



HHS Public Access

Author manuscript

Sci Total Environ. Author manuscript; available in PMC 2018 February 01.

Published in final edited form as:

Sci Total Environ. 2017 February 01; 579: 1745–1755. doi:10.1016/j.scitotenv.2016.11.140.

Indicators of improved water access in the context of schistosomiasis transmission in rural Eastern Region, Ghana

Alexandra V. Kulinkina^{a,*}, Karen C. Kosinski^b, Jeanine D. Plummer^c, John L. Durant^a, Kwabena M. Bosompem^{d,e}, Michael N. Adjei^f, Jeffrey K. Griffiths^g, David M. Gute^a, and Elena N. Naumova^{a,g,h}

^aDepartment of Civil and Environmental Engineering, Tufts University, 200 College Avenue, Medford, USA

^bDepartment of Community Health, Tufts University, 574 Boston Avenue, Medford, USA

^cWater Quality & Treatment Solutions, Inc., 175A Rice Corner Road, Brookfield, USA

^dNoguchi Memorial Institute for Medical Research, University of Ghana, P. O. Box 25, Legon, Accra, Ghana

^eCommunity Directed Development Foundation, P. O. Box AT2374, Achimota, Accra, Ghana

^fUnaffiliated, P.O. Box 399, Teshie, Accra, Ghana

^gTufts University School of Medicine, 136 Harrison Avenue, Boston, USA

^hFriedman School of Nutrition Science and Policy, Tufts University, 150 Harrison Avenue, Boston, USA

Abstract

Populations with poor access to water, sanitation and hygiene (WASH) infrastructure are disproportionately affected by the neglected tropical diseases (NTDs). As a result, WASH has gained increasing prominence in integrated control and elimination of NTDs, including schistosomiasis. In order to identify underserved populations, relevant measures of access to WASH infrastructure at sub-national or local levels are needed. We conducted a field survey of all public water sources in 74 rural communities in the Eastern Region of Ghana and computed indicators of water access using two methods: one based on the design capacity and another on the spatial distribution of water sources. The spatial method was applied to improved and surface water sources. According to the spatial method, improved water sources in the study area were well-distributed within communities with 95% (CI_{95%}: 91, 98) of the population having access within 500 m when all, and 87% (CI_{95%}: 81, 93) when only functional water sources were

*Correspondence: alexandra.kulinkina@tufts.edu; Tel.: 001-617-627-3237.

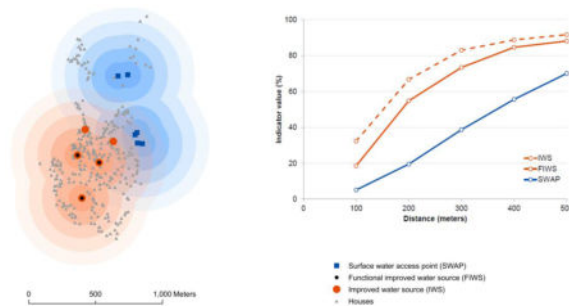
Publisher's Disclaimer: This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final citable form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

Author Contributions: AVK, KCK, ENN, JKG and DMG designed the study. AVK and MNA collected the data. AVK and ENN analyzed the data. AVK drafted the manuscript. All authors have read and approved the manuscript.

Conflicts of Interest: The authors declare no competing interests.

considered. According to the design capacity–based method, indicator values were lower: 63% (CI_{95%}: 57, 69) for all and 49% (CI_{95%}: 43, 55) for only functional sources. Surface water access was substantial with 62% (CI_{95%}: 54, 71) of the population located within 500 m of a perennial surface water source. A negative relationship was observed between functional improved water access and surface water access within 300 m. In this context, perceived water quality of the improved sources was also important, with a 17% increase in surface water access in towns with one reported water quality problem as compared to towns with no problems. Our study offers a potential methodology to use water point mapping data to identify communities in need of improved water access to achieve schistosomiasis risk reduction.

Graphical abstract



Keywords

Water infrastructure; Improved water access indicator; Integrated schistosomiasis control; Geographic Information Systems; Population density; Ghana

1 INTRODUCTION

1.1 Role of WASH in NTD control

Waterborne and water–related infections constitute a significant burden on population health, particularly in low–income countries. Diarrheal diseases alone account for 1.26 million deaths per year (GBD, 2013), an estimated 58% of which can be attributed to inadequate water, sanitation and hygiene (WASH) (WHO, 2014). Populations with poor access to WASH infrastructure are also disproportionately affected by neglected tropical diseases (NTDs) (Esrey et al., 1991; Grimes et al., 2014; Stocks et al., 2014; Strunz et al., 2014). Hence, WASH has recently gained increased prominence in the context of integrated control and elimination of NTDs, including schistosomiasis (Campbell et al., 2014; Grimes et al., 2015; Steinmann et al., 2006; Spiegel et al., 2010; Utzinger et al., 2003). Spiegel et al. (2010), for example, argue that schistosomiasis control efforts can be enhanced by effective partnerships between the health sector responsible for preventive chemotherapy and the engineering sector responsible for the provision of WASH infrastructure.

1.2 Measures of improved water access

In schistosomiasis endemic areas, availability of sanitation facilities to prevent the contamination of water resources with human waste as well as the availability of improved

water sources free from infectious agents are two important components of WASH that affect disease transmission. In the present manuscript we focus on the water rather than the sanitation component; more specifically on identifying populations with poor access to improved water sources in the context of schistosomiasis risk. The WHO and UNICEF's Joint Monitoring Programme for Water Supply and Sanitation (JMP) defines water from piped water systems, boreholes, protected wells or rainwater harvesting systems as "improved". Target 7c of the Millennium Development Goals (MDGs) defines "access" as the availability of at least 20 L of water per person per day from an improved source within 1 km (15 min walking time) of the residence (UNDG, 2003). In general, an indicator of access to improved water sources (I_{iws} ; %) in its simplest form can be expressed as: $I_{iws} = P_{iws}/P_{tot} * 100$, where P_{iws} is the number of people served by improved water sources, and P_{tot} is the total population. P_{iws} can be estimated from consumer (i.e. household survey) or provider (i.e. water authority) data.

When using consumer data (such as those offered by the Demographic and Health Survey and country censuses), I_{iws} is calculated by dividing the number of people who report using an improved water source by the total number of people surveyed. This methodology is used to calculate the JMP indicator, which serves an important purpose of tracking progress towards universal water access over time. However, limitations of the indicator include not fully addressing the accessibility of water services and water quantity and quality (Clasen, 2012). For example, the indicator does not actually account for the walk time or distance to water sources, their functional and seasonal availability, and microbiological or chemical water quality (Kayser et al., 2013).

Furthermore, indicator values are typically derived at an aggregated level (e.g. JMP provides national estimates stratified by urban and rural locality) while significant differences in water access can exist at regional, district and local levels because the density of both water points and populations may be highly variable across these spatial units (Ntozini et al., 2015). Despite recent methodological advances in mapping sub-national indicator estimates using consumer data (Pullan et al., 2014), substantial differences in indicator values can still exist at the village or sub-village levels due to local heterogeneity in topography, functionality of water sources, and other social, economic, demographic and environmental factors (Bartram et al., 2014). These differences are important to capture for sustainable water infrastructure development as technologies are most often implemented at local scales. Geospatial water source data offered by the water point mapping (WPM) approach (WaterAid, 2016), has been utilized in recent studies (Giné-Garriga et al., 2012; Ntozini et al., 2015) and enables a more detailed evaluation of water access at the local level that is centrally relevant to schistosomiasis control.

When using provider data, in contrast with consumer data, several options of calculating I_{iws} are available. For example, the indicator can be estimated based on the design capacity of water sources used in Ghana, such as 300 people per standpipe or borehole or 150 people per protected hand-dug well (CWSA, 2014). In this case, P_{iws} is calculated as the number of improved sources multiplied by the design capacity. Alternatively, if the locations of the water sources are available, such as with the WPM approach, P_{iws} can be calculated with respect to distance (e.g. 1000 m). The disadvantage of working with provider data is that it is

often challenging to define the denominator (P_{tot}) due to unavailability of appropriate population data. In the case of the design capacity–based approach, P_{tot} can be obtained from census data disaggregated to the appropriate spatial unit (e.g. community level), which for remote or rural areas may not be readily available. In the case of the distance–based approach, population density data are necessary, which are even more difficult to obtain.

1.3 Ghanaian water context

In rural Ghana, reliance on groundwater is high, with over 95% of improved water supplies intended for domestic purposes being extracted from this source (Awuah et al., 2010). However, high levels of minerals and metals preclude extensive exploitation of groundwater resources in some areas, including the Eastern Region (Rached et al., 1996; Awuah et al., 2010; CWSA, 2016). There is some evidence that boreholes affected by water quality problems such as high concentrations of iron and manganese are either abandoned entirely or used in a limited capacity for purposes other than cooking, drinking, and laundry, which results in wasted investment in the infrastructure (CWSA, 2016; Siaba, 2004).

The majority of donor funds for rural water supplies in sub-Saharan Africa are dedicated to drilling of communal boreholes (Marks et al., 2014); however, in a review of 20 countries it was estimated that at any time, only about 64% of these are functional, ranging from 33% to 90% (Rural Water Supply Network, 2009). In a Ghanaian study, functionality rate of water sources was higher at 79.4% (Fisher et al., 2015). The literature suggests that functionality and sustainability of rural water supplies are enhanced by local revenue generation through water user fees (Rogers et al., 2002; Montgomery et al., 2009). However, payment for water in many rural areas of Ghana is a relatively new concept and willingness to pay remains low due to the belief that water provision is the government's responsibility and water should be free (Rached et al., 1996; Thorsten, 2007).

In the context of disease risk reduction, the improved water access indicator should account for the consistency with which water sources are used as well as the volume of water collected. Distance, water quality, and price of water are known to influence water use patterns and health benefits offered by improved water sources (Cairncross, 1987; DeGabriele, 2002; Fuest, 2005; Howard & Bartram 2003; Rogers et al., 2002; Overbo et al., 2016; Pickering & Davis, 2012). Households that self–report using an improved water source for the JMP indicator may still extensively rely on unimproved water sources, especially when the improved source is frequently in disrepair, is of poor perceived water quality for domestic purposes, or is too expensive to use exclusively (Kosinski et al., 2016; Kulinkina et al., 2016). Reliance on untreated surface water, even when temporary and sporadic, places populations at risk for waterborne and water–related diseases. For example, in a rural Eastern Region community, Asamama, surface water use is extensive due to poor groundwater quality and lack of borehole maintenance. As a result, schistosomiasis prevalence in Asamama is >60% despite annual mass drug treatment through the public school system (Kosinski, et al., 2016).

1.4 Study goals and objectives

In the present study, we evaluated the availability of public improved water sources at the community level using a distance-based (spatial) and a design capacity-based (non-spatial) approaches. We conducted a field study of all public water sources in 74 rural communities in the Eastern Region of Ghana where surface water is not scarce and schistosomiasis is endemic. Data collection involved water point mapping (WPM); the data were used to meet the following objectives:

1. Estimate access indicators for improved and unimproved water sources using multiple methods and compare the results;
2. Examine the relationship between improved and unimproved water access indicators as modified by payment for water and water quality of improved sources;
3. Compare indicator estimates using two publicly available sources of population density data against ground-truthed field data through a validation study.

Our study intended to promote the development of simple indicators at the local level to provide relevant information for equitable and sustainable water development in rural areas of African countries where water provision is largely decentralized (Giné-Garriga et al., 2013; Thorsten, 2007; WSP, 2011).

2 METHODS

2.1 Study area

The Eastern Region is the third most populous of Ghana's ten administrative regions. Over half of the population (57%) resides in rural areas (GSS, 2012). The primary land cover and land use categories are forests and agricultural land, including hilly areas and low mountain ranges that reach the elevation of approximately 750 meters. Rainy season occurs between March and October and is characterized by two peak rainfall periods; the first lasts from May to June and the second from September to October. The dry season lasts from November to February. Pra, Birim, Ayensu and Densu are major perennial rivers that drain the Eastern Region (Figure 1). Historically, towns located on these rivers exclusively relied on them for their water needs. The Pra and Birim rivers are now polluted by alluvial gold mining activities and are no longer used for domestic purposes due to high turbidity, while the Ayensu and Densu rivers are still used for domestic purposes.

2.2 Sampling strategy

The Eastern Region is divided into 26 administrative districts following the most recent district sub-divisions in 2012. Ten adjacent districts were chosen as the study area because they were similar in their elevation profiles, density of minor rivers and streams, land cover and land use characteristics, and were outside of a 20-km buffer zone of Lake Volta (Figure 1). Communities situated on the shores of large African lakes such as Lake Volta are historically known to be endemic for schistosomiasis (Onori et al., 1963); however, we were

interested in studying exposure constituted by the minor rivers and streams (Gryseels et al., 2006; Kosinski et al., 2016; Salawu & Odaibo, 2016; Ugbomoiko et al., 2010) that are common in tropical parts of West Africa and are not easily detected in satellite images. Although the new (post-2012) district boundaries were used during data collection and all 10 administrative districts were approached, throughout the manuscript, we use older district boundaries in the summary tables to correspond to government data sources that still use older district definitions. We present our results for seven districts: Akyemansa (AKY); Atiwa (ATW); Birim Central (BRC); Birim South (BRS); Kwaebibirem (KBR), which was split in 2012 to be Kwaebibirem and Denkyembour; Suhum-Kraboia Coaltar (SKC), which was split in 2012 to be Suhum and Ayensuano; and West Akim (WAK), which was split in 2012 to be West Akim and Upper West Akim.

To define the universe of towns from which study towns were selected, the most recent settlement-level population data for the Eastern Region from the 2000 Census were obtained from the Ghana Statistical Service (GSS). A data layer of settlement locations was also obtained from the Center for Remote Sensing and Geographic Information Services (CERSGIS). Census data were manually geocoded for all towns within the study districts in the target population range of 500 – 5,000. In Ghana, localities with $\geq 5,000$ inhabitants are termed rural (GSS, 2012). Towns with < 500 residents were excluded from the study because they were difficult to locate on official maps and difficult to access by public transportation, which was relied upon to conduct the study. A total of 226 towns that met the inclusion criteria were mapped in the 10 districts. Subsequently, the 2000 Census populations were projected to 2014 populations using the 2.1% annual population growth estimated for the Eastern Region by the 2000 and 2010 Censuses (GSS, 2012).

The sampling strategy resulted in a slight over-representation (Table 1) of medium-sized towns in the 1000 – 2000 and 2000 – 5000 population categories as classified by the United Nations (United Nations, 2016). Although rural towns are defined as those with populations ≥ 5000 inhabitants, in our study, we considered towns in the lower end of the 5000–9999 population category as rural due to uncertainties associated with population projection (Table 1).

Ghana Health Service (GHS) Disease Control offices in all 10 districts were consulted for a list of known or suspected schistosomiasis endemic towns, which were also mapped. The definitions of “endemic” varied across districts. Some GHS offices relied on the results of historical prevalence surveys and limited hospital diagnostic data from the national surveillance system, others relied on lists where praziquantel is currently included in school-based deworming regimens, while the remaining offices simply provided lists of towns where children are known to swim in local freshwater bodies. Of the 226 towns that met our inclusion criteria, 74 (33%) were purposively selected for the study (Tables 1 and 2). Purposive sampling consisted of selecting ‘endemic’ towns (41/74) and nearby ‘non-endemic’ towns (33/74) with similar population characteristics. Because no standard definition was applied by district GHS offices to identify endemic towns, endemic status was only used in town selection but not in quantitative analyses.

2.3 Field data collection

Field data were collected between December 2013 and April 2014 by a team of two individuals (including one native Twi speaker) and a local guide in each of the 74 towns between 9 am and 6 pm during all days of the week. In each town, all publicly available and accessible water sources were enumerated and mapped, including public standpipes (SPs) in piped water systems (PWSs), drilled boreholes (BHs), hand dug wells (HDWs), and surface water access points (SWAPs). The local guide was asked to show all SWAPs including those that did not contain water in the dry season. Each source was photographed and its GPS coordinates were obtained using GPS Tracks app (version 2.4.3) for the iPad. In addition, brief surveys were completed about BHs and SWAPs using the QuickTapSurvey app (version 5.4.1) for the iPad. Information was obtained verbally from town residents in Twi and recorded in English.

BH attributes included observed pump type, functionality status, reported payment mechanism, and water quality problems. SWAP attributes included observed and reported water uses (fetching, bathing, washing clothes, and swimming). Each SWAP was subsequently classified as 'perennial' if it contained water during the dry season field visit. Observed attributes were collected by the study team during the 5–10 minute visit to the water feature. Reported attributes were based on the responses from users of the water feature at the time of the visit or from nearby residents. The local guide was consulted in rare instances when neither was available. Adult female respondents were preferred due to their role in water management within Ghanaian households (Boateng et al., 2013).

BH survey respondents were asked to state whether and how users pay for water from the BH and to comment on any water quality problems the users experience in an open-ended format. The advantage of this method is that responses are not constrained to a concrete list. The disadvantage is that if not specifically prompted, the user may have forgotten to list all problems. Open-ended format was preferred because we had no prior knowledge of water quality in the study area and we wanted to encourage a wide range of responses. SWAP survey respondents were asked to respond "yes" or "no" to whether or not the source is used by the community for each of the following: fetching water, bathing, washing clothes and swimming. The study was excluded from ethical review because collected information pertained to water sources and not to the survey respondents.

2.4 Data analysis

To achieve the first objective of estimating indicator values, three datasets were created from the field data: 1 – improved water sources (iws) were comprised of public SPs, BHs, and protected HDWs ($n = 365$); 2 – functional improved water sources (fiws) were a subset of improved water sources that were functional at the time of the field visit ($n = 290$); and 3 – perennial surface water sources (psws) were SWAPs that contained water at the time of the field visit ($n = 186$). Using these datasets, two methods were employed to calculate the indicators, namely a design capacity-based method (non-spatial) and a distance-based method (spatial). The non-spatial method was appropriate for calculating the improved water indicators (I_{iws} and I_{fiws}) but not for the surface water indicator (I_{psws}). The spatial method was applied to all three indicators.

The non-spatial method used the design capacity of each type of improved water source: 300 people per tap of a BH/SP and 150 people per covered HDW (CWSA, 2014). The indicator value (% population with access) was calculated as follows:

$$I = [(\# \text{ of SPs} * 300) + (\# \text{ of BHs} * 300) + (\# \text{ of HDWs} * 150)] / P_{\text{tot}} * 100$$

Where P_{tot} is the total population of each town obtained from the census. A total of two indicators were derived using the non-spatial method: I_{iws} and I_{fiws} .

The spatial method used the GPS coordinates of water sources with buffer distances of 100, 200, 300, 400, 500, and 1000 m drawn in ArcGIS software (version 10.2.2) based on evidence from existing literature (Howard & Bartram 2003; CWSA, 2014; UNDG, 2003). The indicator value (% population with access within a predefined distance) was approximated as the % of the town area (proxy for % population) within the buffer and calculated as follows:

$$I_{(\text{buff. dist})} = A_{\text{buff}} / A_{\text{tot}} * 100$$

where A_{buff} is the area within the predefined buffer of the water source and A_{tot} is the total area of the town represented by the town polygon abstracted from Open Street Map using QGIS software (version 2.12.3); uniform population density was assumed throughout the polygons. A total of 18 indicators were derived using the spatial method: $I_{\text{iws}(100-500, 1000)}$, $I_{\text{fiws}(100-500, 1000)}$ and $I_{\text{psws}(100-500, 1000)}$.

To assess the impact of functionality on the indicator values, the differences between I_{iws} and I_{fiws} values for all relevant permutations of the analysis were tested for significance using a paired t-test on the full dataset ($n = 74$) as well as within each district ($n = 7$) and population category ($n = 4$). District and population category averages were also compared to the overall average using a Welch two sample t-test, the results of which are valid with unequal variances and unevenly distributed sample sizes.

To achieve the second objective of examining the relationship between improved and surface water access, Spearman's rank correlations between I_{iws} or I_{fiws} and I_{psws} were explored on the full dataset ($n = 74$) as well as on subsets of the data defined by payment mechanism and reported water quality. To define the subsets, towns were divided into two groups based on whether they did ($n = 38$) or did not ($n = 36$) have a regular proactive payment mechanism for water from improved sources (defined as per use or per unit of time payment); and into three groups by whether they had no reported water quality problems ($n = 25$), one problem ($n = 31$) and two or more problems ($n = 18$). Further information about payment and water quality are provided in Section 3.1.2. After examination of the correlation matrix, $I_{\text{psws}(300)}$ was modeled as a function of I_{fiws} , controlling for population, payment, and WQ problems using generalized linear regression. No interactions between the variables were statistically significant.

To achieve the third objective of validating the spatial indicator method, I_{fiws} values derived using Open Street Map town polygons were compared to those derived with population

density raster data (100 m² grid) abstracted from WorldPop (The Worldpop Project, 2016; Linard et al. 2012) and to those derived using GPS coordinates of households collected in June 2016 as part of a separate study (unpublished). This validation study was conducted for 8 of the study towns representing a range of population sizes (two towns per population category). A potential advantage of using WorldPop data as compared to Open Street Map data is that they represent population density (i.e. uniform population density assumption is not necessary as with Open Street Map polygons); however, the spatial resolution of these data is very coarse. Using WorldPop data, I_{fWS} was calculated as the sum of population grids intersecting each buffer distance (using zonal statistics; Spatial Analyst extension of ArcGIS) and expressed as a percentage of the total town population obtained from the census. Mapped households represent the most accurate population density data that can be obtained at the community level short of enumerating individuals within households. Using household data, I_{fWS} was calculated as the sum of points falling completely within each buffer distance as a percentage of the total number of households in the town. I_{fWS} values for the three population data sources were plotted against buffer distance and visually compared.

3 RESULTS

3.1 Characteristics of public water sources

3.1.1 Piped water systems—A total of 88 public SPs were mapped in 7 of 74 towns (9.5%) that had mechanized PWSs supplying groundwater through a network of metered public, private and institutional connections. Of these, 75 SPs (85.2%) were functional and in use at the time of the study. For all PWSs, a nearby resident was hired by the town to sell water from the public standpipes for several hours per day in the mornings and evenings, charging water consumers on a per-use volumetric basis. More information about PWSs in the study area is found in a prior publication (Kulinkina et al., 2016).

3.1.2 Boreholes—A total of 238 BHs were mapped in 67 of 74 towns (90.5%); the other 7 towns had no BHs. Pump types included India Mark II (144/238, 60.5%), Afridev (52/238, 21.8%), Nira (27/238, 11.3%), and mechanized with multiple spouts (6/238, 2.5%). For 9 BHs (3.8%), pump types were unknown because they were removed due to prolonged disrepair. For mechanized BHs, each spout was considered as an individual water source for a total of 255 spouts. Of the 238 BH locations, 176 had at least one functional spout during the field visit for a total of 190 of 255 (74.5%) functional spouts.

Multiple financing mechanisms existed for BHs. Of 238 BHs, 130 (54.6%) had proactive payment associated with their use, 87 (36.6%) had retroactive payment, 19 (8.0%) BHs were free of charge and for 2 BHs (0.8%) payment type was not available. Proactive payment mechanisms included per-use payment (39.5%) or per unit of time payment (15.1%), most often monthly. Retroactive mechanisms included withdrawing money from a communal fund (26.9%) or collecting money from nearby users (9.7%) once a BH was already broken.

Open-ended questions about BH water quality concerns showed five recurring problems: salty taste, unfavorable scent, oil formation on the water surface, presence of particles, and the water's tendency to stain starchy foods (e.g. plantain, cassava, rice) black/purple color during cooking. Upon derivation of this complete list from the responses, a binary presence

or absence variable for these five problems was assigned to each BH for which reported WQ data were available (203/238). Presence of particles was the most prevalent WQ problem (33/203, 16.3% of BHs), followed by unfavorable scent (24/203, 11.8%), oil formation (19/203, 9.4%), salty taste (18/203, 8.9%) and food staining (15/203, 7.4%). Overall, 27% (55/203) of the BHs had at least one reported WQ problem.

3.1.3 Hand-dug wells—Overall, 112 public HDWs were mapped in 35 of 74 the study towns (47.3%). Of these, 39 (34.8%) were covered and fitted with a pump. The others were open wells from which water was withdrawn by lowering a rope with a bucket attached down the well. Uncovered HDWs included those that were covered at one point, but at the time of the study the pump had been removed. Most of the HDWs were free of charge; few collected a smaller fee than what was charged for BH water. Payment mechanism and water quality data were not collected systematically from HDWs.

3.1.4 Surface water—A total of 205 SWAPs were mapped in 71 of 74 towns (95.9%); 3 towns lacked access to surface water. Of these, 186 (90.7%) were perennial. Fetching water for domestic purposes was reported in 194 of 205 (94.6%) locations, swimming in 120 (58.5%), bathing in 73 (37.6%) and washing clothes in 41 (20.0%). Surface water use was observed in 83 of 205 (42.0%) locations.

3.2 Indicator estimates

3.2.1 Non-spatial design capacity-based method—According to the design capacity-based method, the overall average I_{iws} value was 63% (CI_{95%}: 57, 69) with the corresponding lower I_{fiws} value of 49% (CI_{95%}: 43, 55). Examined by district, only in ATW both I_{iws} and I_{fiws} values were significantly higher ($p < 0.05$) than the overall averages: 82% (CI_{95%}: 71, 93) and 66% (CI_{95%}: 52, 81), respectively (Table S1 in Supporting Information). The average difference between I_{iws} and I_{fiws} values of 14% was statistically significant ($p < 0.001$), indicating that functionality significantly affects improved water access. Furthermore, the effect of functionality was significant in nearly all of the districts with the exception of AKY and BRC, for which differences between I_{iws} and I_{fiws} values were not significant most likely due to low sample size. Functionality also significantly affected water access in the two middle population categories (1000 – 1999 and 2000 – 4999) (Table S1 in Supporting Information).

3.2.2 Spatial distance-based method—According to the distance-based method, improved water access within 100 m was relatively low, with an average $I_{iws(100)}$ value of 22% (CI_{95%}: 19.0, 24) and $I_{fiws(100)}$ value of 18% (CI_{95%}: 15, 20). However, the percentages increased fairly rapidly through the distance bands with $I_{iws(300)}$ value of 79% (CI_{95%}: 75, 84) and $I_{iws(500)}$ value 95% (CI_{95%}: 91, 98). The corresponding $I_{fiws(300)}$ and $I_{fiws(500)}$ values were 70% (CI_{95%}: 63, 76) and 87% (CI_{95%}: 81, 93), respectively. Access within 1000 m was nearly universal with $I_{iws(1000)}$ value of 99% (CI_{95%}: 96, 100) and $I_{fiws(1000)}$ value of 93% (CI_{95%}: 87, 99) (Table S1 in Supporting Information). When examined by district, AKY and BRC had above-average $I_{fiws(1000)}$ values; ATW had above-average $I_{fiws(500)}$ and $I_{fiws(1000)}$ values; KBR had above-average indicator values for most buffer distances. BRS had below-average $I_{iws(100)}$ and $I_{fiws(100)}$ values. When examined by population category, above-

average $I_{fiws(1000)}$ values were observed in the two highest population categories (2000 – 4999 and 5000 – 5999) (Table S1 in Supporting Information).

The average differences between I_{iws} and I_{fiws} values determined by the spatial method were lower (4–9%) as compared to those determined by the non-spatial method (14%), but were still significant for all buffer distances ($p < 0.05$) in the full dataset. When examined by district, primarily ATW and WAK exhibited significant differences ($p < 0.05$) between the I_{iws} and I_{fiws} values and only for the shorter buffer distances (100 – 400 m). When examined by population category, only the middle two population categories (1000 – 1999 and 2000 – 4999) exhibited significant differences between I_{iws} and I_{fiws} values for nearly all buffer distances (Table S1 in Supporting Information).

Surface water access was significantly lower than improved water access as assessed by the differences between I_{iws} or I_{fiws} and I_{psws} ($p < 0.001$) for distances 100 – 500 m (results not shown). On average, 7% ($CI_{95\%}$: 5, 8) of the population had access to a perennial surface water source within 100 m, 37% ($CI_{95\%}$: 30, 43) within 300 m, 62% ($CI_{95\%}$: 54, 71) within 500 m and 85% ($CI_{95\%}$: 77, 92) within 1000 m. Significantly higher than average I_{psws} values for all buffer distances were observed in WAK. Below-average $I_{psws(100)}$ values were observed in ATW and KBR, $I_{psws(100-200)}$ in BRC, and $I_{psws(100-300)}$ in AKY and BRS. Below-average $I_{psws(100-300)}$ values were also observed in the third population category (2000 – 4999) (Table S1 in Supporting Information).

3.2.3 Correlation between improved and surface water indicators—Spearman's rank correlations between I_{iws} or I_{fiws} and I_{psws} values were examined on the full dataset and on subsets based on payment mechanism and reported water quality problems (Table S2 in Supporting Information). In the full dataset, relatively low correlation coefficients (-0.24 to -0.28 ; $p < 0.05$) were observed between I_{fiws} and $I_{psws(200-500)}$. In the subset of towns with no regular payment for water, correlations between I_{fiws} and I_{psws} were stronger (-0.39 to -0.43 ; $p < 0.05$) and evident for all buffer distances. Correlations also emerged in this subset between I_{iws} and I_{psws} . No significant negative correlations were observed for towns with proactive payment mechanisms for water. Similarly, correlations were examined by water quality. Only in the subset of towns with one water quality problem ($n=31$) were there significant negative correlations (-0.36 to -0.38 ; $p < 0.05$) between I_{fiws} and $I_{psws(200-500)}$, but not for towns with no water quality problems or for towns with two or more water quality problems.

The association between I_{fiws} as estimated by the non-spatial method and $I_{psws(300)}$ was more formally investigated using a generalized linear regression model, controlling for population, payment and water quality (Table 3). The results of the model confirmed the negative relationship between the two indicators demonstrating that surface water access decreases by 0.3% for each 1% increase in functional improved water access ($p < 0.05$), controlling for the other parameters. Population size also had a statistically significant negative effect on the $I_{psws(300)}$ indicator value suggesting that larger towns has less access to surface water ($p < 0.01$). Having one water quality problem, however, had a very large effect, increasing surface water access by 17% as compared to having no water quality problems ($p < 0.05$). Payment mechanism was not significant after controlling for the other

variables. The model explained 24% of the variability in $I_{\text{psws}(300)}$ indicator values. It should be noted that although surface water access (as a proxy of surface water use) is chosen as the outcome variable in the model, the relationship is bidirectional and does not imply causality.

3.3 Population density data sources validation study

The validation study (Figure 2) showed that in seven out of eight cases, the WorldPop dataset resulted in significantly underestimated I_{fiws} value, whereas in all 8 cases, indicator values determined using Open Street Map and GPS coordinates of the households were very close to each other. It should be noted that the analysis is limited by the census population serving as the denominator in the calculation of the indicator using the WorldPop dataset. This limitation cannot be addressed because the true denominator population in this case is not possible to determine without imposing artificial town boundaries onto the raster dataset.

4 DISCUSSION

4.1 Major findings

We utilized community level provider water source data (similar to Giné-Garriga et al., 2013 and Ntozini et al., 2015) to compute improved water access indicators using a design capacity-based and a distance-based method for six buffer distances ranging from 100 to 1000 m. Although basic access according to the MDGs is constituted by a water source located with 1000 m of the home (UNDG, 2003), research suggests that optimum water use for good hygiene behavior and better health is achieved when an on-plot water source is available with water use dropping substantially when distance to water source exceeds 100 m (Cairncross, 1987; Curtis et al., 1995; Howard & Bartram 2003; Larson et al. 2006; Overbo et al., 2016; Pickering & Davis, 2012; Thompson et al., 2001). In our study area, water access within 100 m was rather low (18 – 22%) and contributed mostly by towns with PWSs with a higher average density of public SPs than that of BHs. However, the percentages increased rapidly through the distance bands with 87 – 95% of the study population having access within 500 m, and nearly universal access within 1000 m, indicating a uniform spatial distribution and relatively short walking distances to improved sources within the study towns. Design capacity-based indicator values were lower at 63% when all, and 49% when only functional water sources were considered, indicating that the overall low number of functional sources may create long lines and waiting times, potentially negating the benefit of short walking distances.

Furthermore, improved water access was substantially affected by functionality. By district, functionality had a significant effect in all districts according to the non-spatial method and in ATW and WAK districts according to the spatial method. Concurrently, WAK district had significantly higher than average surface water access in all distance buffers, partially due to the presence of Ayensu River that had not yet been polluted by gold mining at the time of the study. By population, only the two middle categories (1000 – 1999 and 2000 – 4999 people) had significantly lower I_{iws} and I_{fiws} than values according to both spatial and non-spatial methods. The findings are consistent with personal observations. Very small towns (<1000 people) typically have few water sources; hence they are motivated to keep them functional. Large towns (> 5000 people) typically have a higher water source density and are less

affected by few non-functional sources, particularly when using the spatial method. Hence the observation that indicator values are most influenced by functionality in the two middle categories.

Overall, surface water use is extensive in the study area; 60% of the study population had access to a perennial surface water source within 500 m and 95% of the mapped sources were used for fetching water for domestic purposes. There was a stable inverse relationship between I_{fws} and I_{psws} indicating that higher access to improved sources could potentially reduce reliance on surface water. This relationship, however, is modified by payment and water quality of the improved water sources. The relationship between the indicators was stronger in towns with no regular proactive payment for groundwater sources and not significant in towns with regular payment. Similarly, when stratified by water quality, the inverse relationship was only significant in the subset of towns with one reported water quality problem but not in towns with no problems or with two or more problems. This suggests that while in general, higher access to improved sources may be associated with lower surface water use, this may not necessarily occur in the presence of payment for water or when groundwater quality is perceived to be poor for domestic purposes as compared to surface water. Water quality was a more important factor than price in the regression analysis.

4.2 Indicator methodology

We explored two methods of computing indicators and multiple sources of population density data required for the spatial method. The two methods produced somewhat different results (e.g. ATW district had higher indicator values according to the non-spatial method and KBR district had higher values according to the spatial method). It should be noted that the two methods measure different aspects of water access and exhibit tradeoffs in their computation in that neither uses all available information. The non-spatial method uses the total number of spouts (i.e. mechanized BHs can have multiple spouts) but doesn't use the distance and hence is an indicator of crowding around water sources and long waiting times. The spatial method uses the location of the water source in relation to population density but does not use the total number of spouts and hence is an indicator of walking distance. Both waiting time and walking distance are important determinants of access (Asaba et al., 2013; Gross et al., 2013).

A major drawback of the spatial method is the need for population density data, which are difficult to obtain for rural areas. The validation study showed that while WorldPop raster data are very valuable for analyses conducted at the national level, the Open Street Map town polygons, even under the uniform population density assumption, provide much more similar indicator values to those obtained using ground-truthed GPS locations of households. This was true for small towns of <1000 people as well as large towns of 5000 people. It is important to note that the true denominator could not be determined for the analysis that utilized WorldPop data, which is a limitation of this assessment. Because the town polygons are easy to extract from a public online data source and to visually verify and adjust using high resolution Google Earth imagery, they show promise for community level water access indicator development in other locations.

The approaches described here use geocoded provider data to more accurately quantify water access at the local level. Our study encourages the district water and sanitation authorities in Ghana to undertake the effort of geocoding improved and unimproved water sources and tracking their functionality and uses as a step towards further developing water infrastructure aimed at achieving consistent use and disease risk reduction. Although the design capacity-based indicator estimates are still most common at the district level, which rely only on tracking the total number of improved water sources per community (9 out of 10 study districts), one district had GPS coordinates of water sources available. Recent publications suggest that spatial data with more attributes are not far out of reach as Ghana is on a positive trajectory towards establishing an inventory of rural and small-town water supplies with the use of mobile phones (IRC, 2014). When collecting field data about water points, additional attributes such as functionality, seasonality, payment mechanism, and water quality, can and should be incorporated. Our study findings suggest that to reduce reliance on surface water where it is readily available, a sufficient number of improved water sources in close proximity is important, but authorities must also ensure acceptable water quality and payment structure.

4.3 Study limitations and future directions

In terms of data collection, our study has three potential limitations. The first limitation is the use of a single guide per community to map all available water sources. While every effort was made to find a knowledgeable person, it is possible that some guides were more familiar with the community layout than others. A limited validation of the approach was possible from the results of a subsequent survey of BHs in 2015. Using a complete list of BHs discovered during both surveys and excluding newly constructed BHs, mapping accuracy was determined at ~95% for both surveys (unpublished data).

The second limitation is that the representativeness of some of the observed or reported variables may be affected by the day of the week or time of the day when data were collected. For example, people typically fetch water more during mornings and evenings, meaning that towns that were visited during these prime water fetching hours contained information from more users and are expected to be more representative. A third related limitation is in the way that payment mechanism and WQ problems were documented. Because responses were obtained from a small number of respondents in each town, our data is likely not representative of all users. Despite this limitation, we believe that the most prevalent and severe WQ problems were represented by this method, and the method can be widely and inexpensively applied to areas where no water quality information is available. Furthermore, a limited analysis of reported WQ problems and measured water quality parameters for salty taste of groundwater showed that in towns where users ubiquitously noted a salty taste, total dissolved solids, chloride and sulfate concentrations were elevated in the water samples (Kulinkina et al., 2016).

In terms of data analysis and indicator development, the following limitation should be noted. Although in the validation study, the uniform population density assumption within the Open Street Map polygon was reasonable for the range of populations tested and the results compared well with those derived using the mapped households, this assumption is

not necessarily valid for all town structures. For example, in our study, very remote communities with small total populations and households that are likely dispersed over a large area were excluded. Therefore, our study findings do not necessarily apply to these communities. Recent advances in rural remote population density mapping that utilize roof reflectance data obtained from remote sensing imagery (Guo et al., 2016; Varshney et al., 2015) demonstrate a promising alternative to the Open Street Map polygon method.

5 CONCLUSIONS

Our first main finding is that the functional water coverage was significantly lower than what might be expected from all mapped water sources. Our second main finding was that while water access within 100 m of residence was low, indicator values increased rapidly through the distance bands with nearly universal access within 500 m and 1000 m indicating a uniform distribution of water sources within communities. Thirdly, we found that surface water use was extensive in the study area in the presence of proximal improved water sources. An inverse relationship was observed between improved water access and surface water access, and was modified by the presence of payment and perception of poor groundwater quality of improved sources. Although access is often intended as a proxy for use, in our study, this assumption is only reasonable for surface water sources, but not for improved water sources, particularly due to interactions with payment and water quality. We suggest that geocoded provider water source data that incorporate information on functionality, payment and water quality would allow for calculation of more representative water access indicators relevant at sub-national and local scales.

Mapping and indicator computation should be undertaken at the district administrative level to support decision making in the context of decentralized water provision schemes. Furthermore, we suggest that local knowledge of infrastructure functionality rates, prevailing payment mechanisms and perceived water quality concerns would likely lead to infrastructure improvements that will be maintained and utilized, resulting in a more long-lasting impact on population health and on the rates of NTDs than that achieved through mass drug treatment alone.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This study was funded by the National Institutes of Health (R34 AI097083-01A1) and Tufts Institute for Innovation grants. We wish to acknowledge members of Ghana Health Service, Ghana Statistical Service and Community Water and Sanitation Agency (particularly Gilbert Ayamgah and Theophilus Mensah) for the provision of various datasets, and members of the traditional leadership of the study communities for allowing us to conduct mapping and survey activities. We are thankful to Miguel Stadecker for providing valuable input to the manuscript and to Michelle Sodipo, Olivia Schultes, Isaac Kwaku Cudjoe, Kezia Osei Bonsu and Emmanuel Asare Agyapong for assisting with the mapping of households for the validation study. We also appreciate the helpful comments and suggestions of the Science of the Total Environment reviewers and editor.

References

- Asaba R, Fagan GH, Kabonesa C, Mugumya F. Beyond distance and time: gender and burden of water collection in rural Uganda. *The Journal of Gender and Water*. 2013; 2(1):31–38.
- Awuah E, Nyarko KB, Owusu PA. Water and sanitation in Ghana. *Desalination*. 2010; 255:43–50.
- Bartram J, Brocklehurst C, Fisher MB, Luyendijk R, Hossain R, Wardlaw T, Gordon B. Global monitoring of water supply and sanitation: history, methods and future challenges. *International Journal of Environmental Research and Public Health*. 2014; 11:8137–8165. [PubMed: 25116635]
- Boateng JD, Brown CK, Tenkorang EY. Socio-economic status of women and its influence on their participation in rural water supply projects in Ghana. *International Journal of Development and Sustainability*. 2013; 2(2):871–890.
- Cairncross S. The benefits of water supply. *Dev World Water*. 1987; 11
- Campbell SJ, Savage GB, Gray DJ, Atkinson JM, Soares Magalhaes RJ, Nery SV, et al. Water, sanitation, and hygiene (WASH): a critical component for sustainable soil-transmitted helminth and schistosomiasis control. *PLoS Negl Trop Dis*. 2014; 8(4):e2651.doi: 10.1371/journal.pntd.0002651 [PubMed: 24722335]
- Clasen TF. Millenium Development Goals water target claim exaggerates achievement. *Tropical Medicine and International Health*. 2012; 17(10):1178–1180. [PubMed: 22845865]
- Community Water and Sanitation Agency. Overview of water quality challenges in rural water supply. (accessed August 2016) http://www.cwsa.gov.gh/cwsa_subcat_linkdetails.cfm?corpnews_scatid=24&corpnews_catid=5&corpnews_scatlinkid=5
- Curtis V, Kanki B, Mertens T, Traore E, Diallo I, Tall F, Cousens S. Potties, pits and pipes: explaining hygiene behavior in Burkina Faso. *Soc Sci Med*. 1995; 41(3):383–393. [PubMed: 7481932]
- DeGabriele, J. Improving community based management of boreholes: A case study from Malawi. Broadening Access and Strengthening Input Market Systems; University of Wisconsin, Madison: 2002. http://pdf.usaid.gov/pdf_docs/Pnacp702.pdf
- Esrey SA, Potash JB, Roberts L, Schiff C. Effects of improved water supply and sanitation on ascariasis, diarrhea, dracunculiasis, hookworm infection, schistosomiasis, and trachoma. *Bulletin of the World Health Organization*. 1991; 69(5):609–621. [PubMed: 1835675]
- Fisher MB, Shields KF, Chan TU, Christenson E, Cronk RD, Leker H, Samani D, Apoya P, Lutz A, Bartram J. Understanding handpump sustainability: determinants of rural source functionality in the Greater Afram Plains region of Ghana. *Water Resour Res*. 2015; 51:8431–8449. DOI: 10.1002/2014WR016770 [PubMed: 27667863]
- Framework for assessing and monitoring rural and small town water supply services in Ghana. Community Water and Sanitation Agency; Accra, Ghana: 2014. http://www.ircwash.org/sites/default/files/framework_assessing_and_monitoring_rural_and_small_towns_wss_in_ghana.pdf
- Fuest, V. Practices and outcomes of demand-oriented community water supply in Ghana: The National Community Water and Sanitation Programme 1994–2004. ZEF Center for Development and Research; Bonn, Germany: 2005. <http://www.ircwash.org/resources/policies-practices-and-outcomes-demand-oriented-community-water-supply-ghana-national>
- Gine-Garriga R, Jimenez-Fernandez de Palencia A, Perez-Foguet A. Water-sanitation-hygiene mapping: an improved approach for data collection at local level. *Sci Tot Env*. 2013:463–464.
- Grimes JET, Croll D, Harrison WE, Utzinger J, Freeman MC, Templeton MR. The relationship between water, sanitation and schistosomiasis: A systematic review. *PLoS Negl Trop Dis*. 2014; 8(12):e3296. [PubMed: 25474705]
- Grimes JET, Croll D, Harrison WE, Utzinger J, Freeman MC, Templeton MR. The role of water, sanitation, and hygiene in reducing schistosomiasis: a review. *Parasites & Vectors*. 2015; 8:156.doi: 10.1186/s13071-015-0766-9 [PubMed: 25884172]
- Gross, E.; Gunther, I.; Schipper, Y. Women: walking and waiting for water the time value of public water supply. Courant Research Centre; Poverty, Equity and Growth — Discussion Papers, No. 134
- Gryseels B, Polman K, Clerinx J, Kestens L. Human schistosomiasis. *Lancet*. 2006; 368:1106–18. [PubMed: 16997665]

- Guo Z, Shao X, Xu Y, Miyazaki H, Ohira W, Shibasaki R. Identification of village building via Google Earth images and supervised machine learning methods. *Remote Sens.* 2016; 8:271.
- Handpump Data: Selected Countries in Sub-Saharan Africa: Sustainable Rural Water Supplies, online database collated by Peter Harvey, UNICEF Zambia. Rural Water Supply Network; St. Gallen, Switzerland: http://www.rural-water-supply.net/_ressources/documents/default/203.pdf
- Howard, G.; Bartram, J. Domestic water quantity, service level and health. World Health Organization; Geneva, Switzerland: 2003. http://www.who.int/water_sanitation_health/diseases/WSH03.02.pdf
- Indicators for Monitoring the Millenium Development Goals. United Nations Development Group; New York, USA: 2003. <http://www.wssinfo.org/definitions-methods/watsan-categories/>
- Information Resource Center. Framework of Service Delivery indicators for Assessing and Monitoring Rural and Small Town Water Supply Services in Ghana. 2014. (accessed August 2016); http://sanitationandwaterforall.org/partner_perspective/framework-of-service-delivery-indicators-for-assessing-and-monitoring-rural-and-small-town-water-supply-services-in-ghana/
- Institute for Health Metrics and Evaluation. Global Burden of Diseases (2013) Data Tool. (accessed August 2016) <http://www.healthdata.org/gbd-data-tool>
- Kayser GL, Moriarty P, Fonseca C, Bartram J. Domestic water service delivery indicators and frameworks for monitoring, evaluation, policy and planning: A review. *International Journal of Environmental Research and Public Health.* 2013; 10:4812–4835. [PubMed: 24157507]
- 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 Pub Health.* 2016; 16:322. [PubMed: 27076042]
- 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 Tot Env.* 2016; 559:291–301.
- Larson B, Minten B, Razafindralambo R. Unravelling the linkages between the millennium development goals for poverty, education, access to water and household water use in developing countries: evidence from Madagascar. *The Journal of Development Studies.* 2006; 42(1):22–40.
- Linard C, Gilbert M, Snow RW, Noor AM, Tatem AJ. Population distribution, settlement patterns and accessibility across Africa. *PLoS ONE.* 2010; 7(2):e31743.
- Marks S, Komives K, Davis J. Community participation and water supply sustainability: evidence from handpump projects in rural Ghana. *Journal of Planning Education and Research.* 2014; 34(3):276–286.
- Montgomery MA, Bartram J, Elimelech M. Increasing functional sustainability of water and sanitation supplies in rural sub-Saharan Africa. *Environmental Engineering Science.* 2009; 26(5):1017–1023. doi: 10.1089=ees.2008.0388.
- Ntozini R, Marks SJ, Mangwadu G, Mbuya MNN, Gerema G, Mutasa B, Julian TR, Schwab KJ, et al. Using geographic information systems and spatial analysis methods to assess household water access and sanitation coverage in the SHINE trial. *CID.* 2015; 61(Suppl 7):S716–S725.
- Onori E, McCullough FS, Rosei L. Schistosomiasis in the Volta Region of Ghana. *Annals of Tropical Medicine and Parasitology.* 1963; 57(1)
- Overbo A, Williams AR, Evans B, Hunter PR, Bartram J. On-plot drinking water supplies and health: A systematic review. *International Journal of Hygiene and Environmental Health.* 2016; 219:317–330. [PubMed: 27118130]
- Pickering AJ, Davis J. Freshwater availability and water fetching distance affect child health in sub-Saharan Africa. *Environ Sci Technol.* 2012; 46:2391–2397. [PubMed: 22242546]
- Preventing diarrhoea through better water, sanitation and hygiene. World Health Organization; Geneva, Switzerland: 2014. http://apps.who.int/iris/bitstream/10665/150112/1/9789241564823_eng.pdf
- Pullan RL, Freeman MC, Gething PW, Brooker SJ. Geographical inequalities in use of improved drinking water supply and sanitation across sub-Saharan Africa: mapping and spatial analysis of cross-sectional survey data. *PLoS Med.* 2014; 11(4):e1001626. [PubMed: 24714528]
- Rached, E.; Rathgeber, E.; Brooks, DB. Water management of Africa and the Middle East: Challenges and Opportunities. International Development Research Centre; 1996.

- Rogers P, de Silva R, Bhatia R. Water is an economic good: how to use prices to promote equity, efficiency and sustainability. *Water Policy*. 2002; 4:1–17.
- Salawu OT, Odaibo AB. Schistosomiasis transmission; socio-demographic, knowledge and practices as transmission risk factors in pregnant women. *J Parasit Dis*. 2016; 40(1):93–99. [PubMed: 27065605]
- Siabi, WK. Application of Mwacafe plant for the removal of Iron and Manganese. 30th WEDC International Conference; Vientiane, Lao PDR. 2004.
- Spiegel JM, Dharamsi S, Wasan KM, Yassi A, Singer B, Hotez PJ, Hanson C, Bundy DAP. Which new approaches to tackling neglected tropical diseases show promise? *PLoS Med*. 2014; 7(5):e1000255.
- Steinmann P, Keiser J, Bos R, Tanner M, Utzinger J. Schistosomiasis and water resources development: systematic review, meta-analysis, and estimates of people at risk. *Lancet Infect Dis*. 2006; 6:411–425. [PubMed: 16790382]
- Stocks ME, Ogden S, Haddad D, Addiss DG, McGuire C, Freeman MC. Effect of water, sanitation, and hygiene on the prevention of trachoma: A systematic review and meta-analysis. *PLoS Med*. 2014; 11(2):e1001605. [PubMed: 24586120]
- Strunz EC, Addiss DG, Stocks ME, Ogden S, Utzinger J, Freeman MC. Water, sanitation, hygiene, and soil-transmitted helminth infection: a systematic review and meta-analysis. *PLoS Med*. 2014; 11(3):e1001620. [PubMed: 24667810]
- Thompson, J.; Porras, IT.; Tumwine, JK.; Mujwahuzi, MR.; Katui-Katua, M.; Johnstone, N.; Wood, L. Drawers of Water II: 30 years of change in domestic water use and environmental health in East Africa. International Institute for Environment and Development; London, UK: 2001. <http://pubs.iied.org/pdfs/9049IIED.pdf>
- Thorsten, RE. Predicting sustainable performance and household satisfaction of community-oriented rural water supply projects: a quantitative evaluation of evidence from Ghana and Peru. University of North Carolina Chapel Hill; 2007. <https://cdr.lib.unc.edu/record/uuid:39fe2d3b-7be0-4167-973f-219cfd12b971>
- Ugbomoiko US, Ofoezie IE, Okoye IC, Heukelbach J. Factors associated with urinary schistosomiasis in two peri-urban communities in south-western Nigeria. *Annals of Tropical Medicine & Parasitology*. 2010; 104(5):409–419. [PubMed: 20819309]
- United Nations. Population density and urbanization. (accessed August 2016) <http://unstats.un.org/unsd/Demographic/sconcerns/densurb/densurbmethods.htm>
- Utzinger J, Bergquist R, Xiao SH, Singer BH, Tanner M. Sustainable schistosomiasis control – the way forward. *Lancet*. 2003; 362:1932–1934. [PubMed: 14667754]
- Varshney KR, Chen GH, Abelson B, Nowocin K, Sakhrani V, Xu L, Spatocco BL. Targeting villages for rural development using satellite image analysis. *Big Data*. 2015; 3(1):1–13. DOI: 10.1089/big.2014.0061 [PubMed: 27442841]
- WaterAid. Water Point Mapper. (accessed August 2016); <http://www.waterpointmapper.org/>
- Water supply and sanitation in Ghana. Water and Sanitation Program; Nairobi, Kenya: 2011. <https://wsp.org/sites/wsp.org/files/publications/CSO-Ghana.pdf>
- WorldPop Project. (accessed August 2016); <http://www.worldpop.org.uk/>
- 2010 Population and housing Census: National analytical report. Ghana Statistical Service; Accra, Ghana: 2013. http://www.statsghana.gov.gh/pop_stats.html

Highlights

- Safe water access is an important component of integrated schistosomiasis control.
- Defining access indicators at local scales can aid in targeted resource allocation.
- Water source functionality significantly reduces access indicator values.
- Surface water access is negatively correlated with improved water access.
- Correlation is modified by groundwater quality and payment for improved water.

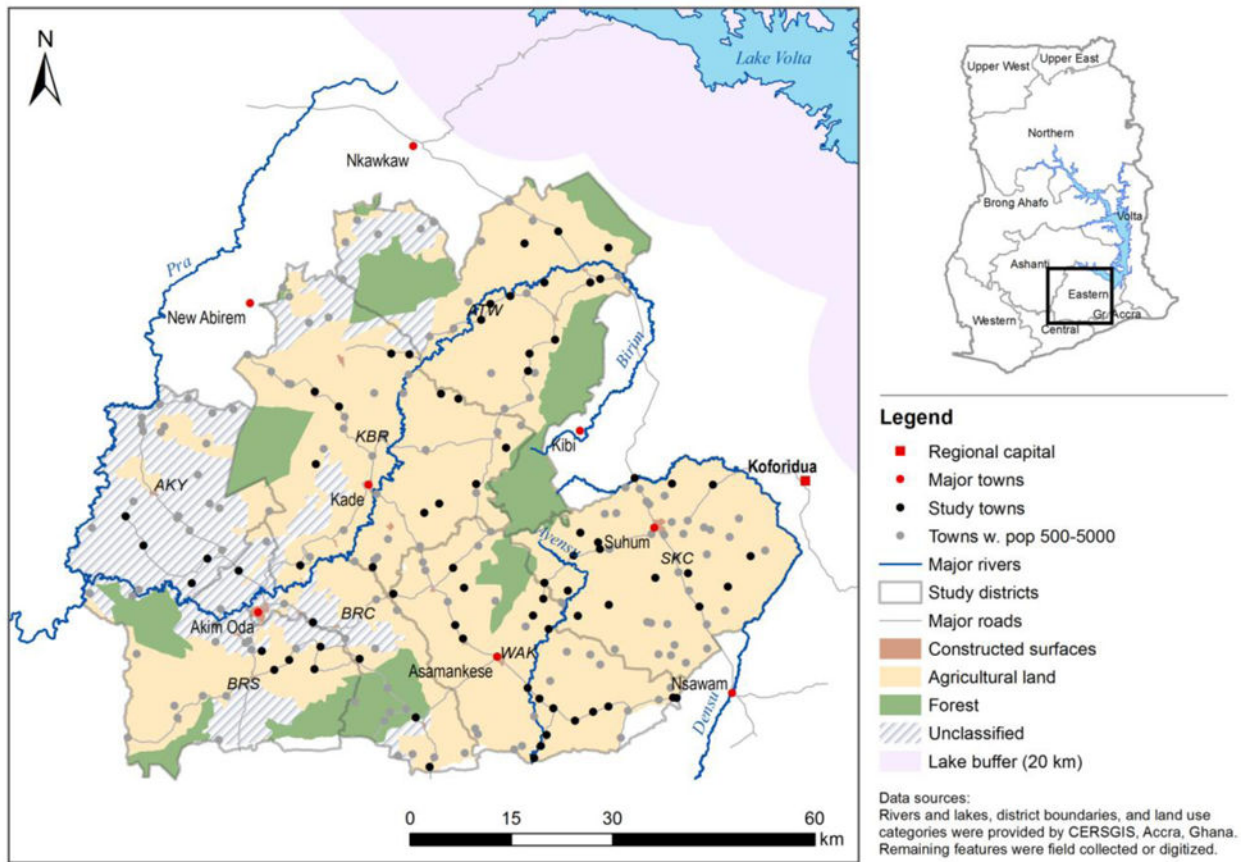


Figure 1.
 Map of the study area.

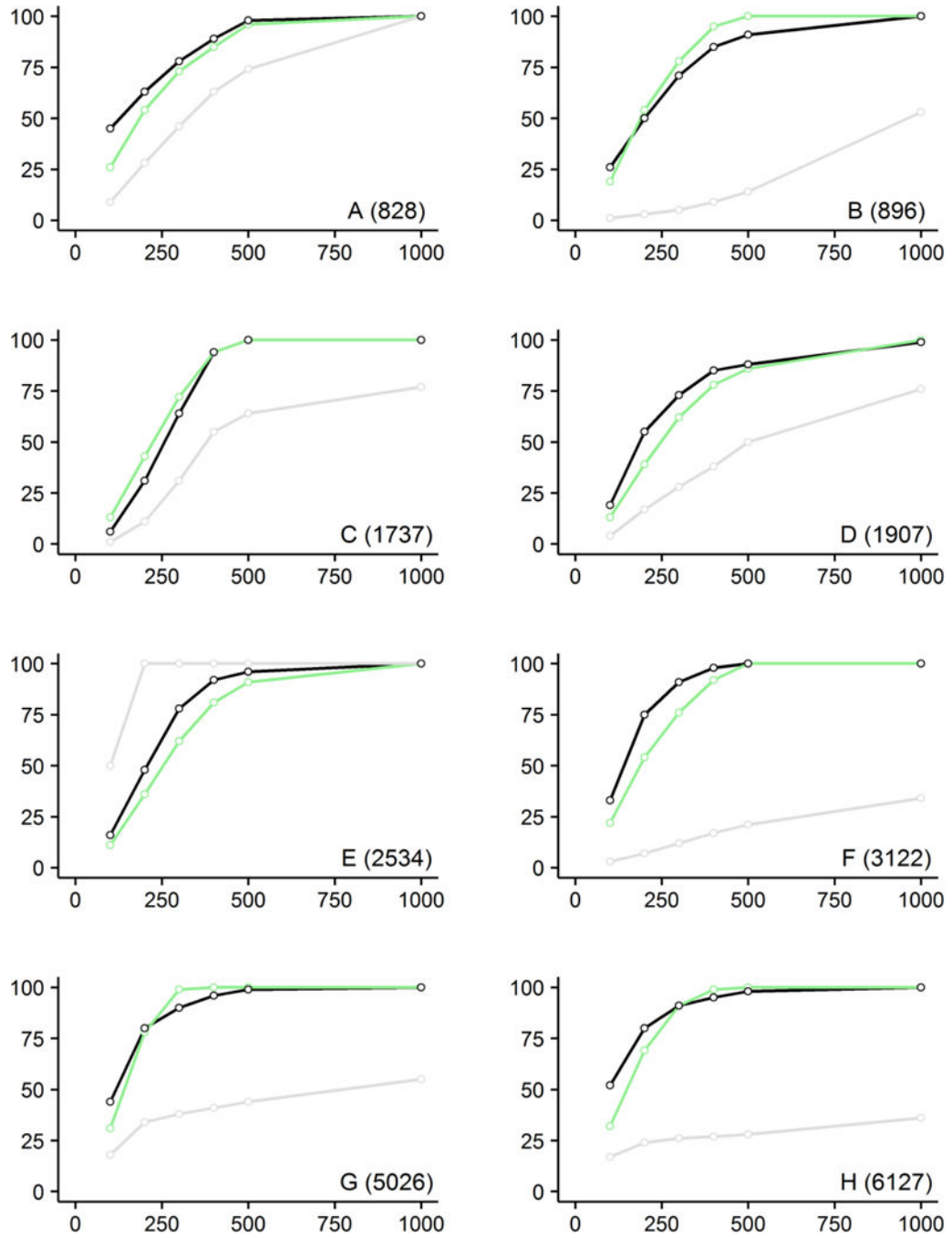


Figure 2. Validation study of the spatial method using three population data sources: mapped households (black), Open Street Map polygons (green) and Worldpop raster data (gray); buffer distance (m) is displayed on the x-axis and I_{fws} indicator value (%) on the y-axis; populations of case study towns A through H are noted in parentheses.

Author Manuscript

Author Manuscript

Author Manuscript

Author Manuscript

Distribution of sampled towns among UN population categories according to projected 2014 population data, based on census data from 2000.

Table 1

UN population category	Total mapped towns	Total mapped town population	Total sampled towns	Total sampled town population	% sampled towns	% sampled population
500 – 999	69	56130	13	10907	19	19
1000 – 1999	76	108093	29	45021	38	42
2000 – 4999	64	204708	27	87239	42	43
5000 – 9999	17	96336	5	28610	29	30
Total	226	465267	74	171777	33	37

Population statistics for the study area, universe of potential study towns, and study towns according to projected 2014 population data (based on census data from 2000).

Table 2

	AKY	ATW	BRC	BRS	KBR	SKC	WAK	Overall
Study area (7 districts)								
Total population	105815	120211	157427	130149	209254	182075	212282	1117213
Rural population	68908	80116	50884	68302	107038	134183	130499	639929
% rural population	65.1	66.6	32.3	52.5	51.2	73.7	61.5	57.3
Mapped towns within study area (226 towns)								
Towns (#)	26	29	22	19	41	48	41	226
Total population	63124	66730	42042	40017	105138	73689	74527	465267
Median population	2102	2119	999	1588	1941	1150	1427	1464
% of study area rural population	91.6	83.3	82.6	58.6	98.2	54.9	57.1	72.7
Study towns (74 towns)								
Towns (#)	4	12	5	5	13	15	20	74
Total population	14345	27796	10760	11558	34876	25098	47344	171777
Median population	3339	2523	1574	1789	2105	1173	1870	1810
% of mapped towns	15.4	41.4	22.7	26.3	31.7	31.3	48.8	32.7
% of mapped town population	22.7	41.7	25.6	28.9	33.2	34.1	63.5	36.9
% of study area rural population	20.8	34.7	21.1	16.9	32.6	18.7	36.3	26.8

Table 3

Results of multivariable regression model exploring the effect of functional improved water access (estimated by the non-spatial method) on surface water access within 300 m.

Variable	β coef	SE	p-value
I_{fiws} (non-spatial)	-0.304	0.116	<0.05
Population	-0.007	0.002	<0.01
Regular payment (ref = no regular payment)	-3.758	6.271	0.55
1 WQ problem (ref = 0)	17.40	7.211	<0.05
2+ WQ problems (ref = 0)	7.130	8.134	0.38