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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

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Abstract

Continuous access to adequate quantities of safe water is essential for human health and socioeconomic development. Piped water systems (PWSs) are an increasingly common type of water supply in rural African small towns. Despite providing the highest and most flexible level of service with better microbiological water quality to their users, these systems remain vulnerable to rural water sustainability challenges. We assessed temporal and spatial patterns in water consumption from public standpipes of four PWSs in Ghana in order to assess clean water demand relative to other available water sources. Low water consumption was evident in all study towns, which manifested temporally and spatially. Temporal variability in water consumption that is negatively correlated with rainfall is an indicator of rainwater preference when it is available. Furthermore, our findings show that standpipes in close proximity to alternative water sources such as streams and hand-dug wells suffer further reductions in water consumption. Qualitative data suggest that consumer demand in the study towns appears to be driven more by water quantity, accessibility, and perceived aesthetic water quality, as compared to microbiological water quality or price. In settings with chronic under-utilization of improved water sources, increasing water demand through household connections, improving water quality with respect to taste and

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appropriateness for laundry, and educating residents about health benefits of using piped water should be prioritized. Continued consumer demand and sufficient revenue generation are important attributes of a water service that ensure its function over time. Our findings suggest that analyzing water consumption of existing metered PWSs in combination with qualitative approaches may enable more efficient planning of community-based water supplies and support sustainable development.

Graphical abstract

Keywords

Rural water; Water consumption; Improved water access; Piped water systems; Functional sustainability; Ghana

1 INTRODUCTION

Continuous access to adequate quantities of safe water is essential for human health and socioeconomic development. Since the 1980s, African governments have been implementing piped water systems (PWSs) in order to increase water availability in rural small towns (WSP, 2010). In Ghana specifically, PWSs began to be introduced to the rural areas in the 1990s as part of the National Community Water and Sanitation Programme, with 198 new small town PWSs constructed between 1994 and 2003 (Fuest, 2005). Today, approximately 16.6% of rural Ghanaian households rely on pipe-borne water as their main water supply, with 11% obtaining water from public standpipes (SPs) and the remaining 5.6% from private or shared household connections (GSS, 2014). Despite providing the highest and most flexible level of service with better microbiological water quality as compared to other water sources used in resource poor settings (Shields et al., 2015), PWSs are still vulnerable to rural water sustainability challenges.

Functional sustainability of a rural water service, or its ability to provide the same quantity and quality of water over time (Abrams et al., 2001; Carter and Rwamwanja, 2006), among other factors, depends on a sustainable financing mechanism (Harvey and Reed, 2006; Harvey, 2007; Montgomery et al., 2009; Nyarko et al., 2007; Rogers et al., 2002). Research

has shown that the vast majority of cost recovery mechanisms in low-income settings do not collect sufficient funds for operation and maintenance (O&M) of water systems, much less retain reserve funds to cover the costs of extending water services as communities grow (Harvey and Reed, 2006; Marks et al., 2014; Nyarko et al., 2007; Singh et al., 1993; Whittington et al., 2009). Low revenue streams are common due to a combination of low water tariffs and willingness to pay, low water consumption (Brikke and Rojas, 2001), and a lack of reliable accounting and auditing processes (Fuest, 2005).

In Ghana, water tariffs that generate sufficient funds for O&M and system expansion and rehabilitation (CWSA, 2014), while not exceeding 1 USD/m³ (Nyarko et al., 2007) are desired. Ideally, tariffs should not be so high that they reduce water consumption (Hopkins et al., 2004), should reflect supply characteristics such as frequency of supply and water quality, and must be perceived as fair by the end users (Rogers et al., 2002). Apart from an appropriate water tariff, cost recovery of community-managed PWSs is affected by the local administrators' management practices (Brikke and Rojas, 2001). Water committees and town leaders are often tempted to appropriate funds generated from water sales to competing priorities such as the construction of schools, markets and sanitation facilities (Fuest, 2005; Montgomery et al., 2009).

Even in instances when appropriate water tariffs are implemented, low water consumption alone can undermine cost recovery. Variable daily water consumption rates from PWSs have been documented, ranging between 5 and 35 L per person (WSP, 2002), as compared to the 20 L per capita per day minimum recommended by the Joint Monitoring Programme (JMP) and the Ghanaian Community Water and Sanitation Agency (CWSA) to constitute "basic access" (CWSA, 2014; WHO, 2015). Low water consumption from improved water sources is often attributed to a combination of seasonal and spatial patterns in water demand due to the availability of alternative traditional water sources that are free or sold at lower prices than piped water (Brikke and Rojas, 2001; Nyarko et al., 2007; WSP, 2002). A study in Rwanda found that 41% of households used rainwater as their primary water source in the rainy season as compared to 27% using improved wells (Hopkins et al., 2004), implying major temporal shifts in water consumption. Alternative water sources that are often of poorer microbiological quality are chosen for a variety of reasons, including but not limited to cost, convenience, tradition, and preference or suitability for domestic uses (Kosinski et al., 2016; Narayan-Parker, 1988; Nyong and Kanaroglou, 2001). For example, salty taste or tastelessness have been reported in the literature as disincentives for using improved groundwater sources for drinking and water hardness for laundry (DeGabriele, 2002; Fuest, 2005; Nyarko et al., 2007).

Chronically low water consumption with an accompanying low revenue stream can lead to the deterioration of water systems, causing communities to move down on the 'water ladder' (WHO, 2015) and perpetuating the concept of water development in sub-Saharan Africa as a bidirectional process (Eguavoen, 2013). Conversely, high water consumption from PWSs is indicative of continued consumer demand while maximizing revenue, which in turn ensures that the service continues to function over time. In light of PWSs becoming an increasingly common type of rural water supply in sub-Saharan Africa, we studied water consumption patterns in four community-managed PWSs in the Eastern Region of Ghana through the use

of water meter records. To our knowledge, no previous studies have provided similar empirical evidence of water demand in low resource settings.

The study had two primary objectives. The first objective was to assess temporal and spatial patterns in water consumption from public SPs. We hypothesized that these patterns are influenced temporally by the rainfall pattern and spatially by the distribution of the SPs and alternative water sources, normalized by the population density. The second objective was to examine how additional PWS attributes, such as perceived appropriateness of PWS water for domestic uses, relative cost, and convenience, may influence water consumption and in turn functional sustainability of the systems. The study objectives were achieved through a mixed-methods community-based approach, which included quantitative and qualitative data.

2 METHODS

2.1 Study area and study design

The study was conducted in the Eastern Region of Ghana, which lies in the deciduous forest agro-ecological zone, characterized by a major and minor peak rainfall periods in June and October, respectively (Frenken, 2005). The Harmattan, a persistent prevailing wind from the Sahara region, brings dry season from November to February. In advance of the present study, our study team conducted a comprehensive survey of public water sources in 74 rural towns in the Eastern Region in 2013–2014. All towns relied on a combination of deep groundwater (boreholes or PWSs), shallow groundwater (hand-dug wells), surface water, and privately collected rainwater when available.

Of the 74 towns, seven relied on PWSs as their primary water supply. A PWS typically consists of one or more mechanized source boreholes, from which water is pumped to an overhead storage tank and distributed throughout the community through a gravity-fed network of public SPs and private household connections. At the conception of the study, all 7 PWS towns were considered for inclusion; however, preference was given to larger towns of 4,000+ residents with at least 10 SPs in order to allow for sufficient spatial variability in water consumption. Two of the 7 towns were excluded because they had significantly lower populations (2,160 and 1,280) and low numbers of SPs (7 and 3, respectively). Another town (4,550 people and 10 SPs) was excluded because the water committee was undergoing a management transition and did not have water meter records available. Thus the four study towns (referred to as A through D in the text) were chosen based upon the following inclusion criteria: population of 4,000+, at least 10 public SPs, and ability to supply at least two years of water meter records for analysis.

All studied PWSs were installed between 2004 and 2010 and offered comparable improved water coverage through the public SPs (382 to 516 people per public SP) (Table 1), as compared to the Ghanaian rural water coverage standard of 300 people per spout at each stand post, SP or borehole (CWSA, 2014). All PWSs reported using chlorination; in addition, Town D had an iron removal treatment process. Paid water vendors sold water from public SPs and charged users a per-bucket fee equivalent to approximately 1 USD/m³. Private connections were relatively uncommon (33, 56, 51 and 20 in towns A through D,

respectively). Private connection fees varied between 90 and 200 Ghana Cedis (GHC, exchange rate was approximately 2.75 GHC per 1 USD) for a complete installation in towns A, B and D. In Town C, the customer was charged 40 GHC for installation only and was responsible for purchasing the meter and associated piping independently. Some of the public SPs were unused (Figure 1) because they were broken, their use had been discontinued due to low patronage, or they were institutional connections (schools, clinics, etc.) and not available or only partially available to the public.

In addition to the PWSs, all study towns had at least one type of alternative public water source available, including boreholes, protected and unprotected hand-dug wells, and surface water (Figure 1). There were no formal rainwater harvesting systems at the time of the study, but the majority of town residents practiced private rainwater collection. All water sources supplementary to the public PWSs were free of charge, with the exception of the Town C borehole, for which users paid the same price as the public SPs on a per-bucket basis. The perennial river in Town C and smaller streams in Town D were used throughout the year, but particularly in the dry season when surface water experienced lower turbidity levels.

2.2 Data sources

To achieve objective 1, water meter records, rainfall records and geospatial data were utilized (Sections 2.2.1 through 2.2.3). To achieve objective 2, interview data and physicochemical water quality data were utilized (Sections 2.2.4 and 2.2.5).

2.2.1 Water meter records—Water meter records containing daily meter readings were obtained for all public SPs. There were 55 total functional SPs in the four study towns (Table 1), of which 54 had meter records available (one SP in Town C had a broken meter throughout the study period). Daily water consumption (m^3) from each SP was calculated as the difference in meter readings, and subsequently aggregated into SP-specific monthly values for analysis (outcome variable) for all months during which complete daily data were available.

Initially, meter records for all four towns were obtained for two complete years (2012 and 2013). Some of the SP-specific monthly values were missing because the SP was out of service altogether or the meter was broken for all or part of a month. Missing observations in Town B were also caused by missing record books; to account for this deficiency, an extra year of data was obtained for Town B. Missing data in the final SP-specific monthly data set ranged from 5% to 29% (Table 1).

2.2.2 Rainfall data—Daily rainfall data for the study period were obtained from the Ghana Meteorological Agency for three meteorological stations located within 5–15 km of each study town. Monthly rainfall totals (mm) from the station nearest to each town were used as predictor variables in the analysis. Towns C and D were closest to the same meteorological station, whereas Towns A and B were closest to their own separate stations.

2.2.3 Geospatial data—Between April 24 and May 12 of 2014 (end of dry season), all publicly available improved and unimproved water sources including public SPs, boreholes, hand-dug wells, and surface water access points were mapped using the iPad GPS Tracks

app (version 2.4.3). Private water sources (household connections and hand-dug wells) were excluded from the mapping. For the 54 public SPs included in the analysis, Euclidian distance (m) to the nearest free alternative water source was determined using the “near” function within the proximity tools in ArcGIS software (version 10.2.2) and used as a predictor variable in the analysis.

A third predictor variable that approximated the total population served by each SP was derived using a combination of census and remote sensing data. The total population of each town was abstracted from a detailed 2000 Census (latest available) obtained from the Ghana Statistical Service. Projected 2014 populations were obtained using a 2.1% annual population growth as estimated for the Eastern Region for the 2000–2010 time period (GSS, 2013). Concurrently, raster images of populated areas were derived using roof reflectance values in ENVI software (version 4.8) from a base image obtained from Google Earth in September 2015 (Google, Mountain View, California). As a proxy for population density, per-pixel (1 m^2) population was approximated by dividing the total 2014 town population by the total number of pixels in the raster image. For each pixel, the likelihood of accessing each individual SP was computed using a Gaussian distribution. Resulting cumulative likelihood was normalized to the 0–1 interval. Approximate population served by each SP was then determined by assigning each populated pixel to a specific SP using the maximum likelihood method. Resulting population raster classification is shown in Figure 2. The methodology is essentially identical to the automated Thiessen (or Voronoi) polygon function within the ArcGIS tools, but is more flexible to accommodate different SP access specifications (e.g. walking routes).

2.2.4 Interview data—We conducted between 5 and 6 interviews in each town during a two-week period in May 2014. Approximate interview locations were purposively selected in advance to represent a range of distances to public water sources using the town maps developed during geospatial data collection (Section 2.2.3). Upon arrival in the pre-determined interview locations, women were approached by one note-taker and one native Twi speaker and were asked to participate in an interview about water source preferences for domestic uses such as drinking, cooking, laundry and bathing. Women were interviewed because of the predominant role they play with respect to water collection, storage and allocation within rural African households (Boateng et al., 2013; Rathgeber, 1996). Verbal informed consent was obtained from each participant prior to the interview in accordance with the study protocol approved by the Tufts University Institutional Review Board (Medford, MA, USA). Women were asked their age and length of residence in the community; only women aged 18+ years who had resided in the community for at least two years were interviewed. Interviews consisted of multiple-choice and open-ended questions and took approximately 1 h. Questions were asked verbally in Twi; responses were verbally translated and recorded in English on an iPad using the QuickTap Survey app (version 5.17). The interview locations were geocoded using the GPS Tracks HD app (version 2.4.3).

2.2.5 Physicochemical water quality data—To further assess reported water quality complaints discovered in the interviews, water samples were collected from the PWSs as part of a larger water sampling study conducted at two time points. In January 7–10, 2015

(dry season), we collected grab samples from two randomly chosen SPs in each town between the hours of 12:35 and 14:30. In June 27–30, 2015 (rainy season), we collected grab samples from three randomly chosen SPs in each town between the hours of 08:00 and 17:55. Water samples were collected in pre-washed and pre-labeled 1-L sampling containers provided by the water quality analytical laboratory. The tap was allowed to run for 30 s, after which the containers were triple rinsed with sample water and filled. Sample ID, time, date, and GPS coordinates were recorded in a field notebook. Samples were kept on ice or refrigerated and delivered to the Water Research Institute (WRI) water quality laboratory in Accra within 2 days of collection, as per laboratory protocol. The samples were analyzed for 24 physicochemical parameters; microbiological water quality was not assessed. Field duplicates were analyzed for quality assurance and quality control during both sampling rounds as part of the larger study.

2.3 Data analysis

Temporal and spatial patterns in monthly water consumption (m^3) in 54 SPs (objective 1) were initially explored using graphical methods, coefficients of variation, Spearman's correlation, and univariate generalized linear regression models. Subsequently, associations between monthly water consumption (outcome variable) and three predictor variables were tested using a multivariate regression model. The temporal pattern was assessed by including monthly cumulative rainfall (mm) as a predictor variable. The spatial pattern was assessed by including the distance (m) from the SP to the nearest alternative water source as a predictor variable. The associations were adjusted for the approximate population served by the SP.

From generalized linear model results, we observed that within-town variability explained a high percentage of the overall variability in monthly water consumption. Therefore, a final mixed effects regression model fit by the restricted maximum likelihood (REML) function was chosen to capture this effect. The model was conducted separately for each town (Eq. (1)), and for all towns combined (Eq. (2)).

$$x_{tj} = \beta_0 + \beta_1 \text{Rain}_{ti} + \beta_2 \text{Dist from SP}_j \text{ to alternative water source} + \beta_3 \text{Pop served by SP}_j + \alpha \text{SP}_j + e \quad (1)$$

$$x_{tj} = \beta_0 + \beta_1 \text{Rain}_{ti} + \beta_2 \text{Dist from SP}_j \text{ to alternative water source} + \beta_3 \text{Pop served by SP}_j + \alpha \text{SP}_j + \gamma \text{Town}_i + e \quad (2)$$

where x_{tj} was the water use in m^3 ($\log_e$ transformed to achieve a normal distribution) for t-month at j-SP, β_0 was the intercept term, β_1 through β_3 were regression coefficients for the three predictor variables, and α and γ were random effects for SP and town of observation, respectively. Random effect for study town (γ) allowed us to control for unquantified town-level effects (e.g. absolute number of private household connections or hand-dug wells) which affect public SP water consumption. Analyses were conducted in R software (version 3.1.2). Interactions between variables were explored but none were systematically statistically significant and were therefore omitted for the ease of regression coefficient interpretation. Model fit was assessed by examining the correlation (r value) between the observed and predicted values as compared to the line of equality, as well as by plotting the

average of the observed and predicted values against their difference and assessing the proportion of predicted observations within the 95% limits of agreement (q value) (Bland and Altman, 2003).

To explore how physicochemical water quality preferences and other relevant attributes of improved and unimproved water sources within the study towns may influence PWS water consumption patterns (objective 2), we relied on qualitative data from the interviews and water quality data. Positive and negative opinions expressed during the interviews were manually grouped into seven categories related to the following: water availability, convenience, payment, general water quality, appropriateness of piped water for drinking and laundry, maintenance, and desired water improvements (Table S1, Supporting Information). Reported water quality concerns with respect to taste and appropriateness for laundry were matched to related physicochemical parameters (Table S2, Supporting Information).

3 RESULTS

3.1 Temporal and spatial patterns in piped water consumption

Exploratory analyses showed substantial variation in water consumption from public SPs. In towns A, C and D, consumption was relatively low with the median monthly water use in the majority of SPs below 100 m³ (87.5%, 80.0%, and 81.8%, respectively). This can be compared to Town B, where the median monthly water withdrawals in 50% of the SPs exceeded 100 m³ (Figure 3a). Monthly water consumption was inversely correlated with rainfall (Figure 3b). In all towns, for the majority of the individual SPs, there was a negative association between monthly water consumption and rainfall with statistically significant Spearman's correlation coefficients ranging between -0.88 and -0.36 (average of -0.55). A stronger negative correlation matched to a lower coefficient of variation in water consumption, indicating consistency in the observed relationship (not shown).

The observed temporal pattern in water consumption was supported by the regression model results (Table 2). Adjusted for the spatial variables, each 100-mm increase in rainfall corresponded to an average decrease of 16.0% (CI_{95%}: -18.8, -13.1) in monthly water consumption. In 2012–2013, during the wettest months (June and October), rainfall on average was 215 mm, which translated into a potential decrease of approximately 30% in monthly water consumption as compared to the especially dry months (January and August) when average rainfall was only 15 mm. The decrease in monthly water consumption associated with 100-mm increase in rainfall ranged between 11.3% in Town C and 21.9% in Town B.

The spatial variables demonstrated independent effects on water consumption when controlling for rainfall (Table 2). Model results suggested a positive association between the distance from the SP to the nearest alternative water source and water consumption in Towns B and C. With each 100-m distance increase, water consumption increased by 36.0% in Town B (CI_{95%}: -15.6, 119) and 7.96% in Town C (CI_{95%}: -19.5, 44.9). In Town A, the same 100-m distance increase was associated with a statistically significant decrease in water consumption (17.7%; CI_{95%}: -25.2, -9.47). In Town D, the association was

inconclusive. Increasing population served by the SP was associated with increased water consumption in Towns A, C and D. The size of the effect was comparable across the three towns, ranging from 11.2% increase in water consumption contributed by additional 100 people served in Town C (CI_{95%}: -14.6, 44.9) to 16.6% in Town A (CI_{95%}: -6.10, 44.8). In Town B, the association was inconclusive.

Model-predicted water consumption values were compared to the observed values using scatter plots. Model performance ranged by town with the lowest correlation between predicted and observed values occurring in Town B ($r = 0.70$) and the highest in Town D ($r = 0.93$). Overall, the model performed well at predicting water consumption values below 200 m³ and tended to underestimate higher values. The mean vs. difference plots also illustrated overall good model performance with approximately 93–95% of the differences between observed and predicted values falling within the 95% limits of agreement for each town and for all towns combined (Figure 4).

3.2 Qualitative analysis of interview responses and physicochemical water quality

Interview locations (Figure 1) were spatially distributed in order to represent a range of distances to public water sources. Distances to the nearest SP in the sample ranged from 35 to 220 m (average 99 ± 53 m). Distances to the nearest alternative water source ranged between 35 and 750 m (average 216 ± 181 m).

Water availability and convenience—Approximately half of the interviewees (13/22) stated increased water availability as one of the primary benefits offered by the PWS. This was particularly true in towns that had lower access to alternative water sources, namely Towns A and B. One of the interviewees in Town B mentioned that prior to the PWS there were very long queues at the limited number of hand-dug wells. An interviewee in Town A mentioned that despite increased water availability offered by the PWS, the town still experiences water shortages in the dry season.

The interviewees generally appreciated the shorter walking distances offered by the relatively high density of SPs as well as the design of the SPs which made fetching water faster and easier as compared to manual pumping of water from boreholes or withdrawing from hand-dug wells. However, there were perceived inconveniences as well, such as water vendors locking SPs during large portions of the day when they are not available to collect the water fees and water unavailability during long power outages. An interviewee from Town D mentioned that if you don't fetch water in the morning, the vendor may lock the SP and go to farm and not come back until the evening. Another interviewee from Town B mentioned that sometimes water doesn't flow from the system for up to three days, even when there is no power outage, and the residents are not given the reason.

Payment for water—All 22 interviewees recognized the need to pay for water in order to cover PWS maintenance and electricity costs and the salaries of water vendors and water committee members. Furthermore, all interviewees agreed that the price they paid for PWS water at the time of the study was fair and affordable (tariff at the time of the study was approximately 1 USD/m³ in all study communities). One interviewee from Town D, however, noted that sometimes when the water quality is poor in the system (supposedly

when the storage tank is being washed), the vendor still requires payment because he/she is accountable for all water that passes through the meter.

Water quality in general and with respect to drinking and domestic uses—

Opinions on general water quality varied. Some interviewees recognized that PWS water is likely less contaminated than river water and unprotected hand-dug wells. One interviewee from Town C mentioned that cholera outbreaks and skin rashes became less common than during the times when the town relied exclusively on river water. The majority of the interviewees expressed negative views, however, particularly with regard to taste and color of PWS water. One of the interviewees from Town D stated that the reason for PWS installation was to bring more water to the town and not better water; hence there are no advantages of PWS water over other sources in terms of water quality. In fact, there was widespread dissatisfaction with the appropriateness of PWS water for drinking and laundry. Interviewee responses also indicated that water from alternative sources is preferred to PWS water for these purposes. Physicochemical water quality results, although limited, suggest that the user complaints are not unfounded (Table 3).

Twelve of the 22 interviewees (55%) reported unfavorable or salty taste as a deterrent from drinking PWS water. All 12 individuals preferred the taste of rainwater; 8 of them also preferred the taste of water from hand-dug wells. Three individuals from Town A stated that they do not drink piped water at all because of taste concerns. Of the measured water quality parameters, total dissolved solids (TDS), chloride, sodium and sulfate concentrations may contribute to salty taste (WHO, 2011). In Town C, where this complaint was most commonly reported (5 of 5 interviewees), TDS, chloride and sulfate levels were elevated as compared to the other three towns.

Fifteen of the 22 interviewees (68%) reported inadequate lathering of soap when doing laundry with PWS water. All 15 interviewees explicitly stated that rainwater is best suited for laundry as compared to all other water sources in their town. In Towns B and C, where all interviewees were concerned about water hardness, the average total hardness concentrations of the water samples were 170 and 229 mg/L as CaCO_3 , respectively, as compared to 111 and 126 mg/L in Towns A and D, where water hardness concerns were expressed less frequently.

Maintenance and desired water improvements—The interviewees expressed general satisfaction with the maintenance of the PWSs, such as water vendors keeping the SPs neat and problems being fixed quickly. It should be noted that the possibility of fear in expressing negative views of management practices contributing to the lack of negative responses cannot be excluded. When interviewees were asked to comment on the types of water related improvements they would like to see in their towns, some of the comments related to the PWSs. Desire for additional public SPs and private connections and improvements in PWS water quality were the most commonly mentioned. Many interviewees, however, stated that they wanted improvements in the quantity and quality of alternative water sources, including education about improving the safety of water from these sources for drinking in their homes.

4 DISCUSSION

4.1 Temporal and spatial patterns in piped water consumption

Water consumption in public SPs in the study varied temporally and spatially. Rainfall contributed to decreased PWS water consumption in all four study towns. The magnitude of the effect varied across towns, with the highest effect exhibited in Town B and the lowest in Town C. The most significant seasonal drop in PWS water consumption in Town B could potentially be due to the highest average number of people served by each SP (516 compared to 382 in Town C), leading to a larger number of people per SP switching from PWS to rainwater when it becomes available. Consistently with this explanation, the second highest effect of rainfall on water consumption was observed in Town D, with an average of 457 people served by each SP. An alternative explanation is that during the rainy season, hand-dug wells, which are more prevalent in towns B and D, typically experience higher water quantity and better quality. The effect of rainfall in these towns may be manifesting through the increased use of hand-dug wells during the rainy season as well as direct collection of rainwater. The diminished effect of rainfall in Town C can be explained by the presence of a perennial river (Figure 1). The river is used extensively in both seasons, but particularly in the dry season with lower turbidity, which attenuates the seasonal peaks in PWS water consumption.

Increasing distance to the nearest alternative water source was expected to increase SP water consumption. Accordingly, a positive association between these variables was observed in towns B and C. In both towns, there was one predominant type of alternative water source (hand-dug wells in Town B and a river in Town C) and these sources were spatially concentrated (Figure 1). In towns A and D, the distance variable did not exhibit sufficient variability to detect a stable association. Town A had very few alternative sources and distances between SPs and these sources were mostly large. Conversely, Town D had a large number of alternative sources that were well spread throughout the community and distances between them and SPs were mostly small.

Temporal variability in water consumption that is correlated with rainfall and corroborated by the interview responses suggests that there is a preference for rainwater when it is available. Further study of people's seasonal preferences of water source types and their relative contamination levels, especially in the presence of a stable improved water supply, may further clarify seasonal patterns in waterborne and water-related diseases (Jagai et al., 2009; Jagai et al., 2012; Kulinkina et al., 2016; Levy et al., 2009). Furthermore, our findings in Towns B and C provide quantitative support to prior research that suggests that presence of alternative water sources in close proximity negatively affects water consumption from improved sources (Brikke and Rojas, 2001) negating the health benefits of improved water supplies.

4.2 Water quality perceptions and measurements

Although conclusions regarding perceived and measured aesthetic water quality are limited by small sample size, concerns about unfavorable taste and hardness of PWS water generally correlated to measured levels of related physicochemical water quality parameters.

According to the WHO Drinking Water Quality Guidelines, high soap consumption is associated with hardness concentrations of 200 mg/L as CaCO_3 and higher (WHO, 2011). Only in Town C, water hardness exceeded the 200 mg/L concentration; however, in all study towns with hardness levels below the guideline value, preference was still given to other water sources for laundry. Salty taste becomes evident at TDS concentration 500–600 mg/L, sodium concentration 200 mg/L, and chloride and sulfate concentrations 250 mg/L (WHO, 2011). All of the parameter concentrations were below these limits in all of the water samples; nonetheless, study town residents were able to experience salty taste. This is not necessarily surprising considering great variability among individuals and populations with regards to both taste and smell (Getchell et al., 1991).

Interview responses suggest that water source choices are driven more by aesthetic concerns than by microbiological water quality. Interviewees were generally aware of superior microbiological quality of piped water. Nonetheless, it was not uncommon for people to prefer the taste of water from hand-dug wells, rivers and rainwater for reasons of familiarity and historical use by their ancestors. Perceived water quality that is shaped by local habits and preferences, rather than by actual contaminant levels, may have substantial bearing on water acceptability and sustained use of water systems (de Franca Doria, 2010; Francis et al., 2015). It is not unlikely that non-preference of PWS water to other available sources for drinking and washing is the underlying reason for low PWS water consumption in the study towns. How people perceive aesthetic water characteristics below regulatory or guideline values, and how their perceptions influence water source choice and improved water consumption, particularly in different cultural contexts, warrant further quantitative study.

4.3 Sustainability implications for existing and future piped water systems

PWSs are an important step towards economic progress, sustainable water infrastructure, and better health. They improve water availability and reduce the time associated with water collection by reducing walking distances and waiting times. They are rooted in the concept of a capital investment and operational cost that are recoverable through water tariffs. Metering and record keeping introduces accountability that is not currently possible with unmetered wells and boreholes on which most rural Ghanaian communities still rely. However, the health and economic benefits offered by PWSs are not optimized when they are under-utilized by the communities. Furthermore, low water demand also compromises their functional sustainability. Designed with a capacity to provide 20 L of water per capita per day (CWSA, 2014), the total average monthly water consumption for a town of 5,000–6,000 people is expected to be between 3,000 and 3,500 m^3 ($\pm$ water consumption from private connections). In contrast, during the study period, study towns were using between 609 and 863 m^3 of water per month from public SPs (Table 1), indicating that on average, the systems are operating at 20–25% of their design capacity. It should be noted that during the driest months, individual SPs with highest consumption did experience water withdrawals of 250–350 m^3 per month (Figure 3a), which approximately equates to the design capacity; meaning that under certain spatial and temporal conditions, desired water consumption can be reached. Under average conditions, however, the study towns obtain a large proportion of their water from alternative sources.

Low water demand from improved water sources and the supplementation of water needs with traditional alternative sources is a complex dynamic. Economic factors such as price of water and willingness to pay have largely been emphasized in cost recovery and sustainability research. However, more recently, there have been calls for studying socio-demographic and cultural factors of water demand to complement the economic factors (Corbella and Pujol, 2009). In the present study, the water tariff of ~1 USD/m³ was consistent with the policies, comparable to other PWSs studied by Nyarko et al. (0.6–1.2 USD/m³), and perceived as fair by the water users. Hence, it appears that consumer demand in the study towns is driven more by water quantity, accessibility, and perceived aesthetic water quality, as compared to price or microbiological water quality. Further research from social science disciplines is necessary to understand domestic water use behaviors and factors that influence it. Environmental psychology has been used to investigate factors that promote water conservation behaviors (Russell and Fielding, 2010). Similar methods may be just as relevant and necessary to promote higher consumption of improved water for health benefit.

We suspect that in the study towns water demand from PWSs is a balance between water quality and water quantity. If access to sufficient water *quantity* is the major motivation for people to choose alternative water sources, improved water consumption can potentially be increased through encouraging and subsidizing household connections that are desired by the community members. If, however, water *quality* is the predominant factor, ways to make PWS water more appealing to the consumers should be prioritized. This can be achieved through appropriate water treatment technologies to specifically address consumer concerns or through education highlighting the superior microbiological quality of piped water (Shields et al., 2015) and associated health benefits.

Research has shown that private household connections constitute the highest level of water service and result in higher per capita water consumption necessary for hygiene (WHO, 2015). At the time of the study, availability of private connections was very low, ranging from 1.7% in Town D to 4.1% in Town B, we suspect due to high installation costs. Water committee members have stated that in some of the towns costs are purposely set high because monthly payments from household connections are more difficult to collect as compared to the pay-as-you-fetch method employed at the public SPs (personal communication). Although not specifically mentioned as a concern, we suspect that discouraging private water resale is an additional factor.

Households with private connections often engage in water resale to their neighbors, a practice that has traditionally been prohibited or discouraged because of concerns about affordability and risks to public health due to the inability to regulate the practice (Kjellén and Mcgranahan, 2006). However, recent research has shown that private water resale is able to offer more convenient ‘opening hours’ and flexible payment mechanisms than public SPs without compromising water quality (Kariuki et al., 2003; Zuin et al., 2011). In the four study towns, perhaps, implementing measures that promote water resale, rather than hinder it, coupled with enhanced means of collecting water fees from households, may help improve water demand for these systems as well as provide more convenient and affordable

water access to remote residents living far away from public SPs (Kariuki et al., 2003; Singh et al., 1993; Zuin et al., 2011).

Our research demonstrated a clear need to engage communities in discussing options to reduce the use of, or improve and integrate, alternative water sources with an overall goal of optimizing access to safe water and ensuring functional sustainability of improved water sources. This need is particularly highlighted by the high preference for rainwater and desire for household water treatment products to improve the quality of water from unimproved sources. A surprising lack of utilization of rainwater harvesting technologies for private, industrial and public water supply has been identified as a deficiency in Ghana (Fuest, 2005).

4.4 Study limitations and areas for future research

The conclusions drawn from this case study are limited by a sample size of only four towns with the following additional limitations. Firstly, we did not consider private water sources (household connections and private hand-dug wells) in our analysis. We believe that because the number of these sources is limited, their effects on the water consumption patterns that we have identified would be small, but we do not know for sure. Secondly, water quality data are limited by the lack of preservation beyond refrigeration as some of the analyses necessitate (e.g. hardness requires acidification). Therefore, the presented values for total hardness and total dissolved solids may be affected by processing time (Table S1, Supplemental Information). We also did not consider microbiological water quality of PWS water. We believe that because the systems are relatively new, bacteria levels would be lower than in the hand-dug wells and surface water sources. We also believe that microbiological contamination is unlikely to affect the water quality conclusions from the study because aesthetic water characteristics were noted as important by the interviewees rather than microbiological water quality concerns. However, incorporating microbiological water quality and chlorine residual testing in future studies is desirable. Thirdly, our sample size of interviewees was rather small and not likely to be representative of entire study towns. In future studies, we recommend longer interviews with 5–10 residents, followed by limited quantitative surveys on perceived water quality with 50–100 residents for a town of approximately 5,000 people. Lastly, we considered only one method of defining populated areas from satellite imagery and of deriving the population served by each SP. While we believe that the methods used are adequate for the purpose of this study, having access to high-resolution remote sensing imagery would have been beneficial. Additionally, numerous other spatial methods exist to define households and estimate improved water access (Dittakan et al., 2013; Ntozini et al., 2015; Varshney et al., 2015). The application of these methods to the presented analysis should be further explored.

With the noted limitations, the methodology of the present study and the resulting regression models, that included only three relatively easily derived variables, are promising. A larger study with quantitative indicators of perceived water quality at the town level would allow for developing a more generalizable model potentially capable of predicting water use of a theoretical PWS based on easily collected variables at potential SP locations in advance of actually constructing the system. In addition, future studies of PWS sustainability should

consider access to reliable sources of electricity, water resale, illegal connections, leaks in the piping as the systems age, and competing water uses for irrigation and other productive purposes.

5 CONCLUSIONS

Our findings suggest that analyzing water consumption of existing metered PWSs may enable more efficient planning of community-based water supplies and support sustainable development. Water consumption patterns of existing systems provide quantitative evidence of consumer demand and water preferences. In areas where preference for alternative water sources manifests temporally and/or spatially, implications on cost recovery should be considered in water resource planning and the development of appropriate water rate structures. Increasing water consumption in under-utilized systems should be prioritized in order to maintain a sufficient revenue stream and prevent existing systems from falling into disrepair. It should be noted that this is not necessarily the task of individual town water committees. Empirical analysis of water consumption patterns, coupled with community-based qualitative approaches, can help identify systemic sustainability issues that are common to numerous water systems. It is then the collective responsibility of central and local governments operating through organizations such as CWSA to implement policies, legislation and effective O&M practices to improve the acceptability of water supply schemes and enable them to provide sustained health and economic benefits to rural communities.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- Low water demand from piped water systems results in a low revenue stream.
- Low revenue stream presents a sustainability challenge to rural water systems.
- Water consumption from piped water systems varies temporally and spatially.
- Poor aesthetic water quality as compared to alternative sources reduces piped water use.
- Increasing improved water demand is a health and sustainability priority.

Figure 1.
Individual town maps showing the layout of the standpipes and alternative water sources.

Figure 2.
Individual town maps showing classification of population pixels by standpipe.

Figure 3.

a) Distribution of monthly water consumption in 54 standpipes in four study towns. Median monthly water use in the majority of the standpipes is below 100 m³; b) Scatter plot with linear trend lines showing an inverse relationship between monthly average water consumption and rainfall.

Figure 4.

Left column: Scatter plot of observed (x-axis) vs. model predicted (y-axis) SP-specific monthly water consumption values. Solid line represents the line of equality; r is the correlation between observed and predicted values. Right column: Scatter plot comparing the average of observed and predicted water use values (x-axis) to the difference between predicted and observed values (y-axis) with mean difference indicated by a solid line and 95% limits of agreement indicated by dashed lines; q is the proportion of predicted values within the limits of agreement. Figures are presented by town (A through D) in rows 1 through 4, with all towns combined model presented in row 5.

Table 1

Study town and data characteristics

	A	B	C	D
Demographic and water coverage characteristics				
2014 population ^a	6,100	6,200	6,100	5,000
Number of households ^b	1,253	1,367	1,268	1,156
Functioning public standpipes	16	12	16	11
Household connections	33	56	51	20
Public alternative water sources	2	7	7	17
PWS water consumption characteristics [Mean (SD)]				
Total monthly consumption (m ³)	826 (153)	741 (286)	863 (243)	609 (133)
Per SP monthly consumption (m ³)	54.6 (9.87)	79.2 (26.6)	68.6 (15.4)	60.5 (13.3)
Temporal and spatial characteristics that affect PWS water consumption [Mean (SD)]				
Monthly rainfall (mm)	110 (80.4)	98.7 (71.4)	104 (80.2)	104 (80.2)
Distance from SP alternative source (m)	413 (256)	213 (142)	250 (161)	171 (74.3)
Population served by SP	386 (116)	516 (159)	382 (185)	457 (344)
Meter record data characteristics				
Water meter record dates	2012–2013	2011–2013	2012–2013	2012–2013
Total months available for analysis	24	36	24	24
Total possible observations (months x SPs)	384	432	384	264
Total observations available	363	308	299	242
% missing observations	5	29	22	8

^aProjected 2014 population from the 2000 Census, rounded to the nearest one hundred.

^bProjected 2014 number of households approximated from 2000 Census household size, calculated as total population divided by the number of households.

Summary of monthly water consumption regression model results for each town separately (A through D) using Eq. (1) and for all towns combined using Eq. (2)

Table 2

Town	Regression Coefficient	SE ^a	RR ^b	95% LCI ^c	95% UCI ^d	% change	95% LCI ^c	95% UCI ^d
Rainfall (mm) ^e								
A	-0.0016	0.0003	0.851	0.798	0.909	-14.9	-20.2	-9.14
B	-0.0025	0.0005	0.781	0.707	0.863	-21.9	-29.3	-13.7
C	-0.0012	0.0002	0.887	0.851	0.926	-11.3	-14.9	-7.43
D	-0.0019	0.0003	0.825	0.785	0.868	-17.5	-21.5	-13.2
All	-0.0017	0.0002	0.840	0.812	0.869	-16.0	-18.8	-13.1
Distance from SP to the nearest alternative free water source (m) ^f								
A	-0.0019	0.0005	0.823	0.748	0.905	-17.7	-25.2	-9.47
B	0.0031	0.0024	1.359	0.844	2.189	36.0	-15.6	119
C	0.0008	0.0015	1.080	0.805	1.449	7.96	-19.5	44.9
D	-0.0015	0.0037	0.862	0.422	1.763	-13.8	-57.8	76.0
All	-0.0005	0.0006	0.948	0.844	1.065	-5.19	-15.6	6.50
Population served by standpipe ^g								
A	0.0015	0.0011	1.166	0.939	1.448	16.6	-6.10	44.8
B	-0.0025	0.0023	0.781	0.501	1.216	-21.9	-49.9	21.6
C	0.0011	0.0013	1.112	0.854	1.449	11.2	-14.6	44.9
D	0.0015	0.0008	1.160	0.987	1.364	16.0	-1.30	36.4
All	0.0010	0.0006	1.105	0.986	1.238	10.5	-1.40	23.8

^aStandard error.

^bRelative risk.

^cLower confidence interval.

^dUpper confidence interval.

^eUnit change = 100 mm.

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f_j Unit change = 100 m.
 g_j Unit change = 100 people.

Table 3

Summary of reported water quality problems and corresponding measured physicochemical parameters

	A	B	C	D
Reported WQ problems	Number of respondents			
Salty taste (drinking)	3 of 6	2 of 5	5 of 5	2 of 6
Soap not lathering (laundry)	4 of 6	5 of 5	5 of 5	2 of 6
Measured WQ parameters	Mean (SD)			
Total dissolved solids (mg/L)***	153 (2.92)	340 (88.3)	369 (17.1)	240 (17.8)
Chloride (mg/L)***	8.50 (0.89)	44.3 (9.00)	75.8 (16.9)	31.0 (2.25)
Sodium (mg/L)**	13.6 (8.83)	47.0 (9.60)	42.7 (17.2)	36.7 (11.1)
Sulfate (mg/L)***	4.00 (3.40)	45.8 (15.7)	71.4 (27.7)	33.6 (7.30)
Total hardness (mg/L as CaCO ₃)***	111 (8.01)	170 (12.0)	229 (59.3)	126 (11.2)

Differences in average concentrations among towns were statistically significant at the $p < 0.01$ (**) or $p < 0.001$ (***) significance level.