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Understanding handpump sustainability: Determinants of rural water source functionality in the Greater Afram Plains region of Ghana

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Key Points:

- Nearly 80% of water sources studied were functional
- Water source functionality depended on management team presence and quality
- Management variables interact synergistically to affect functionality

Supporting Information:

- Supporting Information S1

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Abstract Safe drinking water is critical to human health and development. In rural sub-Saharan Africa, most improved water sources are boreholes with handpumps; studies suggest that up to one third of these handpumps are nonfunctional at any given time. This work presents findings from a secondary analysis of cross-sectional data from 1509 water sources in 570 communities in the rural Greater Afram Plains (GAP) region of Ghana; one of the largest studies of its kind. 79.4% of enumerated water sources were functional when visited; in multivariable regressions, functionality depended on source age, management, tariff collection, the number of other sources in the community, and the district. A Bayesian network (BN) model developed using the same data set found strong dependencies of functionality on implementer, pump type, management, and the availability of tools, with synergistic effects from management determinants on functionality, increasing the likelihood of a source being functional from a baseline of 72% to more than 97% with optimal management and available tools. We suggest that functionality may be a dynamic equilibrium between regular breakdowns and repairs, with management a key determinant of repair rate. Management variables may interact synergistically in ways better captured by BN analysis than by logistic regressions. These qualitative findings may prove generalizable beyond the study area, and may offer new approaches to understanding and increasing handpump functionality and safe water access.

1. Introduction

Access to safe drinking water is critical to human health and development [*WHO*, 2011; *WHO/UNICEF*, 2013]. Lack of continuous access to adequate quantities of safe drinking water can contribute to increased morbidity and mortality, particularly among children under the age of five [*Gunther and Fink*, 2010; *Montgomery and Elimelech*, 2007; *Prüss et al.*, 2002]. The world has already achieved substantive progress in expanding safe drinking water services. However, 663 million people still lack access to an improved source of drinking water, more than 300 million in sub-Saharan Africa alone [*WHO/UNICEF*, 2015]. Furthermore, many improved sources are unsafe [*Bain et al.*, 2014a, 2014b]. Where safe improved sources are available, service may often be discontinuous [*Lee and Schwab*, 2005]; service interruptions can lead to greater use of unimproved sources, which may reduce or eliminate health gains from safe water [*Hunter et al.*, 2009]. Thus, continuous service from safe, improved water sources is vital to ensuring that households have access to adequate quantities of safe water, and is thus essential to maximizing the benefits of safe water for human health and development. In many countries, rural populations lag behind urban communities in gaining access to improved drinking water sources and piped water [*Christenson et al.*, 2014; *WHO/UNICEF*, 2014]. Expanding coverage to unserved individuals, while ensuring that existing sources are functional and provide a continuous supply of safe water to users, is a fundamental development objective for the coming decades [*Bradley and Bartram*, 2013].

For the purpose of this work, we define a given water source (S_i) as *functional* at a given moment in time (t) if water is available from the source at that time (i.e., when a user attempts to produce water by moving a handle, turning a faucet, or lowering a container); if water is not available (for any reason), the source is nonfunctional (these terms are described in greater detail in a forthcoming manuscript by Cronk et al.). We will define *functionality prevalence* as the point prevalence of being functional (e.g., the *functionality prevalence* of rural boreholes in sub-Saharan Africa has been estimated at 50–67%). By contrast, *continuity* refers to the proportion of time that a water source is functional (*idem*), and is equivalent to the average value of functionality over time (i.e., a source that is functional 50% of the time would have a continuity of 0.5). The term "sustainability" has been broadly used in a wide variety of contexts, and lacks a precise definition; thus, while recognizing the importance of many of the connotations of sustainability, this paper will focus narrowly on findings related to water source *functionality*, and their implications for understanding the *continuity* of rural water sources in Ghana. For the purpose of this work, we define a *water source* as any facility from which one or more individuals obtains water. Since the original study on which this work is based did not include surface water sources, our analysis will be limited to sources other than surface water bodies. The standard JMP definitions of improved/unimproved sources are used; briefly, improved sources include: piped water, tubewells or boreholes, protected dug wells, protected springs, and rainwater, while most other sources are classified as unimproved [*WHO*, 2011].

In rural sub-Saharan Africa, the majority of those who enjoy access to water from an improved source rely on boreholes with handpumps [*Sansom and Koestler*, 2009]. The total number of such boreholes in Africa is unknown, but it is estimated that as many as 60,000 new handpumps are installed each year (*idem*). These are generally communal sources shared by multiple users within a community. The value of expanding access to improved water sources in rural sub-Saharan Africa is clear. However, this challenge consists not only of providing service to the more than 300 million people lacking improved drinking water facilities, but also of ensuring that the 670 million with service [*WHO/UNICEF*, 2015] continue to enjoy its benefits. The continuity of drinking water sources (often referred to under the rubric of "water source sustainability") is therefore a pressing issue for governments, Non-Governmental Organizations (NGOs), and donors. However, continuity of water sources has received far less attention than water source construction in both national and international efforts to expand access to improved water sources [*Bain et al*., 2013]. As a result, new water source construction continues at a rapid pace, while a substantial proportion of existing water sources remain nonfunctional. The challenge of ensuring that improved sources provide water of acceptable quality is also a critical one, but is outside the scope of the current work, which will focus on source functionality and continuity.

Studies suggest that at any given time, one third of rural boreholes with handpumps in sub-Saharan Africa (SSA) are nonfunctional [*RWSN*, 2012], while handpump functionality in some countries may be even lower [*Bank*, 1997; *DIWI Consult and BIDR*, 1994]. However, despite the prevalence of source breakdowns in SSA, few adequately powered empirical studies have explored the determinants of handpump functionality in this region. Furthermore, many functional rural sources may produce drinking water that is unsafe due to chemical or microbiological contamination [*Bain et al*., 2014a]. Regular monitoring and inspection of each water source is valuable in supporting the continuity and safety of the water it produces; however, in many low and middle-income country (LMIC) settings, as well as some high-income country settings, some water sources are not inspected frequently, particularly small and rural sources [*Crocker and Bartram*, 2014].

Continuity of water sources depends on multiple determinants. Previous work suggests a number of determinants that contribute to the functionality and/or continuity of rural water sources, including: technical determinants such as construction or maintenance, hydrogeological determinants such as changing water tables or borehole collapse, financial determinants such as funds for maintenance and repairs, and/or social determinants such as competent management to maintain the facility [*Foster*, 2013; *Harvey*, 2004; *P. Harvey and Reed*, 2004; *P. A. Harvey and Reed*, 2007; *Komives et al*., 2008; *Marks et al*., 2014; *O'Keefe-O'Donovan*, 2012; *Parry-Jones et al*., 2001].

In addition, the presence and characteristics of alternative water sources may affect the functionality of a given source. *Komives et al*. [2008] reported that a source is more likely to be functional if it is the only source present in a community, while O'Keeffe–O'Donovan found that handpumps in Tanzania were more likely to be functional if the nearest source was another handpump of the same type [*O'Keefe-O'Donovan*, 2012]. With respect to the latter, benefits to functionality may exist when there are similarities in handpump maintenance and operations. These determinants may also interact, e.g., social problems could lead to financial ones, and financial shortfalls might precipitate technical failures, all of which may be influenced by geographic and hydrogeological determinants. While prior work has suggested various determinants that may affect the continuity of waterpoints, to our knowledge no prior peer-reviewed work has simultaneously

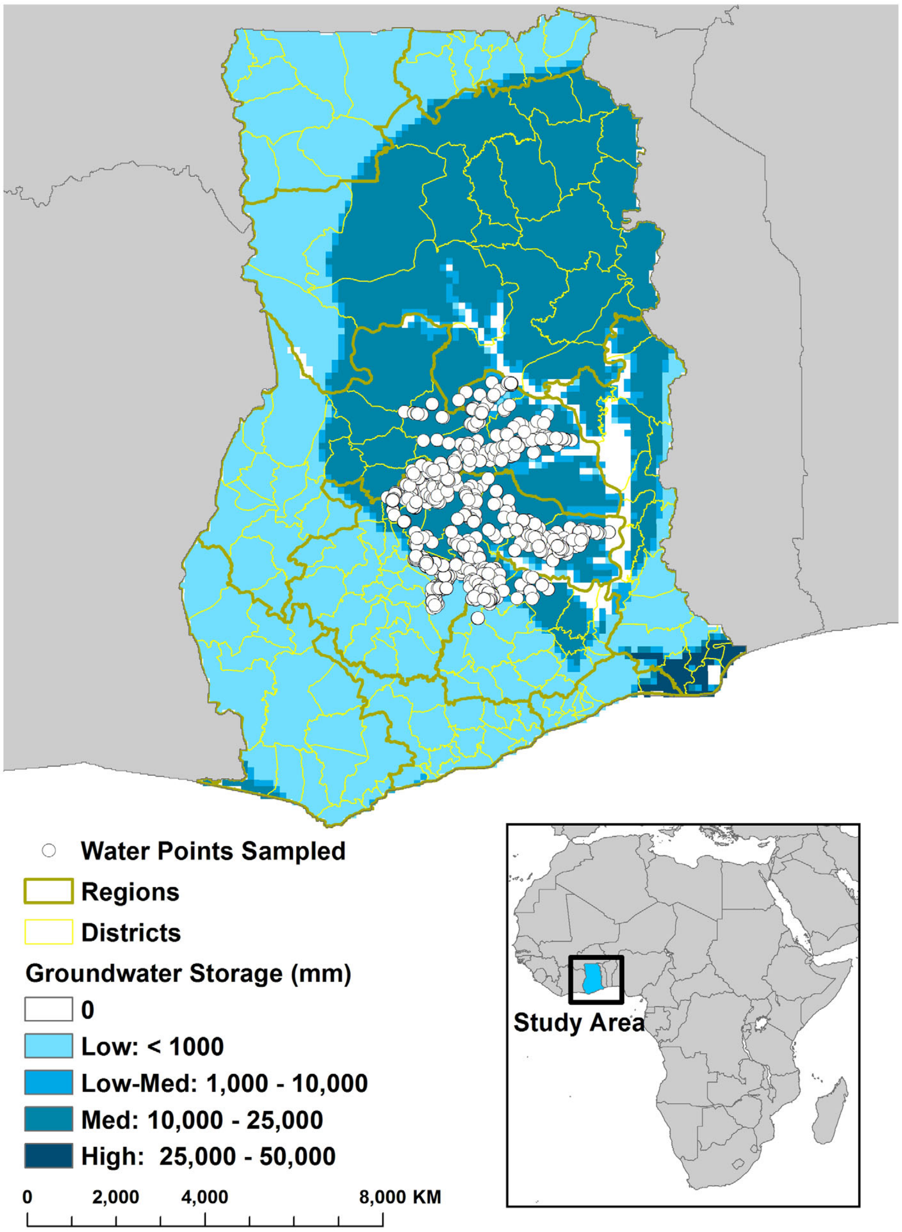

Figure 1. Map of study area.

considered social, financial, mechanical, and hydrogeological determinants (although Foster considered many of these [*Foster*, 2013]), nor assessed the relative importance of determinants across these categories in order to identify options for improving functionality and continuity. Furthermore, to our knowledge, this is the first study to use a Bayesian network (BN), capable of accounting for interdependencies and synergies between such determinants, to analyze the determinants of rural water source functionality.

In response to the need for improvements in the functionality and continuity of rural water sources in sub-Saharan Africa, we sought to assess the functionality of rural boreholes in the Greater Afram Plains (GAP) area of Ghana for communities in which the NGO World Vision (WV) had constructed one or more water sources since 1990 (Figure 1). We also sought to explore the determinants affecting functionality in this context. The GAP is an area of interest because it is a water-scarce region where the majority of households depend on communal water supplies, and where over 1000 boreholes have been installed by WV over the past 25 years, as part of a program supported by The Conrad N. Hilton Foundation.

The GAP study setting included three administrative regions: Eastern, Ashanti, and Brong Ahafo, comprising 13 administrative districts (Figure 1). The GAP spans two hydrologic zones: the Red and White Volta Basin (drained by both the Red Volta and White Volta rivers), and the Black Volta Basin. The shading on the map, indicating different levels of groundwater storage (as defined in section 3 below), shows the hydrogeological variability within the study area (Figure 1).

2. Survey Background

We carried out a secondary analysis of survey data previously collected and anonymized by Water and Sanitation for Africa (WSA), a regional NGO with offices in Ghana. The original survey, conducted in 2011, aimed to capture data on all boreholes (numbering approximately 1000) installed in the GAP by WV's Ghana country program, and on the users and management teams (if any) of these facilities [*WSA*, 2011]. A list of all water sources constructed by WV in the GAP, including the names of the communities in which they were located, was provided by WV to WSA.

During the 2011 data collection, visits were made to all communities in which WV reported having installed one or more water sources, except those which were unreachable due to flooding, or which were no longer populated. A total of 570 communities were visited, and all water sources other than surface water were enumerated in each (Figure 1). A total of 1509 water sources were enumerated in these 570 communities, of which 39 were excluded due to missing information. Of the included 1470 sources, 898 sources were reportedly constructed by WV, 330 water sources were constructed by other organizations, and there were 242 sources for which the constructing organization was not known. In each community where a water and sanitation management team was present (442 in total), this team was also interviewed. Data were collected using a water source survey and a water source management team (WSMT) survey. The water source survey was completed once for every improved water source identified in each of the 570 communities visited.

2.1. Water Source Survey

Data on water source functionality and pump type were collected by direct observation. Data on water source age were obtained by direct observation of borehole identification (ID) plates, when present, or from direct response by survey respondents when an ID plate was not present. Other water source data, such as the number of people currently using each water source, the number of times a water source had failed in the past 12 months, and the availability of mechanics and spare parts, were obtained by self-report from water source management team members, if available, or a community leader or other community member, if a management team was not present.

2.2. WSMT Survey

Data were collected on community and WSMT-level variables, including the population of the community, the number of WSMT members, frequency of meetings, etc. These data were obtained by self-report from water source management team members, if available, or a community leader or other community member, if a management team was not present.

Data collection was carried out by 100 trained enumerators using the Akvo FLOW V. 1.0 mobile data collection software (Akvo, Amsterdam, Netherlands) on Huawei IDEOS mobile phones running the Android operating system (V. 2.2). Preliminary data analysis was conducted by WSA. The final data set obtained by WSA from the above surveys was anonymized by WSA and shared with researchers at the University of North Carolina (UNC) in 2014. The analyses conducted by UNC were submitted for ethics approval from the Institutional Review Board at UNC and received an exemption (study #14-0441).

3. Methods

Once obtained by UNC, data were cleaned as follows: where two data points had community names differing only slightly in spelling (e.g., Konkoma and Konkomba), the two points were considered to be from the same community. Where questions had highly implausible values (water source age $>$100 years, data point coordinates in the ocean), these implausible values were dropped.

Groundwater storage (expressed as the product of saturated thickness and effective porosity, in units of mm), groundwater productivity (L/s), and depth to water (m) were downloaded from the British Geological

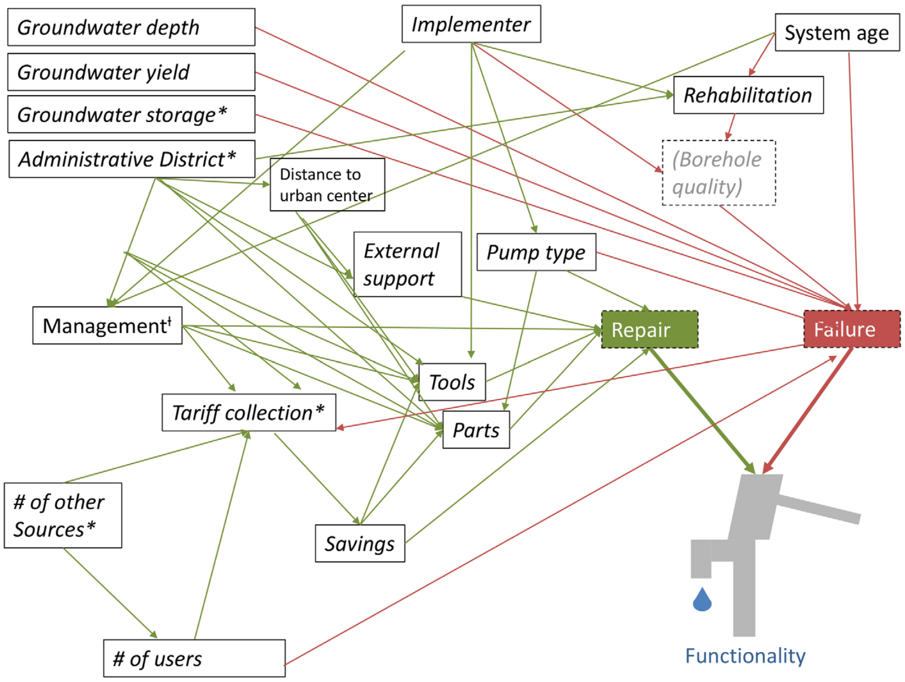

Figure 2. Conceptual model of water source functionality. Determinants marked with an asterisk are significant ($p < 0.05$) in multivariable regressions; determinants marked with a dagger are significant ($p < 0.1$) in multivariable regressions; determinants in dashed boxes and gray type were not directly measured.; green arrows (→) indicate effects predicted to modify the rate of repair; red arrows (→) indicate effects predicted to modify the rate of failure; thin arrows (→) indicate indirect effects on functionality; thick arrows (→) indicate direct effects on functionality.

Survey (BGS) website as 5 km resolution point data for Africa (see Macdonald et al., for method) [*British Geological Survey*; *MacDonald et al*., 2012]. These three variables were used because they comprise the full set of hydrogeological variables available from the BGS data set. Data were converted to a grid surface in ArcGIS 10.2 (Redlands, CA) using the WGS 1984 datum. An elevation map layer was taken from the ASTER global digital elevation model product of METI and NASA at 1 arc sec (~30 m) resolution [*NASA*, 2011] and population density was from AfriPop ~100 m^2 grid (see *Linard et al*. [2012] for method) [*The Worldpop Project*, 2013]. Values for each of these five variables were identified at each water source point location using the ArcGIS point-to-raster tool.

Summary statistics were tabulated for included variables in all surveys. Univariable and multivariable analyses of water source functionality and failure were conducted using a two-level model with clustering at the community level. Univariable and multivariable analyses of active water source management teams were performed using logistic regression. These analyses were conducted for all sampled water sources, and for WV sources only, since the sampling method for WV water sources in the study area was more rigorous than the sampling method for other water sources. Analysis was conducting using Stata 12 (Statacorp., College Station, TX) and SAS 9.3 (SAS Institute Inc., Cary, NC).

The outcome for regression analysis was water source functionality on the day of the visit (direct observation, defined as ability to obtain water from a source within five strokes, if a borehole with manual pump, or ability to obtain water for all other sources). Reported water source failure(s) within the last 12 months (direct response, obtained from the WSMT, facility administrator, or other knowledgeable individual) and presence of an active WSMT (defined as a committee where an average of five or more members were reported to attend meetings one or more times per month) were also tabulated as secondary outcomes. Explanatory variables were selected based on a conceptual model (Figure 2). In addition to the variables shown in Figure 2, we also included a variable indicating whether the respondent was able to estimate the number of users per waterpoint. This was included as a proxy for WSMT quality in logistic regressions. We calculated the odds ratio (OR), evaluated statistical significance with p values of 0.05 and 0.10 (95% and 90% confidence levels (CLs)), and constructed 95% confidence intervals (CIs) for all logistic regressions

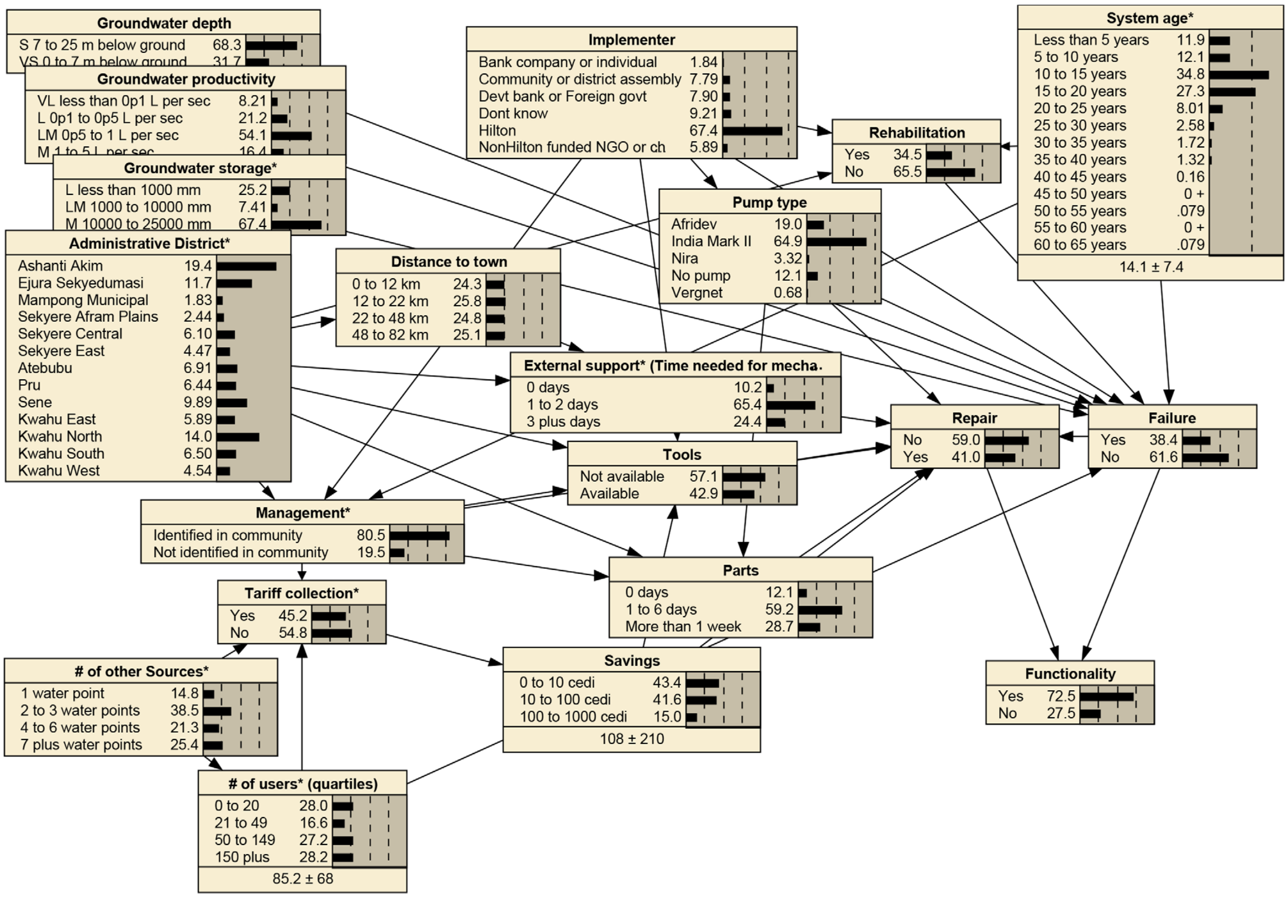

Figure 3. Bayesian network model. This Bayesian network model depicts the overall "baseline case" for the model, with the states of all nodes representing the distribution of states in the data set. Arrows indicate causal relationships in the model.

(*p* values and CIs cannot be calculated for BN models). For univariable models, all variables represented in the conceptual model and available in the data set were included. For multivariable regressions, variables were included if (a) the proportion of missing data for the variable was <20% and was missing at random, and (b) the variable was not an intervening or redundant step on the causal chain in the conceptual model. The resulting multivariable model for functionality included: failure in the past year, pump type (modified to include the option "not a borehole" for the small proportion of other sources), age of waterpoint, number of waterpoints in the community, implementer, presence of an identified management structure in the community, tariff for fetching water, administrative district, groundwater storage, groundwater productivity, depth to groundwater, and distance to a town of 10,000 or more inhabitants.

The conceptual model and the cleaned data were further developed into a Bayesian network model using Netica (www.norsys.com/netica.html, Vancouver, Canada), with water source functionality as the endpoint (Figure 3). Bayesian networks are a useful approach that has been widely used in integrating information from different data sources, including quantitative monitoring data or scientifically parameterized relationships as well as expert knowledge and local beliefs [e.g., *Chan et al.*, 2010, *Shenton et al.*, 2011], and for integrating knowledge from different fields/disciplines [e.g., *Chan et al.*, 2012; *Bromley et al.*, 2005]. The BN approach is useful in this study given the mixed social, financial, mechanical, geographic, and hydrogeological determinants involved in determining water source functionality. BNs are graphically structured based on the causal links between variables within a system, and these links/relationships are described by probability distributions [*Pearl*, 1988]. A good introduction to BNs can be found in *Korb and Nicholson* [2004]. Measured variables included as nodes in the BN model were: pump type (modified to include the option "not a borehole" for the small proportion of other sources), age of waterpoint; number of waterpoints in the community, implementer, presence of an identified management structure in the community, tariff for

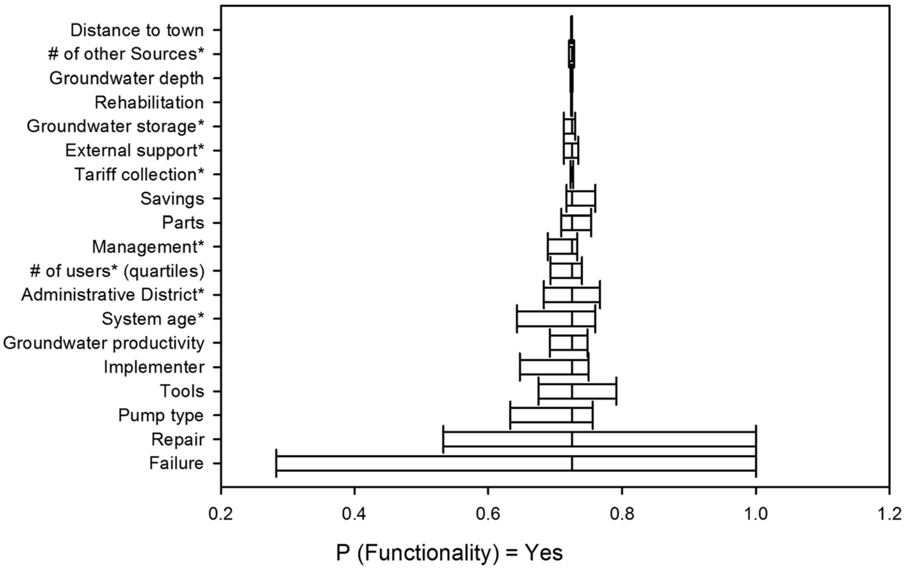

Figure 4. Potential influences of nework variables. Potential influence of network variables on a water source being functional, P(Functionality) = Yes, from least sensitive variables at the top to most sensitive at the bottom. The width of bars indicates the influence of each variable on the likelihood of functionality being in the "Yes" state.

fetching water, administrative district, groundwater storage, groundwater productivity, depth to groundwater, distance to a town of 10,000 or more inhabitants, previous rehabilitation, availability of spare parts, availability of external support (time needed for mechanic to arrive), number of users (quartiles), and WaSH committee savings (quantiles). In addition, key interpolated variables were added as nodes in the model: failure, repair, and availability of tools. It should be noted that BN models allow for a greater number of nodes to be included than the number of variables that can often be included in a meaningful multivariable logistic regression; BNs also allow multiple nodes on the same causal chain to be included in the model; furthermore, BNs can incorporate nodes for which many or even all data are missing without compromising the validity of the resulting model. As a result, more variables were included in the BN model than the multivariable logistic regressions, including sparse and interpolated variables.

The Expectation Maximization (EM) algorithm was used to learn the conditional probability tables in the Bayesian network from the data set [*Dempster et al*., 1977]. This method is particularly useful where there are missing data, as the EM function is used to interpolate from the data that are available, allowing the use of case data (i.e., all the data relevant to a particular water source/handpump), which may be omitted by other methods [e.g., see *Ticehurst et al*., 2011].

Sensitivity analysis of the learned network was performed to determine the variables with the most influence on water source functionality (supporting information Table S1). The sensitivity analysis used here calculates reductions in Shannon's entropy (also known as the "mutual information") and is described in more detail by *Pearl* [1988]. Ranking the nodes according to entropy reduction identifies those nodes with the most influence on the endpoint in relation to added evidence. Note that this considers only individual sensitivities and evidence in combination may be synergistic [*Jensen and Nielsen*, 2007]. Figure 4 illustrates the sensitivity for water source functionality, with the most influential nodes closest to the *x* axis, and the longer the bar, the greater the influence on the functionality being in the state "yes."

If the width of a bar is less than the bar above, this indicates the variable is less sensitive for this particular state of the endpoint relative to the overall endpoint sensitivity. For example, the "Tariff collection" is not very influential on the endpoint being functional, which might be expected if much of the sensitivity for this variable is in the functionality of the water source being in a "no" state rather than "yes."

Additional scenarios were run with the BN to further explore those variables that were found to be of interest from the univariable and multivariable regressions and analyses. Several cases were defined for the BN model: a baseline case, in which the distribution of the states of all nodes corresponds to the data set used; an "optimistic" management scenario, in which all management determinants are in their best possible states (identifiable management present, WaSH committee savings >100 Ghana cedis, tariff collected, all necessary tools available, spare parts available within 1 day, and external support available within 1 day); a "pessimistic" scenario, in which all management determinants are in their worst possible states (no identifiable management present, WaSH committee savings <10 Ghana cedis, no tariff collected, all necessary tools not available, spare parts available within >1 week, and external support available within >3 days).

4. Results

4.1. Water Source Characteristics

A total of 1509 water sources were enumerated in the 570 communities visited. Thirty-nine water source observations were excluded due to missing community identification information, leaving 1470 for analyses. One thousand three hundred and seventy two (93.3%) of the 1470 included water sources were classified as improved, of which 1206 (82.2% of the total) were boreholes with handpumps (Table 1). The median age of included water sources was 14.2 years, with a minimum age of less than 1 year and a maximum age of 60 years; 60% of water sources were between 8 and 18 years old. The median number of water sources per community was 2, and the range was 1–24 sources per community.

The majority (64.7%) of the handpump water sources enumerated were Modified India Mark II pumps, with the remainder comprising primarily Afridev pumps (19.1%), as well as a few Nira (3.4%) and Vergnet (0.7%) pumps. One third of water sources in the study area (31.6%) had reportedly been rehabilitated. The majority of the included water sources (68.1%) were funded by the Conrad N. Hilton Foundation, with the remainder funded by local District Assemblies (local government) and other NGOs.

The median number of users per source, reported for 508 sources, was 50, while the mean was 113. Approximately 7% ($n = 33$) of boreholes with handpumps exceeded the national standard for the maximum allowable number of users per borehole (300). The median number of water sources enumerated per community was three. It should be noted that the total number of sources actually present in each community may have differed from the number of sources enumerated, as some sources may have been missed during data collection activities. While only 21% of sources did not provide water on the day of the visit, nearly half (45.3%) of all visited sources had reportedly experienced one or more breakdowns in the past 12 months (Table 1). Of sources with one or more failures in the past 12 months, 54% had experienced two or more failures.

4.2. Water Source Functionality

Water was available from 79.4% of the 1470 water sources at the time they were visited (Table 1). When these data were disaggregated by source type, 79.7% of boreholes with handpumps were found to be functional, while 76.8% of other improved sources were working. At the community level, 90.7% of communities had one or more functional improved sources on the day of the visit.

There was a significant effect of source age on functionality in univariable regressions, with functionality decreasing with age from sources <5 years old to a minimum for sources 10–15 years old, then increasing slightly (Table 2); however, the effect of age was not significant in multivariable regressions (Table 3); in the BN model, functionality was found to increase for sources 5–10 years old versus sources <5 years old, then decrease with age at a rate of approximately 0.2% per year (Table 4 and supporting information Figure S1). In univariable and multivariable regressions, there was no significant effect of implementer on functionality; however, the BN model found that sources implemented by World Vison on behalf of the Hilton Foundation were more likely to be functional than sources constructed by other implementers. In both univariable and multivariable logistic regressions, the number of water sources enumerated in each community was found to have a significant inverse correlation with the likelihood of each of those water sources being functional (Table 3); in communities where only one water source was present, multivariable logistic regression results suggested that this water source had 4.8 (95% CI: 2.3–10.1) times higher odds of functionality than those of water sources in communities with seven or more enumerated water sources (Table 3); this effect was present, but was far less pronounced, in the BN model (Table 4), with functionality decreasing monotonically from 72.8% to 72.1% with increasing numbers of sources (supporting information Figure S2). It is important to note that in both cases, while increased numbers of water sources were associated with decreased odds of any given water source being functional, they were still associated with increased likelihood that at least

Table 1. Selected Descriptive Statistics for Sources in Study Area

Factor		*N* (%)
Waterpoint functional	No	283 (20.6)
	Yes	1089 (79.4)
Borehole functional	No	245 (20.3)
	Yes	961 (79.7)
Other improved source functional	No	38 (23.2)
	Yes	126 (76.8)
Breakdowns in the past year	No	751 (54.7)
	Yes	621 (45.3)
Number of breakdowns in the past year	0	751 (54.7)
	1	288 (21)
	2+	333 (24.3)
Waterpoint rehabilitation	No	938 (68.4)
	Yes	434 (31.6)
Source type	Borehole with handpump	1206 (82.2)
	Other improved source	164 (11.2)
	Unimproved	98 (6.7)
Pump type	Afridev	256 (19.1)
	India Mark II	868 (64.7)
	Nira	45 (3.4)
	Vergnet	9 (0.7)
	No pump	164 (12.2)
Age of waterpoint	<5 years	154 (11.7)
	5–10 years	158 (12.1)
	10–15 years	460 (35.1)
	15–20 years	359 (27.4)
	20+ years	180 (13.7)
Constructing organization	Bank/company/individual	23 (1.7)
	Community/district assembly	100 (7.6)
	Development bank/Foreign government	101 (7.7)
	Do not know	121 (9.2)
	Hilton	898 (68.1)
	Non-hilton funded NGO/church	75 (5.7)
Waterpoints enumerated in the community	1 waterpoint	217 (14.8)
	2–3 waterpoints	566 (38.5)
	4–6 waterpoints	313 (21.3)
	7+ waterpoints	374 (25.4)
Identified management within the community	Identified management in community	1228 (90)
	No identified management in community	137 (10)
Interviewee's knowledge of number of users	No	864 (63)
	Yes	508 (37)
Number of users (quartiles)	0–20	145 (28.5)
	150+	134 (26.4)
	21–49	81 (15.9)
	50–150	148 (29.1)
Tariff collected	No	713 (52)
	Yes	659 (48)
Time of tariff collection	Paid per unit time (daily, weekly, monthly, yearly)	224 (34.4)
	Per trip/bucket	418 (64.2)
	When broken down, occasionally	9 (1.4)
Savings (cedis)	0–10	366 (41.8)
	10–100	373 (42.6)
	100–1000	136 (15.5)
Time needed to get spare parts	0 days	126 (11.2)
	1–6 days	667 (59.5)
	>1 week	328 (29.3)
Time needed for a mechanic	0 days	118 (10.7)
	1–2 days	711 (64.2)
	3+ days	278 (25.1)
Interviewee's awareness of an area mechanic	No	332 (32)
	Yes	707 (68)
Population density quartiles (Population per 100 m^2)	Q1: < 0.1055 people per 100 m^2	376 (25.6)
	Q2: 0.1058–0.4071 people per 100 m^2	372 (25.3)
	Q2: 0.4104–5.5724 people per 100 m^2	370 (25.2)
	Q3: 5.6142–285 people per 100 m^2	352 (23.9)
Groundwater storage (water depth in mm)	L: <1000 mm	370 (25.2)
	LM: 1000–10,000 mm	109 (7.4)
	M: 10,000–25,000 mm	991 (67.4)

Table 1. (continued)

Factor		*N* (%)
Groundwater productivity (boreholes—L/s)	L: 0.1–0.5 L/s	305 (21.2)
	LM: 0.5–1 L/s	779 (54.2)
	M: 1–5 L/s	236 (16.4)
	VL: <0.1 L/s	118 (8.2)
Depth to groundwater (meters belowground)	S: 7–25 m below ground	1004 (68.3)
	VS: 0–7 m below ground	466 (31.7)
Distance to town of at least 10,000 people	0–12 km	359 (24.4)
	12–22 km	359 (24.4)
	22–48 km	388 (26.4)
	48–82 km	364 (24.8)
District	Ashanti Akim	269 (19.6)
	Atebubu	97 (7.1)
	Ejura Sekyedumasi	167 (12.2)
	Kwahu East	82 (6)
	Kwahu North	157 (11.4)
	Kwahu South	95 (6.9)
	Kwahu West	67 (4.9)
	Mampong Municipal	27 (2)
	Pru	86 (6.3)
	Sekyere Afram Plains	30 (2.2)
	Sekyere Central	86 (6.3)
	Sekyre East	65 (4.7)
	Sene	144 (10.5)
Water sources per community	Median	2
Community has ≥1 functional improved source	Yes	507 (94.4)
	No	30 (5.6)

one water source was functional. In univariable and multivariable regressions, functionality was not found to vary significantly by pump type; by contrast, the BN analysis found a pronounced effect of pump type, with Afridev pumps associated with lower functionality than other pump types in the study area (Table 4).

When breakdown in the last 12 months was included in logistic regressions, it was found to be significantly negatively correlated with functionality in both univariable and multivariable regressions. This variable was not included in the BN model, as interpolated breakdown and repair variables were used instead, to minimize challenges associated with recall bias over such long periods of time.

Water source functionality also varied with local hydrogeological conditions. Of different conditions for which data were available (groundwater storage, groundwater depth, and groundwater productivity), only the association with groundwater storage was statistically significant in the multivariable logistic regression, with water sources in areas of low storage (<1000 mm) having 2.9 times (95% CI: 1.4–5.9 times) higher odds of functionality than those in medium (10,000–25,000 mm) storage areas. By contrast, the BN model showed a slight trend toward higher functionality for sources in areas with medium storage, and also slightly higher functionality for sources with higher groundwater productivity (Table 4).

There were several "software" determinants associated with water source functionality. Tariff collection (binary variable including all collection schedules, i.e., monthly, pay per trip, and ad hoc) was significantly correlated with higher water source functionality (OR = 1.7 (95% CI: 1.2–2.4)) in the univariable logistic model (Table 2). This effect was also significant in the multivariable regression (OR = 1.9 (95% CI: 1.2–3.1), Table 3). However, tariff collection schedule (per trip, per month, or ad hoc), was not significantly associated with functionality in univariable regressions, and was excluded from the multivariable analysis. In the BN model, tariff collection was associated with only slightly higher functionality (72.7% versus 72.3%, Table 4). Water sources with identified management within the community were over 2 times more likely to be functional than those without identifiable management within the community in univariable regressions (OR = 2.3 (95% CI 1.5–3.4)), and this effect was significant at the 90% confidence interval in multivariable regressions as well (OR = 1.6 (95% CI 1.0–2.7)). In BN analyses, identifiable management was also associated with higher functionality (73.3% versus 68.9% functionality, Table 4). Access to spare parts was not significantly associated with functionality in univariable regressions, and was thus excluded from the multivariable logistic regression. In the BN model, there was not a consistent trend in the impact of availability of spare

Table 2. Univariable Logistic Regression Results for All Sources

Contrast	OR	95% CI	*p* Value
Failure in the past year: yes versus no	0.4	(0.3–0.6)	<0.0001
Rehabilitation: yes versus no	1.4	(1–2)	0.0236
Source type: borehole with handpump versus other improved source	1.3	(0.9–2)	0.2435
Pump type: Afridev versus India Mark II	1.6	(1.1–2.4)	0.0742
Pump type: Nira versus India Mark II	1.1	(0.5–2.3)	
Pump type: Vergnet versus India Mark II	0.5	(0.1–2.5)	
Pump type: not a borehole versus India Mark II	0.9	(0.6–1.3)	
Pump type: India Mark II versus all other pump types	0.7	(0.5–1)	0.0534
System age: <5 years versus 20+ years	0.8	(0.5–1.3)	0.0289
System age: 5–10 years versus 20+ years	0.6	(0.4–1)	
System age: 10–15 years versus 20+ years	0.5	(0.3–0.8)	
System age: 15–20 years versus 20+ years	1.1	(0.6–2.1)	
Constructing organization: Hilton versus Other	1.2	(0.9–1.7)	0.2189
Waterpoints enumerated in the community: 1 versus 7+	2.9	(1.5–5.3)	<0.0001
Waterpoints enumerated in the community: 2-3 versus 7+	0.9	(0.6–1.4)	
Waterpoints enumerated in the community: 4-6 versus 7+	1	(0.6–1.7)	
Identified management in the community: Yes versus No	2.3	(1.5–3.4)	0.002
Interviewee's knowledge of number of waterpoint users: yes versus no	2.1	(1.5–2.9)	<0.0001
Number of users: 0–20 versus 150+	0.9	(0.5–1.8)	0.0072
Number of users: 21–49 versus 150+	3.6	(1.2–10.2)	
Number of users: 50-149 versus 150+	1.4	(0.7–2.8)	
Tariff collected: yes versus no	1.7	(1.2–2.4)	0.0022
Daily, weekly, monthly, yearly	1.3	(0.7–2.1)	0.3828
When broken down, occasionally versus per trip/bucket	0.4	(0.1–1.8)	
Savings: 0–10 Cedis versus 100–1000 cedis	1	(0.7–1.6)	0.9756
Savings: 10–100 Cedis versus 100–1000 cedis	1.1	(0.6–2)	
Time needed to get spare parts: 0 days versus 1–6 days	0.8	(0.5–1.5)	0.1978
Time needed to get spare parts: 0 days versus >1 week	1.3	(0.9–1.8)	
Time needed for a mechanic: 0 versus 3+	1.2	(0.7–2.2)	0.0147
Time needed for a mechanic: 1–2 versus 3+	1.8	(1.3–2.7)	
Awareness of an area mechanic: yes versus no	1.3	(0.9–2)	0.1817
Population density increase by 5 people per 100 m2	1	(1–1)	0.2942
Groundwater storage: L (<1000 mm) versus M (10,000–25,000 mm)	1.6	(1.1–2.2)	0.0182
Groundwater storage: LM (1000–10,000 mm) versus M (10,000–25,000 mm)	1.5	(0.9–2.6)	
Borehole productivity: L (0.1–0.5 L/s) versus VL (<0.1 L/s)	0.7	(0.4–1.3)	0.2413
Borehole productivity: LM (0.5–1 L/s) versus VL (<0.1 L/s)	1.1	(0.7–1.9)	
Borehole productivity: M (1–5 L/s) versus VL (<0.1 L/s)	0.8	(0.4–1.5)	
Depth to groundwater: 7–25 m versus 0–7 m below ground	1	(0.7–1.3)	0.8909
Distance: 12–22 km versus 0–12 km	0.9	(0.6–1.4)	0.0927
Distance: 22–48 km versus 0–12 km	0.6	(0.4–0.9)	
Distance: 48–82 km versus 0–12 km	0.7	(0.4–1.1)	
District: Ashanti Akim versus Ejura Sekyedumasi	1.8	(1–3.3)	0.0011
District: Atebubu versus Ejura Sekyedumasi	0.8	(0.4–1.7)	
District: Kwahu East versus Ejura Sekyedumasi	0.6	(0.3–1.2)	
District: Kwahu North versus Ejura Sekyedumasi	0.8	(0.4–1.6)	
District: Kwahu South versus Ejura Sekyedumasi	0.5	(0.3–0.9)	
District: Kwahu West versus Ejura Sekyedumasi	0.5	(0.3–0.9)	
District: Mampong Municipal versus Ejura Sekyedumasi	0.9	(0.4–1.7)	
District: Pru versus Ejura Sekyedumasi	1	(0.4–2.4)	
District: Sekyere Afram Plains versus Ejura Sekyedumasi	0.7	(0.3–1.3)	
District: Sekyere Central versus Ejura Sekyedumasi	3.1	(0.7–13)	
District: Sekyre East versus Ejura Sekyedumasi	0.5	(0.2–0.9)	
District: Sene versus Ejura Sekyedumasi	1.1	(0.5–2.2)	

parts on functionality. While the original data set did not include data on the availability of tools, an interpolated "tools" variable was included as a node in the BN model; the impact of tools was pronounced, with 79.1% functionality for sources where all necessary tools were available, and 67.5% functionality where tools were not available (Table 4).

In univariable logistic regressions, functionality was found to correlate inversely with the number of days required to obtain the services of a mechanic; specifically, water sources for which the management team was able to obtain the services of a mechanic within the same day the problem was detected had a functionality rate of 78.8%, while those who had to wait 3 or more days to get a mechanic had a significantly lower functionality rate of 74.5% (OR = 1.2 (95% CI 0.7–2.2)). This variable (time to obtain a mechanic) was not included in multivariable regressions, due to the large number of missing data for this question

Table 3. Multivariable Logistic Regression Model for Water Source Functionality

Contrast	OR	95% CI	*p* Value
Failure in the past year: yes versus no	0.4	(0.3–0.6)	<0.0001
Pump type: Afridev versus India Mark II	1.2	(0.7–1.9)	0.9336
Pump type: Nira versus India Mark II	1.2	(0.5–2.6)	
Pump type: Vergnet versus India Mark II	1.2	(0.7–2)	
system age: <5 years versus 20+ years	1	(0.5–1.9)	0.1209
system age: 5–10 years versus 20+ years	0.8	(0.4–1.5)	
system age: 10–15 years versus 20+ years	0.6	(0.3–1.2)	
system age: 15–20 years versus 20+ years	1.5	(0.8–3)	
Number of waterpoints: 1 versus 7+	4.8	(2.3–10.1)	<0.0001
Number of waterpoints: 2–3 versus 7+	1.6	(1–2.6)	
Number of waterpoints: 4–6 versus 7+	1.5	(0.9–2.5)	
Constructing organization: Hilton versus Other	1.5	(0.9–2.3)	0.1079
Identified management in the community	1.6	(1–2.7)	0.0918
Tariff: yes versus no	1.9	(1.2–3.1)	0.0105
Groundwater storage: L (<1000 mm) versus M (10,000–25,000 mm)	2.9	(1.4–5.9)	0.0219
Groundwater storage: LM (1000–10,000 mm) versus M (10,000–25,000 mm)	2.2	(0.9–5)	
Borehole productivity: L (0.1–0.5 L/s) versus VL (<0.1 L/s)	0.5	(0.2–1.3)	0.2984
Borehole productivity: LM (0.5–1 L/s) versus VL (<0.1 L/s)	0.9	(0.4–2.3)	
Borehole productivity: M (1–5 L/s) versus VL (<0.1 L/s)	0.6	(0.3–1.2)	
Depth to groundwater: 7–25 m versus 0–7 m below ground	1.3	(0.9–2)	0.1594
Distance: 12–22 km versus 0–12 km	1.5	(0.8–2.9)	0.4673
Distance: 22–48 km versus 0–12 km	1.1	(0.5–2.4)	
District: Ashanti Akim versus Ejura Sekyedumasi	1.2	(0.4–3)	0.0062
District: Atebubu versus Ejura Sekyedumasi	1.6	(0.5–4.8)	
District: Kwahu East versus Ejura Sekyedumasi	0.4	(0.1–0.9)	
District: Kwahu North versus Ejura Sekyedumasi	1.6	(0.6–4.5)	
District: Kwahu South versus Ejura Sekyedumasi	0.2	(0.1–0.7)	
District: Kwahu West versus Ejura Sekyedumasi	0.2	(0.1–0.7)	
District: Mampong Municipal versus Ejura Sekyedumasi	0.2	(0.1–0.7)	
District: Pru versus Ejura Sekyedumasi	0.7	(0.2–3.2)	
District: Sekyere Afram Plains versus Ejura Sekyedumasi	1	(0.4–2.8)	
District: Sekyere Central versus Ejura Sekyedumasi	3.3	(0.6–18.3)	
District: Sekyre East versus Ejura Sekyedumasi	0.6	(0.3–1.3)	
District: Sene versus Ejura Sekyedumasi	0.4	(0.1–1.5)	

(363 missing observations). In the BN model, shorter time to obtain a mechanic was also associated with increased functionality, although the effect size was somewhat smaller than in the univariable logistic regression (Table 4).

The ability of the respondent in water source surveys to estimate the number of people using the water source was also correlated with functionality in logistic regressions. Sources for which the respondent could not estimate the number of users per water source had an average functionality rate of 75.7% in univariable logistic regressions, while those sources whose interviewed respondents were able to estimate the number of users had a significantly higher average functionality rate of 85.6% (OR = 2.1 (95% CI 1.5–2.9)); this variable was not included in multivariable logistic regressions (due to constraints on the number of variables); it was also not included in BN analysis, as it was intended as a proxy for the effects of management quality, and these effects were presumed to be captured by the BN approach.

Source functionality was also found to vary significantly as a function of the number of users reported to be collecting water from each source in univariable regressions. Specifically, sources with 21–49 users were found to have significantly higher odds of functionality (OR = 3.6 95% CI: 1.2–10.2) than those with 150 or more users. It should be noted that data on the number of users per source were only available for 520 out of 1470 sources, and these sources were significantly different from the overall sample in terms of functionality, management structure, and other variables. As a result, this variable was not included in multivariable regressions. User numbers were included in the BN analysis, and sources with 1–20 users were found to have the highest functionality, while sources with 150+ users had the lowest (Table 4).

The effect of district on functionality was highly significant in univariable and multivariable regressions, and the effect of district on functionality was substantive in the BN analysis as well (Tables 2–4).

The BN was subsequently also used to look specifically at the various management determinants impacting functionality. Individually, the impact of having an identifiable management structure, whether tariff

Table 4. Bayesian Network Model for Water Source Functionality

Probability of Funct = "Yes"	States for Each Variable/Node From Top to Bottom												
Failure	Yes 28.3	No 100											
Repair	No 53.3	Yes 100											
Pump type	Afridev 62.7	India Mark II 75.2	Nira 63.3	No Pump 75.6	Vergnet 74.3								
Tools	Not available 67.5	Available 79.1											
Implementer	Bank, company, or individual 66	Community or district assembly 66.1	Development bank or Foreign government 65.9	Do not know 71	Hilton Foundation 75	Other NGO or church 64.7							
Groundwater productivity	Less than 0.1 L/s 69.2	0.1–0.5 L/s 69.3	0.5–1 L/s 74.8	1–5 L/s 70.5									
Source age*	0–5 years 69	5–10 years 76	10–15 years 73.3	15–20 years 72.6	20–25 years 71.4	25–30 years 68.3	30–35 years 69	35–40 years 68.1	40–45 years 63.2	45–50 years 64.3	50–55 years 65.1	55–60 years 64.3	60–65 years 65.1
Administrative District*	Ashanti Akim 71.2	Ejura Sekyedumasi 73.3	Mampong Municipal 71.7	Sekyere Afram Plains 74.2	Sekyere Central 68.3	Sekyere East 76.7	Atebubu 75.4	Pru 73.8	Sene 74	Kwahu East 71.5	Kwahu North 70	Kwahu South 71.7	Kwahu West 77
# of users* (quartiles)	0–20 74.2	21–49 73.2	50–149 73.5	150+ 69.3									
Management*	Identified in community 73.3	Not identified in community 68.9											
Parts	0 days 73.1	1–6 days 70.9	More than 1 week 75.4										
Savings	0–10 cedis 72	10–100 cedis 71.7	100–1000 cedis 76										
Tariff collection*	Yes 72.7	No 72.3											
External support*	0 days 73.4	1–2 days 72.8	3+ days 71.3										
Groundwater storage*	L < 1000 mm 71.3	LM 1000–10,000 mm 71.4	M 10,000–25,000 mm 73										
Rehabilitation	Yes 72.5	No 72.4											
Groundwater depth	7–25 m 72.6	0–7 m 72.3											
# of other Sources*	1 waterpoint 72.8	2–3 waterpoints 72.6	4–6 waterpoints 72.5	7+ waterpoints 72.1									
Distance to town	0–12 km 72.5	12–22 km 72.4	22–48 km 72.5	48–82 km 72.5									

*Variables that were significant in the multivariable logistic regression.

collection occurs (savings in the BN are used as a more direct measure), whether tools and parts are available, and the time needed for a mechanic to arrive, all increase the likelihood of a water source being functional over the baseline case (Figures 4 and supporting information Figure S3 from baseline 72% anywhere up to 79%). However when combined, in an "optimistic" scenario where all these determinants are in the best possible state, the impact is marked (supporting information Figure S4), increasing the likelihood of water source functionality from a baseline 72% to 97%. In comparison, when a "pessimistic" scenario is applied (supporting information Figure S5) the likelihood of a water source being functional decreases precipitously to 59% (also compare last column in supporting information Figure S3).

4.3. World Vision Sources

When the same multivariable regression was repeated for WV-constructed sources only ($n = 898$), the effects of number of water sources, groundwater storage, and failure within the last year remained statistically significant at the 95% confidence level (supporting information Tables S2–S4). However, source age, tariff collection, pump type, and the presence of an identifiable management structure in the community and many other were not significant for WV sources.

5. Discussion

Multiple determinants were found to affect the functionality of water sources. These include several largely uncontrollable determinants including number of water sources per community, district, and hydrogeological variables in multivariable logistic regressions, as well as implementer, source age, and number of users in the BN model. This study also highlighted the importance of more modifiable determinants such as tariff collection and management, in the multivariable logistic regression; it also highlighted the importance of these determinants in addition to pump type, access to tools and parts, savings, and timely access to the services of a mechanic, in the BN model. These latter determinants seem more amenable to control and improvement by implementers and local government agencies, and suggest WSMT capacity as a key area of focus for improving functionality.

The strong effect of the interpolated "access to tools" variable in the BN model may be specifically indicative of the importance of WSMTs having access to the necessary tools to repair waterpoints, or may function as a stand-in for a larger set of critical inputs, including tools, which may enhance the effectiveness of WSMTs. Additionally, the large effect of tools in this model may indicate that the BN model is conflating the impact of tools and/or other inputs with some of the synergistic effects between different management variables. In any event, the results suggest that tools are likely important determinants of functionality in the study setting; further work with directly observed data on the availability of tools may be useful in validating the relative importance of this determinant compared to other critical inputs that enhance the effectiveness of WSMTs.

The potential for synergistic interactions between different management variables to affect, or even dominate functionality was also highlighted by the results of the BN model, which demonstrated that when all management variables are in their optimal state, water supplies are dramatically more likely to be functional than when these variables are in their baseline or worst-case states.

The effect of administrative district was quite pronounced in all models. It should be noted that in Ghana, each administrative district has its own district assembly, which is a local government entity with a water and sanitation technical unit that is nominally responsible for providing external support to communities. In addition, each district roughly corresponds to a different WV area development program (ADP), with its own local office in charge of the training and support of WSMTS. Thus, the observed effect of district in this study may correspond to uncontrollable geographic and/or demographic determinants, to more readily controllable determinants related to external support, or both. The BN model, which does not assume independence among different variables, may be better able to control for the interactions between district, hydrogeology, management and implementation quality, and external support than logistic regressions, which do assume independence among different variables.

The sizable effect of implementer in the BN model is also of interest. While this variable was not significant in multivariable regressions, the OR (1.5) and p value (0.11) suggest that it may be an important determinant to observe in future studies. It is not possible to determine the root cause of any observed differences in functionality attributable to different implementers using the current data set. However, we may speculate that such differences could potentially arise for several reasons. They could be due to differences in borehole drilling and siting practices, with one implementer being more proficient in these practices than others, or selecting sites with better hydrogeology, either intentionally or by chance. Alternatively, some implementers may be more proficient at key aspects of "software" implementation, such as the formation and training of WSMTs. Alternatively, it may be the case that some implementers provide better external support services than others. Any such speculation in the present study would be unwarranted, but it may be interesting to delve deeper into this question in future work.

The effect of pump type on functionality in the BN model is also interesting. While it may be the case that the India Mk II handpump performs better in the study area for intrinsic technical reasons, it may also be the case that, because it is the most prevalent handpump type in the study area, sources with India Mk II pumps benefit from network externalities such as better knowledge and training of WSMTs and external support teams related to repairing India Mk II handpumps, and/or greater availability of tools and spare parts for this pump type, etc. Such network externality effects would be consistent with the findings of *O'Keefe and O'Donovan* [2012].

The significant association of low groundwater storage with increased functionality in the logistic regression model was a counter-intuitive finding. It should be noted that even low groundwater storage levels ($<$1000 mm) are generally sufficient to support the average annual extraction from manual borehole pumps (approximately 3 mm/yr) [*MacDonald et al*., 2012]. Thus, low storage is unlikely to cause changes in borehole functionality, but may correlate with some other unmeasured hydrogeological variable that does, such as specific types of stratigraphy in the GAP region. Furthermore, the observation that increased groundwater storage was in fact associated with increased functionality in the BN model suggests that the latter model may correct for multiple and potentially confounding interactions between geographic and hydrogeological determinants more effectively than logistic regressions, and it is likely that, all things being equal, increased groundwater storage may actually lead to higher functionality. It should also be considered that the groundwater storage data used in this study have fairly course resolution, and that there exists significant localized hydrogeological variation in the GAP area. The results of this study provide an interesting starting point for a more robust evaluation of the local hydrogeology with respect to available borehole driller's logs and other high-resolution data sources.

While tariff collection was significantly correlated with functionality for sources constructed by all implementers, and the presence of an identifiable management structure was significant at the 90% CL, this relationship was not significant for the subset of WV water sources. This may be due in part to the fact that 90.7% of WV water sources in the study area had an identifiable management structure within the community (comparable to 90% for all sources), making the number of water sources without such management too small for effective comparisons given the reduced sample size. The lack of a significant effect of tariff collection was more difficult to explain, since only 42.3% of WV sources reported collecting a tariff. It is also possible that the smaller sample size of WV water sources (898 versus 1470) is responsible for this variable not being significant as well. The finding in the BN model that tariff collection did not have a particularly large effect on functionality being in the "Yes" state, but that there was a large synergistic effects of all management variables being in the most positive state suggests that some management determinants such as tariff collection may be enabling determinants which contribute to functionality when WSMTs are present, and have access to tools and spare parts, etc.

Some of the above findings are consistent with results from one or more previous studies, highlighting the importance of an initial thorough understanding of the hydrogeology [*Harvey*, 2004] and external (postconstruction) support [*Whittington et al*., 2009]. Others had also suggested that source age and tariff collection [*O'Keefe-O'Donovan*, 2012] might be important.

The importance of the number of water sources per community in multivariable logistic regressions in this study is in agreement with the findings of *Whittington et al*. [2009] from Ghana, but differs from Foster's observation that water source density had no significant effect on functionality in Liberia, Sierra Leone, and Uganda [*Foster*, 2013; *O'Keefe-O'Donovan*, 2012]. By contrast, the BN model's finding that the effects of number of sources per community were relatively small compared to other determinants, seems more consistent with Foster's observations (although it should be noted that sources per community (this study) and spatial density of sources [*Foster*, 2013] are not directly comparable metrics). Furthermore, several predictors of functionality observed in this study have not previously been considered, such as the influence of district, multiple indicators of management quality, and the hydrogeological characteristics of the site.

Finally, the effect sizes of many of these functionality determinants were previously unknown, and have important implications for the management of rural community water sources in the study area and beyond; for example, the finding that management determinants in the study context were far more important than system age suggest that management efforts may seek to increase their focus on rehabilitating software, relative to hardware, in the future. Furthermore, to our knowledge, no previous studies have considered all of these determinants in combination, or addressed causal relationships and interactions between these determinants as in the current BN approach. The results of the BN model, indicating a dramatic impact of synergistic effects and interactions among management variables, suggest that the presence of good management teams with the tools, resources, and support to repair waterpoints may have a disproportionate impact on water source functionality relative to what would be predicted using regression models.

Overall, we suggest that water source functionality prevalence can be understood as a dynamic equilibrium between failure and repair; in the present setting, the rate of failure appears largely determined by variables such as geography and hydrogeology, which are difficult to modify, while the rate of repair appears to have more modifiable determinants; efforts to shift the equilibrium towards greater functionality may thus focus here.

5.1. Limitations of This Study

It is important to acknowledge several limitations of the data and methods this study, as well as the limited generalizability of the conclusions of this work. The secondary data used in this work were collected by approximately 100 different enumerators who received limited training, and standard QA/QC methods were not used to validate data quality. Thus, while the quality of the data used may be adequate for a useful discussion of major determinants of functionality in the study context, they are likely not equal to the quality of data typically obtained in nationally representative surveys such as USAID's Demographic and Health Surveys (DHS), UNICEF's Multiple Indicator Cluster Surveys (MICS), etc., in high-quality national censuses, or in rigorous field studies such as RCTs. While acknowledging these limitations, we believe that the data are of adequate quality for the purposes to which they are put in the present study, particularly since many of the variables used (functionality, presence of management, etc.) are relatively objective, and less subject to recall bias, socially desirable response bias, and other forms of bias and error. Comparison to future studies using BNs to model data collected in similar contexts using more rigorous methods will be of interest to validate many of the findings presented here. Additional limitations include the potential for recall bias and other biases in direct response questions, particularly those covering longer recall periods, such as failure in the past 12 months. It should be noted that these limitations do not apply to hydrogeological data (obtained from a separate high-quality source), or to geographic data such as district and distance from a population center, as these were collected via GPS, and are thus relatively objective.

A further limitation is the set of variables collected in the primary data set. While this is a relatively rich data set capable of supporting complex analysis, additional information on household and community wealth would be of interest, to enable us to control for these variables in analyses. Future studies involving primary data collection may seek to capture high-quality data on wealth and other potential confounders.

While the results of this study cover a substantial proportion of the communities and water sources in the Greater Afram Plains area, and are likely representative of that area at the time of the initial data collection, the specific quantitative findings should not be generalized to other spatial or temporal contexts. By contrast, the qualitative findings with respect to the relative importance of key determinants of water source functionality may have some applicability to similar water sources in other contexts in sub-Saharan Africa, and potentially beyond; further work is needed to determine the extent to which this is the case.

5.2. Implications

To maximize the continuity of water sources in the context of the current study, local governments and other WaSH implementers may wish to prioritize the establishment of durable and effective water source management teams with access to all necessary tools, the ability to collect adequate user tariffs and maintain savings, and to rapidly obtain the services of local mechanics. Building and maintaining these capacities may be essential to maximizing the continuity of water service in the study setting.

While rehabilitation and eventual replacement of aging sources will remain a necessity, the results of this study suggest that a new source with poor management (i.e., no WSMT, no savings, no tariff collection, and without ready access to tools, spare parts, or external support) is far less likely to provide water at any given time than a 30 year-old source with optimal management (i.e., the converse, optimistic scenario). Rehabilitating management teams and other "software" may be far less costly than rehabilitating or replacing boreholes, handpumps, and associated "hardware." Thus, governments and other WaSH implementers in the study area may be able to increase the functionality and sustainability of water sources cost-effectively by expanding their use of reliable, low-cost methods for training and regularly monitoring water source management teams as well as of borehole functionality, providing regular refresher training for management teams, ensuring access to all necessary tools and spare parts, as well as timely external support, and rehabilitating or reconstituting inactive or ineffective management teams as necessary. Furthermore, since sources in certain districts are far less likely to be functional than others, and areas with adverse hydrogeology may be more prone to functionality problems, sources in such areas should be seen as being at elevated risk of failure, and active monitoring to facilitate effective, high-quality management may be particularly important in such areas.

Water source failure is inevitable, as most sources will eventually fail due to mechanical breakdown, siltation, changing groundwater levels, and/or other determinants. Effective management teams with access to critical resources and external support may be able to more rapidly repair such failures, increasing source functionality and continuity, and contributing to efforts to achieve more continuous access to safe drinking water. Our results suggest that increased, targeted investment in ensuring the quality, longevity, support, and maintenance of these teams may increase rural handpump functionality and continuity in the GAP. Future monitoring and evaluation efforts may seek to track the determinants that are most strongly associated with water source functionality, including management team presence, activity, and quality, as well as tariff collection and access to tools and external support, with a reasonable frequency (e.g., once every 6–24 months).

In addition, it may be useful to track service quality determinants such as water source functionality and microbiological water quality (which tend to have large seasonal fluctuations in many contexts [*Kostyla et al*., 2015]) with appropriate temporal and spatial resolution (e.g., once every 6–24 months in every community), while geographic and hydrogeological determinants may be monitored with relatively lower frequency (perhaps once every 5–10 years) and reduced spatial resolution.

It should be noted that addressing the modifiable management determinants most strongly linked to functionality in the study area might be effectively accomplished by local government, national government, NGOs, or other WaSH implementers. However, the limited spatial and temporal scope of the present study makes extrapolation to the national policy level problematic, since the results of this work are not necessarily generalizable outside the study area. Further work is needed to determine the extent to which the software determinants identified in this work are key predictors of water source functionality elsewhere in Ghana, and/or elsewhere in West Africa and beyond. If such work reveals similar findings with respect to the impact of management on a larger scale, national policies and regulations that support the creation, monitoring, support, and maintenance of effective management teams may be useful tools for increasing the functionality and continuity of community water sources.

6. Conclusion

The results of this work suggest that the functionality prevalence of water sources installed in the Greater Afram Plains region is high relative to other sub-Saharan African water sources in general, and functionality prevalence was not found to decrease dramatically with age. However, increasing functionality prevalence further in this and other settings remains of great interest and importance in terms of providing continuous access to safe drinking water, and realizing the associated health, economic, social, and human rights benefits thereof. Several determinants were found to be associated with functionality in multivariable logistic regressions and/or BN analysis, including management determinants (such as the presence of identifiable management, access to tools and spare parts, savings, the collection of a tariff, and external technical support), as well as pump type, implementer, local hydrogeology and the administrative district. In the BN model, synergistic effects of management determinants were found to play a particularly large role in determining source functionality, with 97% functionality prevalence predicted when all management determinants are in their optimal states. Regular monitoring of the determinants most strongly associated with water source functionality, such as the presence and activity of a functional, high-quality water source management team that collects a tariff and has access to savings, tools, parts, and external support, may be an important step in improve the functionality and continuity of water sources in the region. Where such monitoring reveals gaps, action may be warranted to rehabilitate and retrain management teams in water source management and repair, and to provide access to critical tools and spare parts, either directly or by linking WSMTs to local vendors, as may strengthening the links between community WSMTs and external support teams. Additional work is needed to evaluate the benefits of regularly monitoring, retraining, and rehabilitating water source management teams in this way. The current study also illustrates the value of BN models for characterizing complex systems such as water sources in rural communities, in which multiple determinants may interact to affect outcomes of interest such as functionality.

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Erratum

In the originally published version of this article, the first line in Table 3 contained two errors in the columns OR and 95% CI regarding the Contrast "Failures in the past year: yes versus no." The values have been corrected to 0.4 and (0.3–0.6) respectively.