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Physicochemical parameters affecting the perception of borehole water quality in Ghana

Alexandra V. Kulinkina[a,*], **Jeanine D. Plummer**[b], **Kenneth K.H. Chui**[c], **Karen C. Kosinski**[d], **Theodora Adomako-Adjei**[e], **Andrey I. Egorov**[f], and **Elena N. Naumova**[a,c,g]

[a]Tufts University School of Engineering, Medford, MA, USA

[b]Water Quality & Treatment Solutions, Inc., Brookfield, MA, USA

[c]Tufts University School of Medicine, Boston, MA, USA

[d]Tufts University School of Arts and Sciences, Medford, MA, USA

[e]Community Water and Sanitation Agency, Accra, Ghana

[f]U.S. Environmental Protection Agency, Chapel Hill, NC, USA

[g]Tufts University Friedman School of Nutrition Science and Policy, Boston, MA, USA

Abstract

Rural Ghanaian communities continue using microbiologically contaminated surface water sources due in part to undesirable organoleptic characteristics of groundwater from boreholes. Our objective was to identify thresholds of physical and chemical parameters associated with consumer complaints related to groundwater. Water samples from 94 boreholes in the dry season and 68 boreholes in the rainy season were analyzed for 18 parameters. Interviews of consumers were conducted at each borehole regarding five commonly expressed water quality problems (salty taste, presence of particles, unfavorable scent, oily sheen formation on the water surface, and staining of starchy foods during cooking). Threshold levels of water quality parameters predictive of complaints were determined using the Youden index maximizing the sum of sensitivity and specificity. The probability of complaints at various parameter concentrations was estimated using logistic regression. Exceedances of WHO guidelines were detected for pH, turbidity, chloride, iron, and manganese. Concentrations of total dissolved solids (TDS) above 172 mg/L were associated with salty taste complaints. Although the WHO guideline is 1000 mg/L, even at half the guideline, the likelihood of salty taste complaint was 75%. Iron concentrations above 0.11, 0.14 and 0.43 mg/L (WHO guideline value 0.3 mg/L) were associated with complaints of unfavorable scent, oily sheen, and food staining, respectively. Iron and TDS concentrations exhibited strong spatial clustering associated with specific geological formations. Improved groundwater sources in

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[*]Corresponding author at: 200 College Avenue, Medford, MA, 2155, USA. alexandra.kulinkina@tufts.edu (A.V. Kulinkina).

Competing interests
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Author contributions
AVK, JDP, KCK and ENN designed the study. AVK and KCK carried out the field data collection. AVK, KKHC, AIE and ENN analyzed the data. AVK drafted the manuscript. All authors have read and approved the manuscript.

rural African communities that technically meet WHO water quality guidelines may be underutilized in preference of unimproved sources for drinking and domestic uses, compromising human health and sustainability of improved water infrastructure.

Keywords

Water quality; Water preferences; Ghana; Rural water supplies

1. Introduction

Basic water access under the Millenium Development Goals (MDGs) was defined by the WHO/UNICEF Joint Monitoring Programme (JMP) as using water from an ‘improved’ source, such as a piped system, borehole (BH), protected well, or rainwater harvesting system, located within 1 km (15 min walking time) of the residence (UN, 2003). Although water from improved sources is not always microbiologically safe (UNICEF/WHO, 2011), these sources, in general, have been shown to have lower levels of microbiological contamination compared to unimproved sources such as untreated surface water (Bain et al., 2014; Shields et al., 2015). In light of the Sustainable Development Goals (SDGs), the definition has been revised to emphasize ‘safely managed’ water sources, while also requiring that these sources be located on premises, be available when needed, and be free of fecal and priority chemical contamination (UN-Water, 2016).

Physicochemical parameters, such as pH, total dissolved solids (TDS), hardness, and levels of non-toxic compounds, such as iron, manganese, sulfate, and phosphate ions, do not pose a health threat at the levels normally found in groundwater supplies. However, these parameters define the organoleptic and aesthetic quality of water, which affects its acceptability for drinking and domestic uses (de Franca Doria, 2010). Groundwater with unpleasant taste or excess hardness, even when readily available, can drive consumers to continue using microbiologically contaminated unimproved sources (DeGabriele, 2002; Fuest, 2005; Kulinkina et al., 2016; Nyarko et al., 2007). Neither the MDG nor the SDG definition considers the organoleptic properties of improved water sources and the potential impact they may have on the utilization of these sources.

In rural Ghana, over 95% of improved water supplies intended for domestic purposes are groundwater supplies, primarily communal BHs (Awuah et al., 2009; Marks et al., 2014). Unfortunately, high levels of minerals and metals in groundwater may preclude extensive exploitation of some of these water sources (Awuah et al., 2009; Rached et al., 1996; Siabi, 2003). In the Eastern Region, drilling records indicate that 20–30% of rural BHs have iron and manganese concentrations well in excess of the WHO water quality (WQ) guidelines (0.3 mg/L and 0.1 mg/L, respectively) (Siabi, 2003; WHO, 2011), causing them to be abandoned or marginally used (Kosinski et al., 2016; Siabi, 2004).

In a prior study of public water sources in 74 rural Eastern Region communities conducted in 2014, we found that BHs were indeed the most common public water source type, with surface water access points located on rivers and streams being just as common (Kulinkina et al., 2017). Our findings were in accordance with the most recent census (2010) that listed

BHs as the most common primary source of drinking water (42.5% on average), with rivers and streams being second (21.5%). The use of bottled (0.2%), sachet (4.0%), or tanker/vendor supplied (0.1%) water was rare (GSS, 2013). To shed some light on why surface water use was so common despite relatively good access to improved groundwater sources, in the 2014 survey, BH users were asked to comment on any problems they experienced with groundwater quality using an open-ended question format. Five recurring WQ complaints emerged: salty taste, unfavorable scent (most commonly described as the smell of fresh fish), oily sheen formation on the water surface, presence of particles, and staining of starchy foods (e.g. plantain, cassava, rice) during cooking.

The 2014 study demonstrated that higher improved water access (according to the JMP definition) was indicative of lower surface water use, but the relationship was modified by the presence of reported groundwater quality problems. The study suggested that organoleptic characteristics of improved water sources, concurrently with other factors such as distance and water fees, play a role in water source choice and dynamic water use from multiple available sources (Kulinkina et al., 2016, 2017). The present study was designed to follow up on the 2014 study with the following objectives:

1. To characterize groundwater quality in the study area in the dry and rainy seasons;
2. To identify WQ parameters predictive of the five reported complaints; and
3. To determine cutoff concentrations with respect to complaints and compare them to WHO WQ guidelines.

This study is a significant first step in matching consumer perception with actual WQ, which should be followed by a quantitative assessment of its impact on the dynamic water consumption patterns from multiple water sources available in rural communities.

2. Methods

2.1. Study design

This study focused on factors that affect the perceptions of WQ in existing rural BHs. Other improved water sources, such as piped systems and hand-dug wells, were not included. The study was excluded from ethical review because collected information pertained to water sources and not to the survey respondents. To design the WQ sampling and survey protocol, we used information gathered during the 2014 study (Kulinkina et al., 2017), which identified a total of 238 BHs in 67 communities. Of these, 176 BHs in 61 communities were functional and constituted the sample frame for this study. A random subset of BHs was chosen using a stratified approach defined by the following rules:

1. In communities where no WQ problems had been reported (n = 28), only one BH was selected;
2. In communities with 1–2 types of WQ problems reported by at least one individual (n = 22), two BHs were selected, unless only one functional BH existed; and

3. In communities with 3–4 types of reported WQ problems (n = 11), 80% of BHs were selected.

This selection method was chosen over random sampling in order to maximize the overall geographic spread of sampled BHs by selecting at least one BH in each community, as well as to allow for assessing heterogeneity in WQ among BHs within communities with multiple reported complaints. Using this scheme, a total of 111 BHs in 61 communities were selected for sampling, of which 94 (in 55 communities) were sampled during the dry season (January 2015), and 68 of the 94 were sampled again in the rainy season (June–July 2015) (Fig. 1A). Ability to sample all planned BHs was affected by dynamic functionality status and poor access to some of the study communities during the rainy season.

2.2. Data collection

2.2.1. Measured borehole water quality data—During dry season sampling (January 6–11, 2015), upon arrival in a given study community, the first BH to be sampled was randomly selected by spinning a pointed object and choosing the closest BH in the direction the object was pointing. If more than one BH was to be sampled, the team asked a community member to be taken to the next closest functioning BH. The method was continued until the appropriate number of BHs was sampled. During the rainy season sampling (June 27–July 3, 2015), the team navigated to previously sampled boreholes using GPS coordinates and took repeat samples if the BH was still functioning.

Water samples were collected between the hours of 7:30 a.m. and 6:30 p.m. in pre-washed and pre-labeled 1 L sampling bottles provided by the WQ analytical laboratory. The bottles were triple rinsed with sample water prior to sample collection. If the BH was being used at the time of sampling, the sample was collected right away. If the BH was visited in the middle of the day when no one was fetching water, it was pumped for 30 s before collecting the sample. If a community member informed the team that the BH was rarely used, water was pumped for 2 min prior to collecting the sample. The BH was photographed and sample ID, time and date of sampling, and GPS coordinates were recorded. GPS coordinates were obtained using either a handheld GPS unit (Garmin GPS 165 72H Portable Navigator, Garmin, Ltd.) or the GPS Tracks app (version 2.8.2) for the iPad.

Samples were kept on ice or refrigerated and delivered to the nationally certified Water Research Institute (WRI) WQ laboratory in Accra, Ghana within 2 days of collection. Samples were analyzed for 24 common physicochemical parameters using standard methods. All ‘below detection limit’ measurements (turbidity < 1 NTU; iron < 0.01 mg/L; sulfate, fluoride and manganese < 0.005 mg/L; nitrate and nitrite < 0.001 mg/L) were replaced with the value 1/2 of the detection limit for data analysis. Six parameters were subsequently excluded from statistical analysis due to redundancy with other parameters and lack of variability (Table 1). Field duplicate samples were examined for quality assurance using coefficients of variation.

2.2.2. Survey of consumer satisfaction with borehole water quality—The survey about WQ complaints, developed based on previous work (Kulinkina et al., 2017), included five closed-ended yes/no format questions: 1) Do people who use this water usually think it tastes salty? 2) Do people who use this water usually think it has particles? 3) Do people who use this water usually think it has a bad scent/odor? 4) Do people who use this water usually think it has an oily sheen? 5) Do people who use this water usually think it turns plantain or cassava purple or black when boiled? Surveys were conducted concurrently with WQ sampling (between 7:30 a.m. and 6:30 p.m.) on all seven days of the week in the local language Twi by a native speaker. Responses about each BH were solicited from individuals fetching water at the time of the sampling, or from nearby residents who expected to be frequent users of the BH. Adult women were preferred because of the predominant role they play with respect to water collection, storage, and allocation within rural African households (Boateng et al., 2013; Rached et al., 1996). In the dry season, the survey was administered to one person at each BH, resulting in 94 responses that corresponded with the 94 samples collected. In the rainy season, responses were solicited from three or four individuals (62 BHs had 3 responses; 5 BHs had 4 responses; for 1 BH reported WQ information was missing) resulting in a total of 206 responses that corresponded with the 68 water samples collected.

2.3. Data analysis

Exploratory analyses included summary measures for the 18 WQ parameters, stratified by season. Seasonal differences in average concentrations were tested using an independent sample *t*-test on the full dataset (94 dry vs. 68 rainy season observations) and a paired sample *t*-test on the 68 matched observations. Seasonal differences in reported problems were explored in the matched dataset using a mixed effects regression model with a random intercept and a binary variable for dry or rainy season as a fixed effect. Correlations among measured WQ parameters and among reported problems were explored using Spearman’s rank and Kendall’s Tau methods, respectively.

In the second stage of exploratory analyses, data from both seasons were combined, WQ parameters were $\log_{10}$ transformed (except pH) and standardized into z-scores. Standardized data were used to compare the distribution of each parameter by reported problem. Subsequently, each parameter was used as a predictor of each reported problem in a univariate logistic regression analysis. All analyses were conducted in R software (version 3.2.2)

Final univariate logistic regression models for each reported WQ problem were conducted using untransformed and unstandardized data. Explanatory parameters for the final models were selected based on the fitting properties of the exploratory models as well as the plausibility of the association based on water chemistry and WQ literature. Model-predicted probabilities of reported complaints were plotted against parameter concentrations for visual comparison to WHO guideline values. WQ parameter cutoff values for predicting the presence of reported complaints were determined using the Youden index that maximized the sum of sensitivity and specificity (López-Ratón et al., 2014). Observed concentrations were subsequently categorized as being above or below the respective threshold and the odds of complaint were compared between the two categories using odds ratios and 95% confidence intervals (OR, $CI_{95\%}$). Lastly, iron and TDS concentrations were spatially interpolated using Empirical Bayesian Kriging within the Geostatistical Analyst extension in

ArcGIS (version 10.2.2) to examine their spatial distribution. Default general properties were used, with smooth circular neighborhood type (smoothing factor of 0.8 and search radius of 25,000–30,000 m).

3. Results

3.1. Measured and reported borehole water quality

WHO guidelines were available for 16 of the 18 selected parameters, except phosphate and total alkalinity (WHO, 2011). Exceedances were detected for five of these 16 parameters. Specifically, most pH values (73.4% of the dry season and 94.1% of the rainy season samples) were outside of the WHO recommended guideline range of 6.5–8.5 (most were <6.5). Turbidity values exceeding the 1 NTU guideline were more common in the rainy season (35.3%) compared to the dry season (6.4%). The maximum turbidity value in the rainy season was 39 NTU, suggesting very poor microbiological WQ potentially affected by surface runoff. The manganese concentration exceeded the WHO organoleptic acceptability guideline (0.1 mg/L) in 61.7% of the dry season and 58.8% of the rainy season samples. The higher health-based WHO guideline for manganese (0.4 mg/L) was exceeded in 10.6% of the dry season and 14.1% of the rainy season samples (Table 1). The iron concentration exceeded the 0.3 mg/L WHO guideline in 29.8% and 28.4% of the dry and rainy season samples, respectively. Finally, chloride concentrations exceeded the WHO guideline of 250 mg/L in only 1% of the dry season samples. The national WQ standards in Ghana had identical guideline values to those of the WHO for the majority of the parameters; several national standards that differed from corresponding WHO guidelines (Table 1) did not affect the interpretation of the findings.

TDS, chloride, sulfate, calcium, potassium, and ammonia levels were significantly higher in the dry season ($p < 0.05$ for independent and paired *t*-tests), while phosphate level was higher in the rainy season (Fig. 2; Table 1). Presence of particles was the most prevalent reported complaint; the remaining complaints, although not as prevalent as particles, were still common (Table 2). Controlling for multiple responses in the second sampling round, presence of particles was more prevalent in the dry season (62% vs. 50%, $p < 0.01$) and oily sheen complaint was more common in the rainy season (36% vs. 27%, $p < 0.05$).

3.2. Associations between measured parameters and reported complaints

As an exploratory analysis, distributions of $\log_{10}$ transformed and standardized WQ parameter concentrations were compared for boreholes with and without each reported complaint (Figs. S1–S5, Supplemental Information). The results showed that the salty taste complaint was related to TDS, as well as many of the constituents comprising TDS (e.g. calcium, magnesium, sodium and sulfate). All of these parameters were inter-correlated (Table S1, Supplemental Information). The reported complaints of scent, oily sheen and food staining were related to iron concentration. Furthermore, the three complaints were inter-correlated (Table S2, Supplemental Information). In the univariate regression analysis of standardized z-scores, parameters most strongly related to salty taste were TDS, total hardness, and calcium based on the regression coefficient, p-value, and R^2. For the cooccurring scent, oily sheen, and food staining problems, iron was the most strongly associated WQ parameter (Table 3).

In the final univariate logistic regression model, for every 100 mg/L increase in TDS, the odds of salty taste complaint increased 1.89 times ($CI_{95\%}$: 1.55, 2.31) (Table 4). The cutoff TDS concentration above which reporting salty taste was expected was 172 mg/L. For BHs with TDS levels above the cutoff, the OR of salty taste complaint was 10.1 ($CI_{95\%}$: 5.60, 19.1) compared to BHs with concentrations below the cutoff. The cutoff concentration was far below the WHO guideline value of 1000 mg/L for drinking water (WHO, 2011). At 1000 mg/L TDS, the predicted probability of salty taste complaint from the logistic regression model was near 1.0. Even at 500 mg/L, the probability was nearly 0.75 (Fig. 3).

In the final univariate logistic regression models, with every 1 mg/L increase in iron concentration, the odds of reporting unfavorable scent increased 2.89 times ($CI_{95\%}$: 1.99, 4.20), the odds of reporting oily sheen increased 15.0 times ($CI_{95\%}$: 7.05, 32.1), and the odds of reporting food staining increased 5.19 times ($CI_{95\%}$: 3.23, 8.35) (Table 4). The cutoff iron concentrations for scent and oily sheen (~0.1 mg/L) were below the recommended WHO guideline value of 0.3 mg/L (WHO, 2011); the cutoff concentration for food staining was 0.43 mg/L. In samples with iron above the cutoff concentration, iron-associated complaints were 10–22 times more likely to be reported as compared to samples with concentrations below the cutoff. At the guideline value, the predicted probability of iron-associated complaints of each type was approximately 0.25 (Fig. 3). However, at highest iron concentrations observed in the samples (up to 4.54 mg/L) the predicted probability of each type of complaints was essentially 1.0.

The interpolated iron and TDS concentrations showed distinct geographic patterns. A high iron cluster was located on the western side of the Atiwa Mountain Range in the upper part of the Birim River watershed (Fig. 1B), corresponding with the Upper Birimian geological formation (Schluter, 2008) (Fig. S6A, Supplemental Information). The high TDS cluster was located in the south eastern corner of the study area in the watersheds of the Densu and Ayensu Rivers (Fig. 1C), corresponding with the granites and granodiorites (Fig. S6A, Supplemental Information). The south western part of the study area had relatively low concentrations of both iron and TDS. The spatial trends in predicted concentrations were consistent with the rates of reported WQ problems.

4. Discussion

Our study showed strong associations between levels of iron and TDS in BHs and WQ complaints from water users. Furthermore, the results demonstrated that complaints start at levels below the WHO guidelines for these parameters. Prior research in the Eastern Region suggests that groundwater sources are underutilized in part due to these WQ problems (Kosinski et al., 2016; Kulinkina et al., 2016). Undesirable organoleptic characteristics of groundwater from BHs are also likely linked to consumption of microbiologically and chemically contaminated surface water (Kulinkina et al., 2017), which can lead to substantial detrimental public health impacts. Examining geographic clustering of WQ problems and patterns in dynamic water consumption from multiple water sources using spatial analyses (Alarcon Falconi et al., 2017) can be explored in future studies.

The geographic clusters of WQ problems are consistent with the local groundwater flow patterns (Ganyaglo et al., 2011). High iron concentrations are found in the upper Birim watershed (Atiwa District), an area affected by artisanal alluvial gold mining. Interestingly, Atiwa District also has a high rate of improved water access in terms of the number of water sources per population (Kulinkina et al., 2017), potentially as a result of having to drill more BHs to find acceptable water quality. Despite this, surface water is highly preferred and extensively used in some communities (Kosinski et al., 2016), a particularly unsafe practice in the presence of gold mining activities. While the extremely high turbidity levels from several years of mining pollution have rendered the Birim River unusable, mining activities are beginning to affect many of its tributaries that are still used for drinking, cooking, and laundry. Individuals relying on these streams may be exposed to hazardous chemicals used in mining practices (e.g. mercury, arsenic) (Babut et al., 2003; Basu et al., 2011; Donkor et al., 2006), while BHs are readily available in their communities. High TDS concentrations are found on the eastern side of the Atiwa Mountain Range, with salinity likely caused by dissolution of minerals in the aquifers, rather than by saltwater intrusion (Yidana and Yidana, 2010).

Iron commonly exceeded the WHO guideline value of 0.3 mg/L with highest observed concentrations near 5 mg/L. To combat the iron and manganese problem, Community Water and Sanitation Agency (CWSA), responsible for rural water supplies in Ghana, has commissioned locally designed Mwacafe iron and manganese removal filters for use at BHs, which include granular activated carbon and iron/manganese oxide coated sand as filter media (Siabi, 2004). The activated carbon is locally produced from wood charcoal (RCN, 2009; Siabi, 2004, 2003). Of the 238 BHs evaluated during the 2014 water sources survey (Kulinkina et al., 2017), 14 BHs had these filters. However, in 13 cases, they had been disconnected and were not in use due to rapid clogging of the filter pores resulting in very low flow rates, and not having a mechanism in place for washing the filter media.

Excessive salinity is not amenable to treatment in rural areas due to high cost. Furthermore, salty taste in the Eastern Region is reported at much lower concentrations than the identical WHO guideline and national standard values for TDS and constituents that comprise it, and also at much lower concentrations than at which salty taste is expected. In this area that appears to be particularly sensitive to salty taste, taste-altering substances could provide an alternative for increasing the use of BH water for drinking. For example, Ghanaians are known to drink smoke flavored water (Tano-Debrah et al., 2007) and to add camphor (naphthalene) to drinking water as a method of “treatment” and to enhance flavor of the water (GSS, 2015; Hydroconseil, 2011; Soghoian et al., 2012; Stoler et al., 2015); both practices are potentially harmful to health. Alternatives to improve taste without compromising health may help increase favorability of groundwater in geographic areas where there are known issues with taste.

Overall, the associations we found were consistent with the literature. TDS, as well as compounds that comprise it (calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulfates) are logical causes of reported salty taste (WHO, 2011). Iron is a plausible cause of unfavorable (metallic) scent and oily sheen on the water surface (SCDHEC, 2013). Staining of clothes, utensils and foods can also be attributed to high iron and manganese concentration (Siabi, 2004; WHO, 2011). However, our study has several potential limitations.

First, aesthetic perceptions of water vary among individuals, as well as among regions and countries (de Franca Doria, 2010; Getchell et al., 1991). Therefore, the results of this study may not be generalizable to other regions of Ghana and to other developing countries. Soliciting responses from one individual per BH in the dry season did not allow for characterizing the variability in perception of WQ at a BH level. However, analysis of data stratified by season produced consistent results (Table S3, Supplemental Information), suggesting that both sampling approaches produced unbiased data on perceptions of WQ.

Second, the accuracy and precision of the laboratory analyses may have affected measured WQ data. In our study, for relatively high concentration parameters, such as TDS and total hardness, duplicate samples were consistent with coefficients of variation (CV) in the range of 0–10%. For relatively low concentration parameters, such as phosphate and ammonia, the CV was in the range of 40–60%, indicating a need for improving laboratory instruments and/or protocols. WQ data with improved accuracy and precision of low concentration measurements and larger sample size may have enabled us to find a stronger association between manganese and food staining. Strengthening laboratory capacity to conduct WQ testing in low-income countries is a recognized priority (Crocker and Bartram, 2014; WHO, 2011), of even greater importance as WQ monitoring becomes more common to ensure compliance with the SDG targets.

5. Conclusions

Our previous studies showed that despite adequate access to improved water sources, reliance on surface water in the study area is high, and improved sources are underutilized (Kulinkina et al., 2016, 2017). Our findings highlight that consumer preferences may determine the level of utilization, cost recovery, and associated health benefit of improved water sources. Therefore, constructing more BHs does not ensure sustainable access to safer water supplies in rural communities. Treating water in locally sustainable ways and/or making sure that water quality is consistent with consumer preferences may be necessary before the health benefits of improved water sources can be fully realized. Further research on the effects on consumer perception of WQ in various cultural, geographic and economic settings is needed to support the development of international policies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

1. Alarcon Falconi TM, Kulinkina AV, Mohan VR, Francis MR, Kattula D, Sarkar R, Ward H, Kang G, Balraj V, Naumova EN. Quantifying tap-to-household water quality deterioration in urban communities in Vellore, India: the impact of spatial assumptions. Int J Hyg Environ Health. 2017; 220:29–36. http://dx.doi.org/10.1016/j.ijheh.2016.09.019.
2. Awuah E, Nyarko KB, Owusu PA. Water and sanitation in Ghana. Desalination. 2009; 248:460–467. http://dx.doi.org/10.1016/j.desal.2008.05.088.
3. Babut M, Sekyi R, Rambaud A. Improving the environmental management of small-scale gold mining in Ghana: a case study of Dumasi. J Clean Prod. 2003; 11:215–221.
4. 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. p. 11http://dx.doi.org/10.1371/journal.pmed.1001644
5. Basu N, Nam DH, Kwansaa-Ansah E, Renne EP, Nriagu JO. Multiple metals exposure in a small-scale artisanal gold mining community. Environ Res. 2011; 111:463–467. http://dx.doi.org/10.1016/j.envres.2011.02.006. [PubMed: 21397224]
6. Boateng JD, Brown CK, Tenkorang EY. Socio-economic status of women and its influence on their participation in rural water supply projects in Ghana. Int J Dev Sustain. 2013; 2:871–890.
7. Crocker J, Bartram J. Comparison and cost analysis of drinking water quality monitoring requirements versus practice in seven developing countries. Int J Environ Res Public Health. 2014; 11:7333–7346. http://dx.doi.org/10.3390/ijerph110707333. [PubMed: 25046632]
8. DeGabriele, J. Improving Community Based Management of Boreholes: A Case Study from Malawi A Case Study. Malawi: 2002.
9. de Franca Doria M. Factors influencing public perception of drinking water quality. Water Policy. 2010; 12:1–7. http://dx.doi.org/10.2166/wp.2009.051.
10. Donkor AK, Bonzongo JC, Nartey VK, Adotey DK. Mercury in different environmental compartments of the Pra River Basin, Ghana. Sci Total Environ. 2006; 368:164–176. http://dx.doi.org/10.1016/j.scitotenv.2005.09.046. [PubMed: 16243381]
11. Fuest, V. Policies, Practices and Outcomes of Demand-oriented Community Water Supply in Ghana: The National Community Water and Sanitation Programme. Bonn: 2005.
12. GSS. 2010 Population and Housing Census: Regional Analytical Report. Accra: 2013.
13. GSS. Ghana Demographic Health Survey. Accra: 2015.
14. Ganyaglo SY, Banoeng-Yakubo B, Osae S, Dampare SB, Fianko JR. Water quality assessment of groundwater in some rock types in parts of the eastern region of Ghana. Environ Earth Sci. 2011; 62:1055–1069. http://dx.doi.org/10.1007/s12665-010-0594-3.
15. Getchell, TV., Doty, RL., Bartoshuk, LM. Smell and Taste in Health and Disease. Raven Press; 1991.
16. Hydroconseil. World Vision's WASH-HD Phase II Evaluation: Ghana Country Report. Châteauneuf de Gadagne: 2011.
17. Kosinski, KC., Kulinkina, AV., Abrah, AFA., Adjei, MN., Breen, KM., Chaudhry, HM., Nevin, PE., Warner, SH., Tendulkar, SA. A mixed-methods approach to understanding water use and water infrastructure in a schistosomiasis-endemic community: case study of Asamama, Ghana; BMC Public Health. 2016. p. 16http://dx.doi.org/10.1186/s12889-016-2976-2
18. Kulinkina AV, Kosinski KC, Liss A, Adjei MN, Ayamgah GA, Webb P, Gute DM, Plummer JD, Naumova EN. Piped water consumption in Ghana: a case study of temporal and spatial patterns of clean water demand relative to alternative water sources in rural small towns. Sci Total Environ. 2016; 559:291–301. http://dx.doi.org/10.1016/j.scitotenv.2016.03.148. [PubMed: 27070382]
19. Kulinkina AV, Kosinski KC, Plummer JD, Durant JL, Bosompem KM, Adjei MN, Griffiths JK, Gute DM, Naumova EN. Indicators of improved water access in the context of schistosomiasis transmission in rural Eastern Region, Ghana. Sci Total Environ. 2017; 579:1745–1755. http://dx.doi.org/10.1016/j.scitotenv.2016.11.140. [PubMed: 27939198]

20. López-Ratón M, Rodríguez-Álvarez MX, Suárez CC, Sampedro FG. OptimalCutpoints: an R package for selecting optimal cutpoints in diagnostic tests. J Stat Softw. 2014; 61:1–36. http://dx.doi.org/10.18637/jss.v061.i08.
21. Marks, SJ., Komives, K., Davis, J. Community participation and water supply sustainability: evidence from handpump projects in rural Ghana; J Plan Educ Res. 2014. p. 1-11.http://dx.doi.org/10.1177/0739456X14527620
22. National Drinking Water Quality Management Framework. Accra:
23. Nyarko KB, Oduro-Kwarteng S, Adama I. Cost recovery of community-managed piped water systems in Ashanti region, Ghana. Water Environ J. 2007; 21:92–99. http://dx.doi.org/10.1111/j.1747-6593.2006.00051.x.
24. RCN. Mwacafe Plants Rescue 250 Boreholes by Removing Iron and Manganese. WASH News; 2009. [WWW Document]URL http://www.washghana.net/content/download/851/7205/file/150909RCNNewsletter-09-6.pdf [Accessed 1 January 2016]
25. Rached, E., Rathgeber, E., Brooks, DB. Water Management in Africa and the Middle East Challenges and Opportunities. 1996.
26. SCDHEC. [Accessed 1 January 2016] Drinking Water: Common Water Quality Problems and Their Treatment. 2013. [WWW Document], URL https://www.scdhec.gov/library/CR-006453.pdf
27. Schluter, T. Geological Atlas of Africa: With Notes on Stratigraphy, Tectonics, Economic Geology, Geohazards, Geosites, and Geoscientific Education of Each Country. Springer; 2008. Ghana; p. 110-113.
28. Shields KF, Bain RES, Cronk R, Wright JA, Bartram J. Association of supply type with fecal contamination of source water and household stored drinking water in developing countries: a bivariate meta-analysis. Environ Health Perspect. 2015; 123:1222–1231. http://dx.doi.org/10.1289/ehp.1409002. [PubMed: 25956006]
29. Siabi, WK. Potential of activated carbon for manganese and iron removal. Proc. 29th WEDC Int. Conf; 2003. p. 152-155.
30. Siabi, WK. Application of Mwacafe plant for the removal of Iron and Manganese. Proc. 30th WEDC Int. Conf; 2004. p. 632-636.
31. Soghoian S, Nyadedzor C, Ed Nignpense B, Clarke EEK, Hoffman RS. Health risks of using mothballs in Greater Accra, Ghana. Trop Med Int Heal. 2012; 17:135–138. http://dx.doi.org/10.1111/j.1365-3156.2011.02885.x.
32. Stoler J, Tutu RA, Winslow K. Piped water flows but sachet consumption grows: the paradoxical drinking water landscape of an urban slum in Ashaiman, Ghana. Habitat Int. 2015; 47:52–60. http://dx.doi.org/10.1016/j.habitatint.2015.01.009.
33. Tano-Debrah K, Amamoo-Otchere J, Karikari AY, Diako C. Quality characteristics and safety of smoke-flavoured water. Food Chem Toxicol. 2007; 45:962–970. http://dx.doi.org/10.1016/j.fct.2006.11.017. [PubMed: 17250943]
34. UN. Indicators for Monitoring the Millennium Development Goals. 2003.
35. UN-Water. Metadata on Suggested Indicators for Global Monitoring of the Sustainable Development Goal 6 on Water and Sanitation Compiled by UN-Water for the Inter-agency and Expert Group on Sustainable Development Goal Indicators (IAEG-SDGs) About UN-Water Goal. 2016:6.
36. UNICEF/WHO. Drinking Water Equity, Safety and Sustainability. JMP Thematic Report on Drinking Water. 2011
37. WHO. WHO Guidelines for Drinking-water Quality. 4. WHO chronicle; 2011.
38. Yidana SM, Yidana A. An assessment of the origin and variation of groundwater salinity in southeastern Ghana. Environ Earth Sci. 2010; 61:1259–1273. http://dx.doi.org/10.1007/s12665-010-0449-y.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ijheh.2017.05.008.

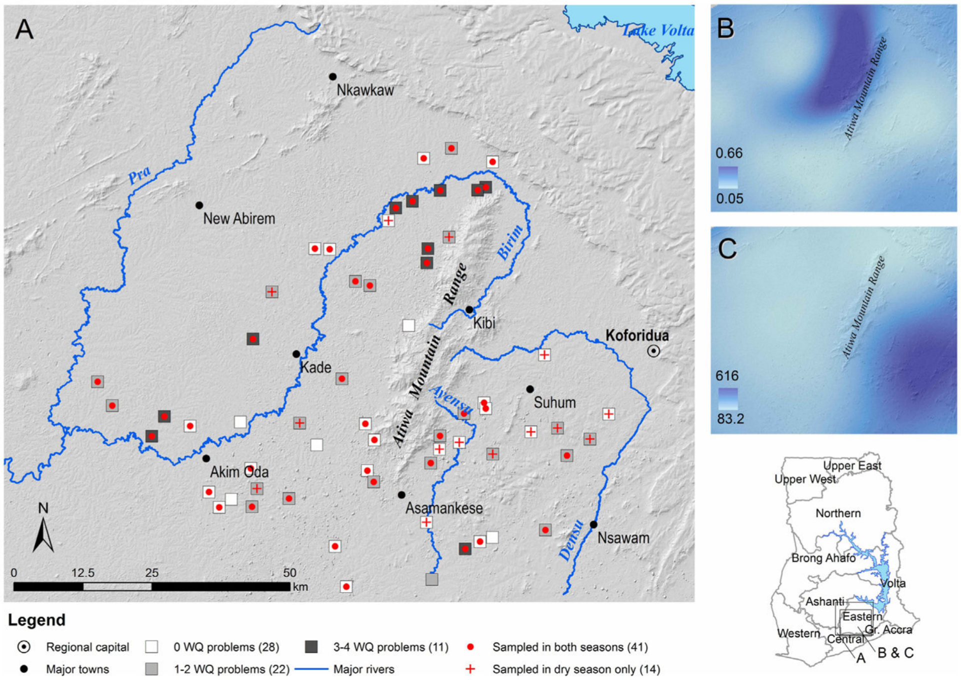

Fig. 1.

(A) Map of the study area and collected samples; (B) interpolated iron concentration ranging from 0.05 to 0.66 mg/L; (C) interpolated total dissolved solids concentration ranging from 83.2 to 616 mg/L.

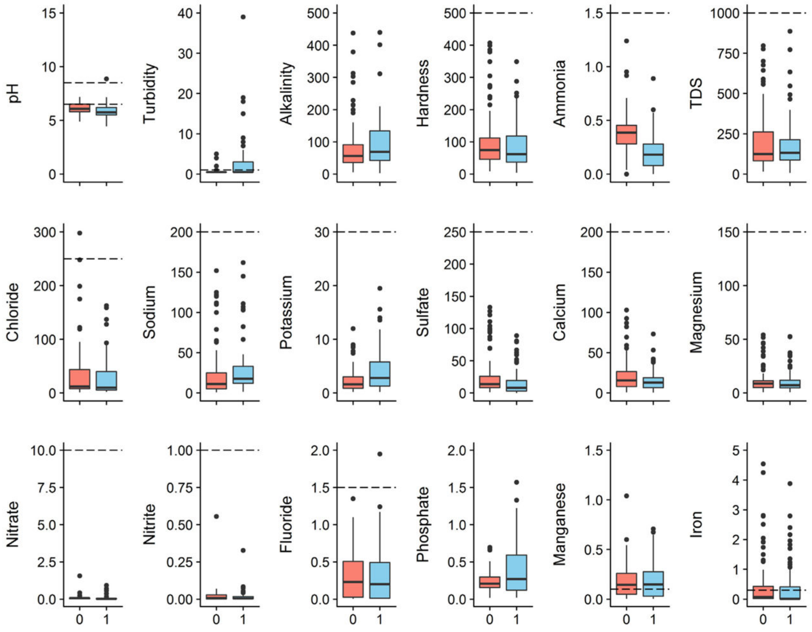

Fig. 2.

Distribution of water quality parameters by season (0 = dry; 1 = rainy) as compared to WHO guideline values (horizontal dashed lines).

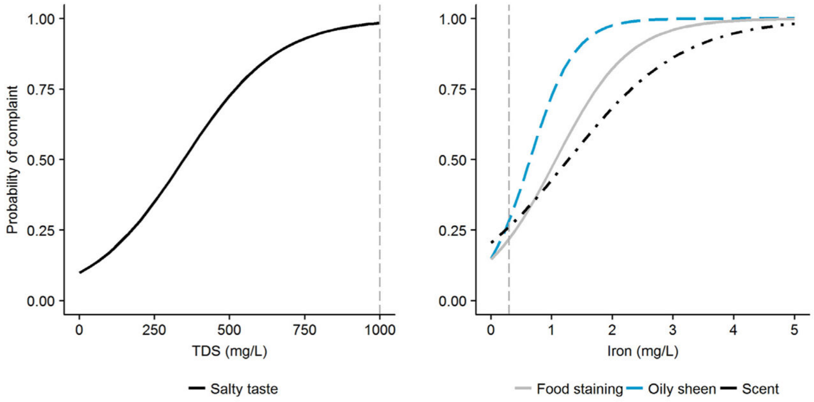

Fig. 3.

Model predicted probability of complaints (y-axis) against measured parameter concentrations (x-axis); dashed vertical lines indicate WHO guideline values.

Table 1

Summary of measured water quality parameters.

WQ parameter (unit)	Abbr.	WHO guideline	% exceeding guideline (dry)	% exceeding guideline (rainy)	Δ seasonal p-value (full)	Δ seasonal p-value (matched)
pH (−)	pH	6.5–8.5	74.5[#]	94.1[#]	<0.001[*]	<0.001[*]
Turbidity (NTU)	Turb	1.00[b]	6.4	35.3	<0.001[*]	0.002[*]
Total alkalinity (mg/L $CaCO_3$)	TotA	–	–	–	0.118	<0.001[*]
Total hardness (mg/L $CaCO_3$)	TotH	500	–	–	0.114	0.807
Ammonia (mg/L)	NH_3-H	1.50	–	–	<0.001[*]	<0.001[*]
Total dissolved solids (mg/L)	TDS	1000	–	–	0.596	0.043[*]
Chloride (mg/L)	Cl^-	250	1.1	–	0.175	0.819
Sodium (mg/L)	Na^+	200	–	–	0.262	<0.001[*]
Potassium (mg/L)	K^+	30.0	–	–	<0.001[*]	<0.001[*]
Sulfate (mg/L)	SO_4^{2-}	250	–	–	0.015[*]	0.005[*]
Calcium (mg/L)	Ca^{2+}	200	–	–	0.014[*]	0.025[*]
Magnesium (mg/L)	Mg^{2+}	150	–	–	0.593	0.096
Nitrate (mg/L)	NO_3-N	10.0[b]	–	–	0.749	0.819
Nitrite (mg/L)	NO_2-N	1.00[b]	–	–	0.378	0.394
Fluoride (mg/L)	F^-	1.50	–	–	0.795	0.616
Phosphate (mg/L)	PO_4^{3-}	–	–	–	<0.001[*]	0.006[*]
Manganese (mg/L)[a]	Mn	0.10/0.40	61.7/10.6	58.8/14.1	0.778	0.726
Iron (mg/L)	Fe	0.30	29.8	28.4	0.811	0.219
Conductivity (μS/cm)	Cond	–	–	–	0.077	0.654
Color – apparent (Hz)	Col	15[b]	–	–	0.017	0.225
Total suspended solids (mg/L)	TSS	–	–	–	<0.001[*]	<0.001[*]
Ca hardness (mg/L $CaCO_3$)	CaH	–	–	–	0.006[*]	0.014[*]
Mg hardness (mg/L $CaCO_3$)	MgH	–	–	–	0.617	0.085
Bicarbonate (mg/L $CaCO_3$)	HCO_3	–	–	–	0.107	<0.001[*]

Last six parameters were excluded from statistical analysis due to redundancy with other parameters and lack of variability.

[*] Statistical significance ($p < 0.05$).

[#] Most pH values were acidic (<6.5).

[a] Acceptability-based guideline is 0.10 mg/L; health-based guideline is 0.40 mg/L.

[b] Ghana Standards Authority limits are 5 NTU for turbidity, 50 mg/L for nitrate, 3 mg/L for nitrite, and 5 Hz for color (National Drinking Water Quality Management Framework, 2015); guideline values for the remaining parameters are identical to those of the WHO.

Table 2

Summary of reported water quality complaints in the dataset matched across two seasons.

	DRY			RAINY			Δ seasonal
	Total	**Yes**	**% Yes**	**Total**[a]	**Yes**	**% Yes**	**p-value**
Salty taste	68	20	29.4	198	54	27.3	0.606
Particles	68	42	61.8	206	102	49.5	0.003 *
Scent	68	23	33.8	205	59	28.8	0.290
Oily sheen	68	18	26.5	206	75	36.4	0.030 *
Food staining	68	18	26.5	202	60	29.7	0.580

* Statistical significance ($p < 0.05$).

[a] Missing data were contributed by inability of a respondent to comment on the specific problem.

Table 3

Results of univariate logistic regression models using $\log_{10}$ transformed and standardized data.

	Salty taste				**Particles**				**Scent**				**Oily sheen**				**Food staining**			
	β	**SE**	**p**	**R^2**	**β**	**SE**	**p**	**R^2**	**β**	**SE**	**p**	**R^2**	**β**	**SE**	**p**	**R^2**	**β**	**SE**	**p**	**R^2**
pH	0.96	0.17	0.00	0.12	0.01	0.12	0.95	0.00	0.37	0.13	0.00	0.02	0.44	0.13	0.00	0.03	0.65	0.15	0.00	0.06
Turb	0.10	0.14	0.45	0.00	0.12	0.12	0.32	0.00	0.36	0.12	0.00	0.02	1.04	0.16	0.00	0.15	0.77	0.14	0.00	0.10
TotA	1.26	0.20	0.00	0.16	−0.12	0.12	0.29	0.00	0.40	0.14	0.00	0.02	0.58	0.15	0.00	0.05	0.82	0.17	0.00	0.08
TotH	**1.43**	**0.21**	**0.00**	**0.20**	−0.09	0.12	0.45	0.00	0.29	0.13	0.03	0.01	0.30	0.13	0.02	0.01	0.56	0.15	0.00	0.05
NH_3 -H	0.54	0.14	0.00	0.05	0.20	0.12	0.09	0.01	0.40	0.13	0.00	0.03	0.29	0.12	0.02	0.01	0.57	0.14	0.00	0.05
TDS	**1.45**	**0.20**	**0.00**	**0.22**	−0.27	0.12	0.02	0.01	0.13	0.13	0.30	0.00	0.14	0.12	0.27	0.00	0.38	0.14	0.01	0.02
Cl^-	0.81	0.14	0.00	0.11	−0.37	0.12	0.00	0.02	−0.22	0.13	0.09	0.01	−0.49	0.14	0.00	0.04	−0.17	0.13	0.21	0.00
Na^+	1.05	0.17	0.00	0.15	−0.30	0.12	0.01	0.02	−0.11	0.13	0.39	0.00	−0.05	0.12	0.71	0.00	0.20	0.13	0.12	0.01
K^+	0.68	0.14	0.00	0.08	−0.45	0.12	0.00	0.03	0.00	0.13	1.00	0.00	−0.15	0.13	0.22	0.00	0.06	0.13	0.64	0.00
SO_4^{2-}	1.08	0.16	0.00	0.15	−0.20	0.12	0.09	0.01	−0.04	0.13	0.77	0.00	−0.11	0.12	0.39	0.00	0.22	0.13	0.10	0.01
Ca^{2+}	**1.43**	**0.21**	**0.00**	**0.21**	−0.04	0.12	0.71	0.00	0.39	0.14	0.00	0.02	0.41	0.13	0.00	0.03	0.70	0.15	0.00	0.07
Mg^{2+}	1.15	0.17	0.00	0.17	−0.11	0.12	0.34	0.00	0.23	0.13	0.08	0.01	0.22	0.12	0.08	0.01	0.36	0.13	0.01	0.02
NO_3 -N	−0.62	0.28	0.02	0.03	−0.06	0.12	0.58	0.00	−1.06	0.37	0.00	0.00	−1.62	0.45	0.00	0.07	−1.23	0.42	0.00	0.05
NO_2 -N	0.05	0.12	0.71	0.00	−0.05	0.12	0.68	0.00	−0.52	0.29	0.08	0.01	−0.16	0.16	0.34	0.00	−0.07	0.15	0.62	0.00
F^-	0.53	0.13	0.00	0.05	0.10	0.12	0.41	0.00	0.24	0.12	0.06	0.01	0.41	0.12	0.00	0.03	0.41	0.13	0.00	0.03
PO_4^{3-}	−0.19	0.14	0.17	0.01	0.41	0.13	0.00	0.03	0.27	0.12	0.03	0.01	0.49	0.13	0.00	0.04	0.56	0.13	0.00	0.06
Mn	0.53	0.13	0.00	0.05	0.04	0.12	0.75	0.00	0.52	0.13	0.00	0.05	0.71	0.14	0.00	0.08	0.80	0.14	0.00	0.10
Fe	0.09	0.13	0.52	0.00	0.38	0.13	0.00	0.02	**0.92**	**0.14**	**0.00**	**0.14**	**1.91**	**0.24**	**0.00**	**0.34**	**1.35**	**0.17**	**0.00**	**0.26**

Most significant associations based on the size of the p-value, regression coefficient β, and R^2 are bolded.

Table 4

Results of final analyses using untransformed data.

Univariate logistic regression analysis

Complaint	**WQ**	**Unit Δ (mg/L)**	**OR ($CI_{95\%}$)**	**p-value**	**R^2**
Salty taste	TDS	100	1.89 (1.55, 2.31)	<0.001	0.17
Scent	Iron	1.00	2.89 (1.99, 4.19)	<0.001	0.12
Oily sheen	Iron	1.00	15.0 (7.05, 32.1)	<0.001	0.32
Food staining	Iron	1.00	5.19 (3.23, 8.35)	<0.001	0.22

Youden index threshold analysis

Complaint	WQ	Cutoff (mg/L)	OR ($CI_{95\%}$)	Sens/Spec	AUC
Salty taste	TDS	172	10.1 (5.60, 18.1)	0.72/0.79	0.80
Scent	Iron	0.11	10.4 (5.76, 18.7)	0.78/0.75	0.78
Oily sheen	Iron	0.14	22.7 (12.1, 42.6)	0.82/0.84	0.87
Food staining	Iron	0.43	21.8 (11.2, 42.6)	0.67/0.92	0.82