised of three individuals: a native Twi speaker, a note taker, and a knowledgeable community member serving as a guide.

The 16-question survey instrument (Table S1, Supporting Information) contained "yes/no" questions about each of the following with respect to groundwater from BHs: perceived problems of salty taste, oily sheen, unfavorable scent, and food staining. These questions were based on commonly-reported problems in an earlier study (Kulinkina et al., 2017b). We also asked if respondents used each type of water source available to them during the rainy season (BH, HDW, and/or SWAP) for the purposes of drinking, cooking, bathing and washing clothes. A "yes" answer represented any use of the water source, independent of frequency and quantity of water.

2.2.2. Geospatial data

We recorded geographic positioning system (GPS) coordinates of all sampled and unsampled households in the study communities and all public water sources using either the GPS Tracks app for the iPad (Version 2.8.7) or a handheld GPS unit (Garmin GPS 165 72H Portable Navigator, Garmin, Ltd.). Household GPS coordinates were matched to survey responses. Euclidean distances (in meters) from each household to the nearest BH, HDW, and SWAP were calculated using the "near" function within the proximity tools in ArcGIS software (version 10.4.1). Euclidean, or straight-line, distances have been found to be more reliable measures of proximity to water sources, as compared to self-reported travel times (Ho et al., 2014).

2.3. Ethical approval

Prior to conducting this study, we obtained written permission from regional and district level officials of the Community Water and Sanitation Agency (CWSA). All acting community leaders also approved the study. Adult survey participants gave verbal informed consent. The study was approved by the Social, Behavioral, and Educational Research Institutional Review Board of Tufts University in Medford, MA, USA (protocol #1402026).

2.4. Data analysis

We used exploratory data analysis techniques to assess spatial trends in the data and to calculate descriptive statistics. We used the Mann-Whitney-Wilcoxon Test and univariate logistic regression models to confirm that the study communities were allocated appropriately to the BH water quality clusters by ensuring that reported salty taste was most prevalent in the high salinity cluster, and the iron-associated complaints of oily sheen, scent, and food staining were most prevalent in the high iron cluster. We also used the Mann-Whitney-Wilcoxon Test to compare distances to the various water sources between sampled and non-sampled houses to assess our household selection method for spatial biases.

After exploratory analyses, we addressed our study objective by using multivariate mixed effects logistic regression models to determine whether the likelihood of BH, HDW, and SWAP use depended on BH water quality cluster and distances to the three types of available public water sources (Equation (1)).

$$log\frac{p(x)}{1-p(x)} = \beta_o + \beta_1 GWQ\ cluster + \beta_2 Dist_{BH} + \beta_3 Dist_{HDW} + \beta_4 Dist_{SWAP} + \alpha Town + e \quad (1)$$

where x is the likelihood of using the water source of interest, β_0 is the intercept term, β_1 through β_4 are regression coefficients for the four predictor variables, α is the random effect to control for unquantified town-level variability, and e is the error term. The Birim River that flows through towns 12 and 14 is polluted by alluvial gold mining and is not used for domestic purposes; hence there are no SWAPs in these towns (Table 1). Observations from these communities were excluded from the regression models (because distance to the nearest SWAP could not be calculated), but included in other types of analyses.

Distance to each type of water source was measured as a continuous variable and transformed into a binary categorical variable due to non-normal distributions and for ease of interpretation. Two categories were defined, 0–299 m and ≥300 m, ensuring an adequate number of observations in each category (Fig. S1, Supporting Information), with the shorter distance serving as reference in the regression models. We chose a lower cut-off (300 m) than the approximately 1000 m distance represented by a 15-min walk (30 min round-trip excluding queueing time) recommended by the Joint Monitoring Programme (WHO & UNICEF, 2017b). In the study area, improved water sources are located within 300 m of more than 70% of households (Kulinkina et al., 2017a) and other studies also showed shorter median distances and one-way walking times to water sources in sub-Saharan African countries – 200 m (Nygren et al., 2016) and 10 min (Pickering and Davis, 2012), respectively.

Predicted probabilities of using each type of water source for each domestic purpose were calculated for the eight possible permutations of distance scenarios. Distance scenarios were as follows, representing distance to BH, HDW, and SWAP, respectively, with ‘C’ for ‘Close’ (< 300 m) and ‘F’ for ‘Far’ (≥300 m): CCC, CFC, CFF, CCF, FCC, FCF, FFC and FFF. For example, CFC indicates a scenario in which BHs and SWAPs are close and HDWs are far. All statistical analyses were conducted using R software (version 3.6.1).

3. Results

3.1. Descriptive statistics

We identified and mapped 74 BHs (59 functional), 94 HDWs, and 28 SWAPs (Table 1; Fig. S2, Supporting Information). We confirmed appropriate allocation of study communities to BH water quality clusters by comparing total dissolved solids and iron concentrations and prevalence of complaints across towns and clusters (Fig. 2). Iron concentrations in the high iron cluster (mean = 1.16, SD = 1.15 mg/L) commonly exceeded the 0.3 mg/L guideline value, while total dissolved solids concentrations (mean = 643, SD = 178 mg/L) were well below the 1000 mg/L cutoff (Kulinkina et al., 2017b; WHO, 2017). Respondents in the high salinity cluster had much higher odds of reporting salty taste complaints (OR = 46.2, $p < 0.001$), and respondents in the high iron cluster of reporting scent (OR = 2.44, $p < 0.001$), oily sheen (OR = 23.0, $p < 0.001$), and food staining (OR = 50.1, $p < 0.001$) complaints, as compared to the control cluster.

We also plotted the distribution of distances to various water sources by cluster, town, and household sampling status (Fig. S3, Supporting Information). Overall, BHs were the closest (mean = 165 m, SD = 115 m) and SWAPs were the farthest (mean = 369 m, SD = 254 m) water sources to an average household. Mean distance to HDWs in the study towns was 215 m (SD = 189 m). There were no statistically significant differences between sampled and non-sampled households in terms of distance to the nearest BH in any of the clusters. However, there were small in magnitude but statistically significant differences in sampled and non-sampled households in terms of distances to HDWs and SWAPs in some of the groundwater quality clusters (Fig. S3, Supporting Information).

3.2. Water use by cluster

In all clusters, most respondents reported using BH water for drinking, cooking, bathing, and washing clothes (Fig. 3) with an overall prevalence of use at approximately 85% and no differences among the four uses. HDWs and SWAPs were used less frequently than BHs, but the prevalence of parallel use of these unimproved sources was consistently high. HDWs were least popular in the high iron cluster, with 33% of people reporting use as compared to 42% in the high salinity and 50% in the control cluster. In the high salinity cluster, HDWs were used at similar rates for all purposes. In the control cluster, HDW use for more water-intensive activities like bathing and clothes washing was significantly higher than for drinking (e.g. towns 2, 3, and 5). Surface water use was most prevalent in the high salinity cluster (59%), as compared to 36% in the high iron cluster and 27% in the control cluster. The largest differences in surface water use between more and less water-intensive activities were also observed in the high salinity cluster (e.g. towns 7 and 10).

3.3. Water use as predicted by cluster and distance

Multivariate mixed effects logistic regression models explained the likelihood of using BHs, HDWs, and SWAPs as predicted by groundwater quality cluster and distance to water sources (Table 2).

3.3.1. Borehole use

Regression models showed that BH use was generally not affected by water quality cluster, distance to the nearest HDW, or distance to the nearest SWAP. As expected, households located ≥300 m away from BHs were significantly less likely to report using them, as compared to those with closer BHs (OR = 0.17–0.25; $p < 0.001$) (Table 2). The models explained 16–23% of the variability in BH use.

The effect of distance on the predicted probability of using BHs was prominent in all clusters, with households located within 300 m of a BH (scenarios CCC, CFC, CFF and CCF), having consistently higher probability of using a BH for any purpose, as compared to households located farther than 300 m from BHs but less than 300 m from an alternative source (scenarios FCC, FCF, and FFC). When water sources of all types were farther than 300 m from home (scenario FFF), the probability of using BHs did not appear to be affected. Furthermore, probabilities of using BH water for drinking and all other purposes were similar in the control and high salinity clusters, whereas the probability of using BH water for drinking was lower in the high iron cluster compared to cooking, bathing, and washing clothes,ooking, and bathing across all distance scenarios (Fig. 4).

3.3.2. Hand-dug well use

In the high iron cluster, people were significantly less likely to use HDWs for all purposes compared with the control cluster (OR = 0.12–0.22; $p < 0.05$). Distance to HDWs had the highest impact on their use, but distances to other sources were also important. Households located ≥300 m away from HDWs were very much less likely to use them (OR = 0.02; $p < 0.001$), as compared to households located closer. Households with no BHs within 300 m were significantly more likely to report using HDWs for any purpose (OR = 2.10–3.41; $p < 0.05$), as compared to those with nearby BHs (Table 2). The models explained 44–49% of the variability in HDW use.

Predicted probabilities of using HDWs for all purposes were extremely low (< 0.05) in all clusters if HDWs were located ≥300 m away (scenarios CFC, CFF, FFC and FFF). These probabilities increased significantly to approximately 0.50 or above if HDWs were closer (scenarios CCC, CCF, FCC and FCF), except in the high iron cluster, where probabilities of HDW use for all purposes remained below 0.25. HDW use for drinking also tended to be lower in the control cluster, as compared to the high salinity cluster, as well as when compared to other purposes. HDW use was also lower in households with BHs located within 300 m (scenarios CCC and CCF) in all clusters (Fig. 4).

3.3.3. Surface water use

Respondents were significantly more likely to report surface water use in the high iron and high salinity clusters, especially for more water-intensive activities like cooking, bathing, and clothes washing (Table 2). Respondents in the high salinity cluster had 6.46 ($CI_{95\%}$: 1.78, 23.5) times greater odds of reporting cooking and 7.89 ($CI_{95\%}$: 2.40, 26.0) greater odds of washing with surface water than in the control cluster. Similarly, residents of the high iron cluster had 8.24 ($CI_{95\%}$: 1.94, 34.9) times greater odds of using surface water for cooking

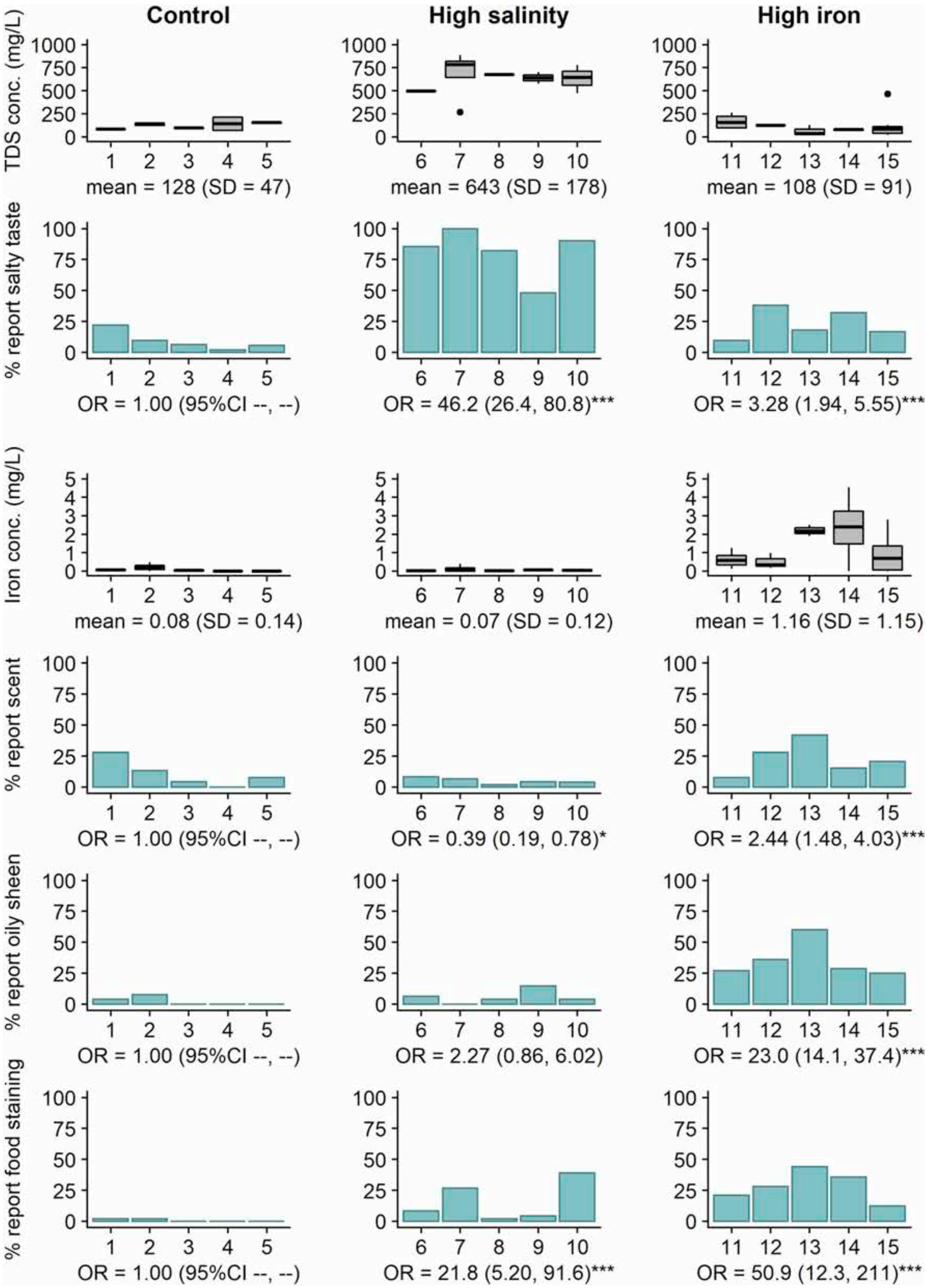

Fig. 2. Boxplots of total dissolved solids (TDS) and iron concentrations (available from a prior study), and corresponding prevalence of reported water quality problems by cluster and town. Odds ratios (OR and $CI_{95\%}$) from univariate logistic regression models represent the odds of reporting each problem as compared to the control cluster (statistical significance noted as * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

and 8.64 ($CI_{95\%}$: 2.29, 32.7) times for washing than those in the control cluster. Residents of the high salinity cluster were also more likely to use surface water for drinking (OR = 4.28; $CI_{95\%}$: 1.15, 15.9). Distance ≥300 m to SWAPs reduced their use, with statistically significant effects observed again for water-intensive activities: bathing (OR = 0.50; $CI_{95\%}$: 0.31, 0.81) and clothes washing (OR = 0.44; $CI_{95\%}$: 0.27, 0.71). Distance to BHs and HDWs had no bearing on SWAP use. The models explained 23–34% of the variability in SWAP use.

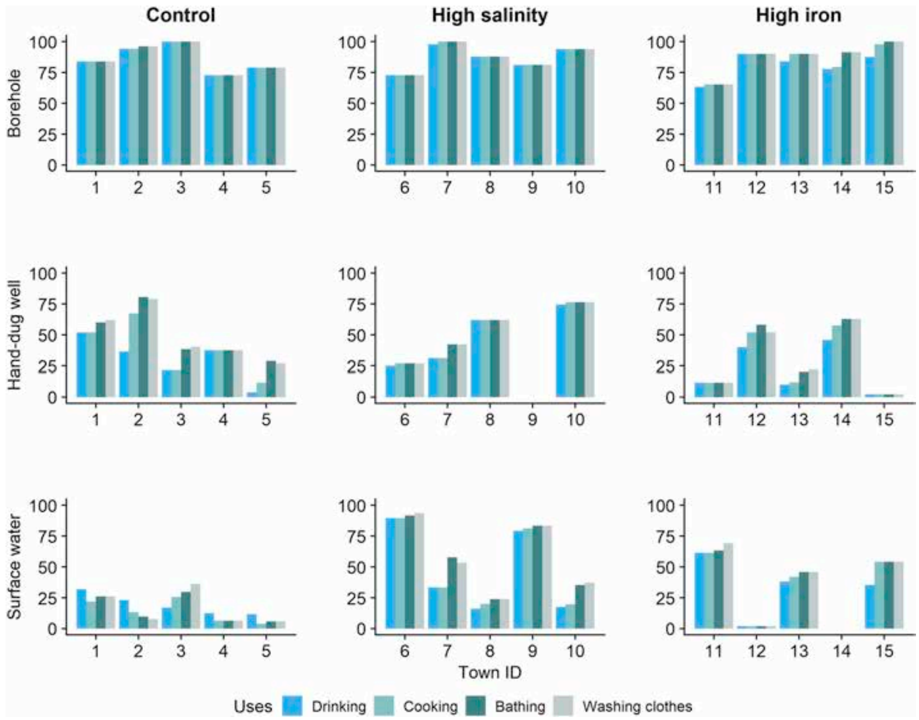

Fig. 3. Percentage of respondents who reported using each water source (y-axis) across clusters (control, high salinity, and high iron) and towns 1 through 15 (x-axis) for various purposes; bars for each town are presented in the order of drinking, cooking, bathing and washing clothes.

Table 2

Multivariate mixed effects logistic regression model results for the reported use of boreholes (BHs), hand-dug wells (HDWs), and surface water access points (SWAPs), controlling for town as a random effect.

	BH use OR ($CI_{95\%}$)	HDW use OR ($CI_{95\%}$)	SWAP use OR ($CI_{95\%}$)
Drinking	R^2 = 0.159	R^2 = 0.442	R^2 = 0.233
High salinity	1.44 (0.36, 5.87)	1.74 (0.54, 5.66)	4.28 (1.15, 15.9)*
High iron	0.48 (0.10, 2.29)	0.22 (0.05, 0.92)*	3.91 (0.90, 17.1)
BH (≥300 m)	0.25 (0.13, 0.50)***	2.91 (1.45, 5.83)**	0.80 (0.44, 1.46)
HDW (≥300 m)	2.02 (0.80, 5.09)	0.02 (0.01, 0.13)***	0.83 (0.35, 1.96)
SWAP (≥300 m)	1.94 (1.08, 3.48)*	0.52 (0.29, 0.93)*	0.86 (0.53, 1.39)
Cooking	R^2 = 0.215	R^2 = 0.481	R^2 = 0.294
High salinity	1.61 (0.27, 9.64)	1.23 (0.37, 4.13)	6.46 (1.78, 23.5)**
High iron	0.98 (0.13, 7.55)	0.16 (0.04, 0.68)*	8.24 (1.94, 34.9)**
BH (≥300 m)	0.18 (0.08, 0.37)***	3.41 (1.69, 6.87)***	0.98 (0.54, 1.80)
HDW (≥300 m)	2.68 (0.89, 8.10)	0.02 (0.01, 0.11)***	1.00 (0.42, 2.41)
SWAP (≥300 m)	1.81 (0.95, 3.45)	0.61 (0.34, 1.10)	0.62 (0.38, 1.02)
Bathing	R^2 = 0.234	R^2 = 0.487	R^2 = 0.311
High salinity	1.52 (0.21, 11.0)	0.80 (0.27, 2.39)	7.89 (2.62, 23.7)***
High iron	1.24 (0.12, 12.4)	0.12 (0.03, 0.44)**	7.77 (2.29, 26.4)**
BH (≥300 m)	0.17 (0.08, 0.36)***	2.16 (1.12, 4.18)*	1.46 (0.81, 2.63)
HDW (≥300 m)	2.49 (0.80, 7.74)	0.02 (0.01, 0.11)***	1.13 (0.50, 2.54)
SWAP (≥300 m)	1.81 (0.93, 3.51)	0.54 (0.31, 0.94)*	0.50 (0.31, 0.81)**
Washing clothes	R^2 = 0.234	R^2 = 0.480	R^2 = 0.337
High salinity	1.52 (0.21, 11.0)	0.81 (0.28, 2.37)	7.89 (2.40, 26.0)***
High iron	1.24 (0.12, 12.4)	0.13 (0.04, 0.46)**	8.64 (2.29, 32.7)**
BH (≥300 m)	0.17 (0.08, 0.36)***	2.10 (1.09, 4.04)*	1.50 (0.83, 2.72)
HDW (≥300 m)	2.49 (0.80, 7.74)	0.02 (0.01, 0.11)***	1.05 (0.46, 2.42)
SWAP (≥300 m)	1.81 (0.93, 3.51)	0.54 (0.31, 0.93)*	0.44 (0.27, 0.71)***

The control cluster served as the reference category for high iron and high salinity clusters; distances < 300 m served as reference categories for BH, HDW and SWAP distance variables; statistical significance is denoted as * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

The probability of surface water use was at least two times higher in the high salinity and high iron clusters for all purposes and across all distance scenarios. The effect of distance to a SWAP was most prominent for bathing and washing, with higher probabilities observed in scenarios CCC, CFC, FCC and FFC as compared to the other four scenarios with farther SWAPs (Fig. 4).

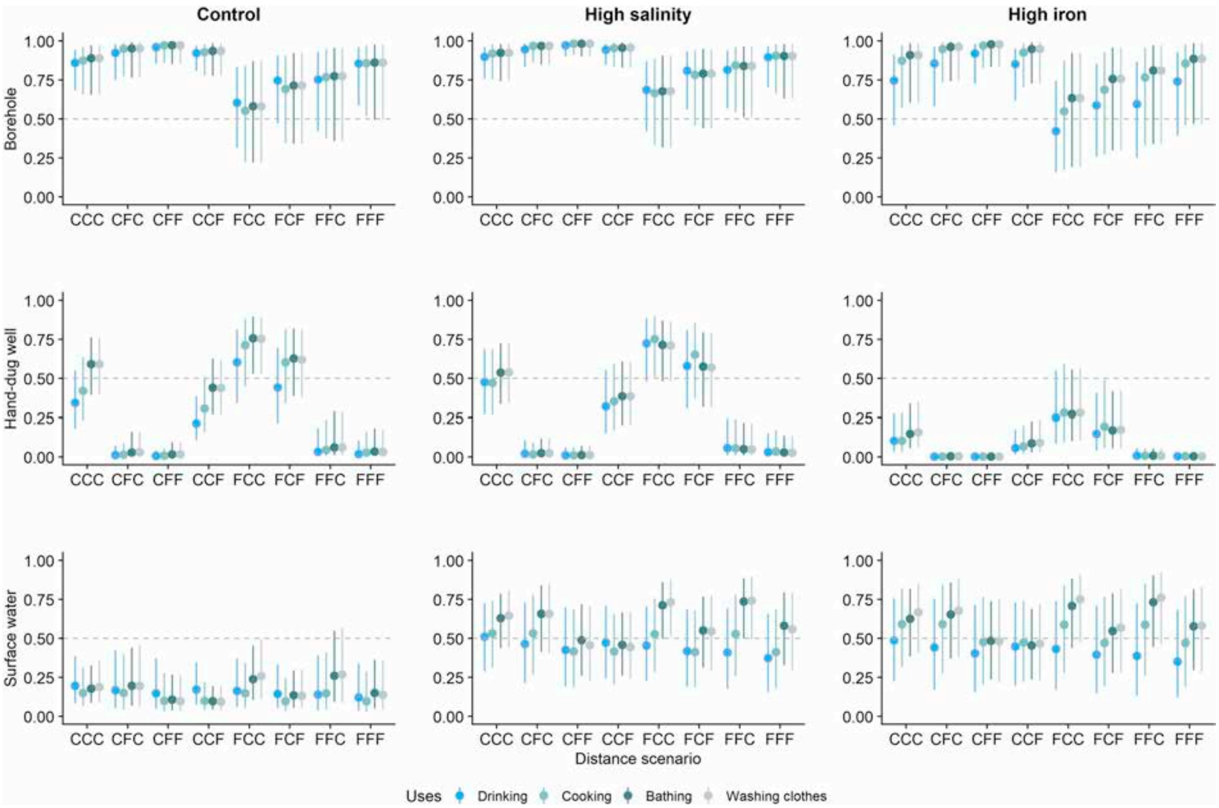

Fig. 4. Predicted probabilities (dots) with 95% confidence intervals (vertical lines) of using each type of water source (y-axis) for various purposes, displayed in the order of drinking, cooking, bathing and washing clothes, across three water quality clusters (control, high salinity and high iron). Eight distance scenarios (x-axis) represent distances to BHs, HDWs, and SWAPs ("**C**lose" or "**F**ar", with "C" $<$ 300 m and "F" $\geq$ 300 m): CCC, CFC, CFF, CCF, FCC, FCF, FFC and FFF.

4. Discussion

Our study demonstrated that undesirable organoleptic characteristics of BH water, such as excessive salinity and iron levels, were significantly associated with the use of alternative unimproved water sources for drinking, cooking, bathing and clothes washing. This finding implies that the health benefits of improved water sources in rural African communities may be disrupted or reduced when groundwater has organoleptic characteristics that water consumers perceive as undesirable, even at concentrations below maximum recommended values under the WHO guidelines (Kulinkina et al., 2017b). This information is relevant to community leaders, policy-makers, public health officials, and engineers, particularly in the context of realizing full public health benefits of SDG 6.

In 1998, the Government of Ghana created the Community Water and Sanitation Agency (CWSA) to oversee rural water supply development activities, such as drilling and maintaining BHs and building piped water distribution systems (Obeng-Odoom, 2012). This initiative achieved high improved water source coverage in the Eastern Region and high reported use of BHs in our study. However, substantial parallel use of unimproved water sources in high salinity and high iron groundwater quality clusters significantly undermine the health benefits of the initiative.

Increased use of unprotected HDWs and surface water sources for drinking in the high salinity cluster is especially concerning. These practices put community members, and especially children, at risk of diarrheal diseases (Osei and Stein, 2017) and stunting (Darteh et al., 2014). Increased reliance on surface water for cooking, bathing, and washing in the high salinity and high iron clusters can also increase the risk of schistosomiasis, a highly endemic water-related disease in the study area (Kosinski et al., 2012; Kulinkina et al., 2019). In a previously conduced study with school children, we found that living in the high iron cluster was a major risk factor for *Schistosoma haematobium* infection (Kulinkina et al., 2018).

Consistent with past studies, we found that when distance to any of the water sources exceeded 300 m, the likelihood of their use was significantly reduced. Other studies have found negative impacts of distance on water use and health outcomes, such as diarrheal disease and respiratory infections (Nygren et al., 2016; Pickering and Davis, 2012; Wang and Hunter, 2010). For some water sources in our study, distance to alternative water sources was also important. For example, HDW use was reported to be lower when BHs were within 300 m. Interestingly, BH use was not affected by the presence of other nearby water sources. This implies that as BHs are converted into mechanized piped systems, with a higher density of communal standpipes or household connections, there is substantial opportunity to bring groundwater closer to people's homes and increase its use. Our findings also suggest that it may be prudent to protect unimproved HDWs by chlorinating and capping them and fitting them with pumps, when possible, given that they are already conveniently located near many homes and remain in widespread use. These types of steps should only be undertaken in collaboration with communities after a thorough assessment of their needs and preferences.

Although our findings support reducing the distance to BHs (e.g. drilling new BHs, fixing non-functional BHs), public health benefits, as well as cost recovery and long-term sustainability of these sources could be compromised if groundwater quality challenges are not addressed (Braimah and Kheni, 2013; Foster, 2013; Nyarko et al., 2007). Local water committees often rely on user fees from groundwater sources (BHs and piped systems) to cover their operation and maintenance costs (Alexander et al., 2015; Kulinkina et al., 2016). Willingness to pay, water consumption, and subsequent revenue recovery from these sources can be impacted by unfavorable groundwater quality. For example, excess hardness in BH water, which often accompanies iron and salinity, has the effect of reducing soap lather (Abeliotis et al., 2015). Because cleanliness and 'neatness' in Ghana are very highly valued (Scott et al., 2015) and soap costs money, people may be additionally inclined to use free water sources for clothes washing. This was the case in an earlier case study in four communities in the high salinity cluster in which piped water systems with communal standpipes charging user fees experienced underutilization and low revenue recovery (Kulinkina et al., 2016).

Our study has several limitations. First, we did not consider all water sources. The study included only public water sources; although private water sources were uncommon, we cannot exclude the possibility that some households had private HDWs. We also did not consider bottled or sachet water for drinking, which is probably available in most if not all study communities (Stoler et al., 2015). According to the Ghana DHS, the prevalence of drinking bottled or sachet water among the rural population has increased from 1.1% in 2008 (GSS & GHS, 2009) to 8.1% in 2014 (GSS & GHS, 2015), but remains significantly below that of the other water sources that were included in the study. The use of privately collected rainwater, which is ubiquitous in the Eastern Region of Ghana, was also not analyzed in this study.

Second, we did not assess the quality of HDW or surface water. The main source of iron and salinity in the groundwater in the study area is the dissolution of minerals in the aquifer (Gibrilla et al., 2010; Yidana and Yidana, 2010). Prior research suggests that shallow HDWs and surface water bodies have iron and salinity problems to some extent (Amoako et al., 2010; Gibrilla et al., 2010). When exposed to air, iron is oxidized from the ferrous to the ferric form and precipitated as insoluble hydroxides (USGS, 1962; WHO, 2017). Soluble iron concentrations in surface water streams are typically low compared to iron-enriched groundwater. However, relatively low HDW usage in the high iron cluster (Table 2) suggests that HDWs may have been affected by elevated iron levels. Salinity was also likely to be much lower in surface waterbodies compared to BHs because of the effect of rainwater dilution (Gibrilla et al., 2010).

A third but minor limitation is the sampling strategy. There were small in magnitude but statistically significant differences in the spatial distribution of sampled and unsampled households in relation to the water source locations (Fig. S3, Supporting Information). These differences of < 100 m are unlikely to have a substantial impact on the generalizability of our findings. General unavailability of people in the communities during daytime hours in the rainy season because of farming activities may have further contributed to a small participant selection bias in the study.

Lastly, we collected data only in the rainy season, did not quantify the relative amounts of water used from each source, and did not systematically assess all possible factors that could influence water source selection as part of the present analysis. Future studies should consider seasonality, quantities of water used from each source, cost and pricing mechanisms (Alexander et al., 2015), management capacity and training (Klug et al., 2018), and broader political, social, and cultural factors that may play a role in water source functionality, selection, and use. It would also be useful to conduct substantially larger studies to evaluate the relative impacts of the aforementioned variables on health, revenue recovery, and long-term sustainability of water systems. Despite these limitations, the findings are consistent with our prior studies conducted in the Eastern Region, and they illuminate some of the factors that influence the use of a variety of water source types.

5. Conclusions

In the Eastern Region of Ghana, despite high access to improved water sources, exclusive use of BHs was rather uncommon. Surface water use was especially prevalent in communities with organoleptic groundwater quality problems, such as high iron or salinity. This poses significant challenges to water authorities and might compromise the sustainability of BHs due to the reduced likelihood of use and corresponding reduction in the revenue stream (Kulinkina et al., 2016). Intermittent use of unsafe water sources also poses challenges to public health authorities, as the majority of health benefits offered by safe water supplies are negated if their use is inconsistent (Brown and Clasen, 2012; Hunter et al., 2009). The inverse association between distance to BHs and their usage indicates that bringing groundwater closer to people's homes in the form of new and rehabilitated BHs and piped water systems could reduce the use of unsafe unimproved sources in some communities. Our findings also suggest the need to improve the collection of nationally-representative data through the DHS and similar surveys, as these often only account for *primary* water source access (Adams et al., 2016). Failure to account for continuing parallel water use from unimproved sources may lead to overestimating public health benefits of improved water systems.

Author contributions

AVK and MS designed the study; MS, OLS, BGO, EAA, AVK collected the data; AVK, MS, KCK analyzed the data; AVK, MS, KCK drafted the manuscript; AIE and ENN provided analytical and structural guidance. All authors have read, made substantive edits, and approved the manuscript.

Declaration of competing interest

The authors declare no competing interests. The views expressed in this article are those of the authors and do not necessarily represent the views or policies of author affiliated organizations. Mention of trade names, products, or services does not convey, and should not be interpreted as conveying official approval, endorsement or recommendation of the affiliated organizations.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijheh.2020.113514.

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