Chemical Drinking Water Quality in Ghana: Water Costs and Scope for Advanced Treatment

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Abstract

To reduce child mortality and improve health in Ghana boreholes and wells are being installed across the country by the private sector, NGOs and the Ghanaian government. Water quality is not generally monitored once a water source has been improved. Water supplies were sampled across Ghana from mostly boreholes, wells and rivers as well as some piped water from the different regions and analysed for the chemical quality. Chemical water quality was found to exceed the WHO guidelines in 38% of samples, while pH varied from 3.7 to 8.9. Excess levels of nitrate (NO_3^-) were found in 21% of the samples, manganese (Mn) and fluoride (F^-) in 11% and 6.7%, respectively. Heavy metals such as lead (Pb), arsenic (As) and uranium (U) were localised to mining areas. Elements without health based guideline values such as aluminium (Al, 95%) and chloride (Cl, 5.7%) were found above the provisional guideline value.

Economic information was gathered to identify water costs and ability to pay. Capital costs of wells and boreholes are about £1200 and £3800 respectively. The majority of installation costs are generally paid by government or NGO, while the maintenance is expected to be covered by the community. At least 58% of the communities had a water payment system in place, either an annual fee/one-off fee or “pay-as-you-fetch”. The annual fee was between £0.3-21, while the boreholes had a water collection fee of £0.07-0.7/m^3, many wells were free. Interestingly, the most expensive water (£2.9-3.5/m^3) was brought by truck. Many groundwater sources were not used due to poor chemical water quality. Considering the cost of unsuccessful borehole development, the potential for integrating suitable water treatment into the capital and maintenance costs of water sources is discussed. Additionally, many sources were not in use due to lack of water capacity, equipment malfunction or lack of economic resources to repair and maintain equipment. Those issues need to be addressed in combination with water quality, coordinated water supply provision and possible treatment to ensure sustainability of improved water resources.

Keywords: Ghana, drinking water, improved supply, chemical water quality, boreholes, wells, groundwater, cost

1. Introduction

Approximately 880 million people still lack access to safe drinking water, the lowest coverage found in sub-Saharan Africa. Waterborne diseases, such as diarrhoea, cause 1.5 million deaths a year, prominently to children in developing countries (JMP, 2008). It is estimated that child mortality and could be significantly reduced and general health improved by providing access to safe potable water and improving sanitation and hygiene (WHO, 2004). This is the compelling motivation for governments and aid organisations to avoid acute problems of waterborne diseases by constructing boreholes and wells to improve coverage of safe water sources. However, these new sources, if not adequately monitored, may instead be a source of chronic health problems due to high concentrations of inorganic contaminants such as arsenic (As), fluoride (F^-) and nitrate (NO_3^-) (Bissen and Frimmel, 2003a; Reimann and Banks, 2004)

Ghana, in West Africa, celebrated 50 years of independence from colonial rule in 2008, and is often hailed as an African economic and political success (Naylor, 2003). Yet, Ghana is still struggling to provide safe drinking water and sanitation to all its inhabitancy, especially in rural areas (UNICEF, 2007). Although Ghana is doing better than its immediate neighbours (*e.g.* Côte d'Ivoire and Togo), nearly 12% of Ghanaian children die before they reach the age of five compared to *e.g.* 6% of children in South Africa and 0.6% of children in the UK (UNICEF, 2007). Access to safe water is an important factor to reduce the number of deaths. According to JMP (2008), 29% of the rural population rely on unimproved water sources. The majority of the improved sources in rural Ghana are boreholes and protected wells.

Ghana has 10 administrative regions: Western Region, Eastern Region, Central Region, Greater Accra, Volta Region, Ashanti Region, Brong-Ahafo, Northern Region, Upper West and Upper East. The population according to the last census (2000) was 18.9 million and with a growth rate of bout 2.6% is estimated at 23 million people (UNICEF, 2007). Although most of the population growth is taking part in cities, the majority of Ghana's population still live in rural areas. Ghana's Water Policy expresses the need to both ensure access to enough safe water to meet basic human needs and at the same time ensure the environmental and financial sustainability of the water source (Government of Ghana, 2007). In an attempt to make the water delivery in the country more effective, Ghana's water supply has, amidst much controversy, been made parastatal (Agyeman, 2007). The Ministry of Water Resources, Works and Housing remains the government institution responsible for water resource management and drinking water supply, while the Ghana Water Company Ltd (GWCL) is in charge of urban water provision. The Community Waste and Sanitation Agency (CWSA) is in charge of facilitating safe water provision and providing technical assistance to the District Assemblies, who are responsible for planning and operation of the water supply to rural communities on a local level (Agyeman, 2007). The CWSA standard is one well or borehole per 300 people. The community are responsible for operation and maintenance. Regional progress reports (Government of Ghana, 2007), report 40-80% coverage depending on the region; however some organisations and individuals do not operate through the CWSA and thus the total number of improved sources is not accurately known (Nyarko *et al.*, 2009). As the boreholes are constructed, the chemical water quality should be analysed for fluoride (F^-), manganese (Mn), iron (Fe), magnesium (Mg), calcium (Ca), sulphate (SO_4^{2-}), arsenic (As), lead (Pb), copper (Cu), nitrate (NO_3^-), nitrite (NO_2^-), chloride (Cl), phosphate (PO_4^{3-}), aluminium (Al), sodium (Na), zinc (Zn) and alkalinity ($CaCO_3$). Water quality is seldom monitored once a borehole has been established due to financial and logistical constraints.

Studies on the water quality in particular problem areas in Ghana have been conducted, such as the northern parts (Pelig-Ba *et al.*, 1991; Pelig-Ba, 1998; Pelig-Ba *et al.*, 2001, 2004), along the coast (Gill, 1996) and in mining areas (Smedley, 1996; Pelig-Ba *et al.*, 2001; Ahmad *et al.*, 2004; Asante *et al.*, 2007; Buamah *et al.*, 2008; Kortatsi *et al.*, 2008b). In these mining areas, elevated concentrations of Fe, Mn, As, F^-, Pb, Hg and Cr have been found in water sources, soil and air (Kortatsi, 1994; AmonooNeizer *et al.*, 1996; Golow *et al.*, 1996; Obiri *et al.*, 2006; Kortatsi *et al.*, 2008b). Elevated concentrations of NO_3^- have also been found (Kortatsi *et al.*, 2009), but further study is needed to establish the NO_3^- distribution in Ghana (British Geological Survey, 2000). Gill (1996) reported brackish water and high concentrations of Fe, Mn, Cl and NO_3^- in boreholes and wells in the Volta and Upper and Northern regions.

The aim of this study was to gain an overview of the chemical water quality of drinking water sources in the country, particularly of "other improved" sources such as wells and boreholes through a survey of rural water supplies. The potential need for further treatment of the water is discussed in the context of current water prices and how treatment and maintenance costs could be incorporated.

2. Materials and methods

2.1. Sample collection in Ghana

A total of 230 samples were collected out of which 199 were from improved drinking water sources, mainly boreholes and wells but also some standpipes and trucked water during the 2007 rainy season (July/August) from different regions throughout Ghana. In this paper we analyze the samples from the improved drinking water sources. Where possible the name of the location, age of the water source and pump, funding agency, water charge, money collection system, maintenance arrangements and proximity of other water sources in the area were registered. Difficulties arose when trying to distinguish between boreholes and wells with hand pumps as information on the depth of the source was usually not available. However, the type of pump installed was used as an indication (see Asklund and Eldvall (2005) for a detailed discussion on this problem). Samples were collected from the source in 500 mL plastic bottles (washed three times with the sample water prior to collection), 20 mL of it filtered through a 0.45 µm syringe filter (Sartorius Minisart, non-pyrogenic CE) and stored in a 20 mL polypropylene vial. The pH of the remaining sample was checked upon collection and measured again at the end of the day as was conductivity (Multiline P4 multimeter, WTW) and turbidity (Turbidimeter TN-100, Eutech Instruments). Drinking water was likely to be exposed to the atmosphere before consumption as it was carried back in open basins and buckets and thus this reflects the pH which would be consumed. Filtered samples were stored at ambient temperature and airlifted to the UK at the completion of the data collection.

2.2. Chemical analysis

The samples were kept at 4°C and separated into two portions. One portion was acidified to pH < 2 (concentrated Aristar HNO_3) and left to equilibrate at for at least 3 days before ICP analysis. The other portion was kept untreated at 4°C for ion chromatography (IC) analysis. Laboratory blanks were prepared by using MilliQ water and treating it in the same way as the samples. Major cations (> 0.1 mg/L) were detected by inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Perkin Elmer Optima 5300 DV, USA). Cations of concentrations as low as 0.01 µg/L were analysed with inductively coupled plasma – mass spectroscopy (ICP-MS) (Agilent 7500ce, Japan). Calibrations were verified by a standard reference material (ICP Multi Element Standard Solution VI CertiPUR) and a reference water (SRM 1640). Anions were analysed using IC (Dionex, CA, USA).

3. Results and discussion

3.3. Physico-chemical water quality

The results from the chemical analysis (mean, minimum median, lower inter-quartile range (Q1), median, higher inter-quartile range (Q3) and maximum values) are displayed in Table 1. The number of samples analysed (N), the applicable WHO drinking water guidelines and the percentage of samples with concentrations out with the guideline values are also presented. The following elements do currently not have a WHO guideline value: bromium (Br), calcium (Ca), magnesium (Mg), potassium (K), sulphur (S), vanadium (V) and cobalt (Co). The following elements did not exceed the WHO guideline value in any location: cadmium (Cd), selenium (Se), Copper (Cu), zinc (Zn), cobalt (Co) and chromium (Cr). The following elements exceeded the health-based WHO guideline value in at least one location: boron (B), manganese (Mn), iron (Fe), arsenic (As), lead (Pb), uranium (U), fluoride (F^-), nitrate (NO_3^-), sulphate (SO_4^{2-}) and nickel (Ni). The most widespread parameters exceeding a health based WHO guideline, were NO_3^- (21%), Mn (11%) and F^- (6.7%). Numerous samples exceeded the recommended guidelines based on water treatment considerations or taste for Al (95%) and Cl (5.7%). Turbidity and pH were also outside the recommended range for 90% and 53% of the samples, respectively.

(Table 1)

Sampling locations which contained parameters exceeding the WHO guideline for chemical quality are shown in Figure 1. Only parameters of greatest concern are shown in this map (Fe, Mn, F^-, B, As, Pb, U, Cl and NO_3^-). It is important to note that the concentrations of the analytes are likely to be higher during the dry season (von der Heyden and New, 2004), and hence from a health aspect, the values displayed are conservative since measured during the wet season.

(Figure 1)

As can be seen in Figure 1, several water sources across the country contain concentrations of inorganic contaminants above the WHO drinking water guideline. Many of the water sources along the coast had elevated TDS, due to proximity to the sea. High concentrations of NaCl are expected to some extent due to seawater influence. Other ions such as F^-, Mn, Fe and NO_3^- were also above the WHO guideline along the coast. Further inland, a variety of elements exceeded the guideline value, in particular in the Western, Central, Ashanti and Upper East Regions, where F^- and NO_3^- concentrations exceeded the guideline. Overall 38% of the samples exceeded the health-based WHO drinking water guidelines for a minimum of one parameter. The graphs of pH, cumulative frequency versus concentration for TDS, conductivity, turbidity and the main inorganic parameters of interest are displayed in Figure 2 to 5. This shows the range of the concentrations found and the percentage of samples found within a certain concentration. The dotted lines mark the WHO drinking water guidelines, where applicable. A more detailed discussion of the individual contaminants found in the waters sources follows.

There is no health based guideline for pH, although a range of 6.5-8.5 is often used suggested because aquatic life is negatively affected below pH 6.0 (Mason, 1990). Additionally at low pH, the water is corrosive and can cause wear to equipment. About 50% of the samples fell outside the recommended pH range, with the majority being too acidic (Figure 2). Acidity is more prominent in environments with granite based rocks with low buffering capacity (Mason, 1990). Of particularly high acidity (pH 3.7) was a borehole close to the mining town Obuasi in the Ashanti Region. The borehole also had high concentrations of Al, Mn, Pb and NO_3^-, indicating contamination from mining. Other acidic waters (pH 4-5.5) were found in the Ashanti, Western and Central Region. Some had high concentrations of Al, Mn or Pb, indicating contamination from mining. These regions are also subject to much mining on both small and large scale. The Western, Central and Ashanti regions would be naturally more acidic both due to their geology (British Geological Survey, 2000) and due to forest coverage (Gill, 1996). Forests are naturally expected to be somewhat acidic, both due to the organic acids from the breakdown of organic matter and the higher precipitation they receive (Spiro and Stigliani, 1996). This same area also receives the highest rainfall in the country (1500-2200 mm/yr, compared to 700-1000 mm/yr in the northern parts and east coast) (Gill, 1996).

(Figure 2)

Turbidity does not have a health based guideline, but it is recommended that it should ideally be below 0.1 NTU for effective disinfection (World Health Organisation, 2006). Ninety percent of the samples were above this guideline (Figure 3) and the turbidity was generally highest in surface waters, although high values (up to 266 NTU) were also found in boreholes. Ghana has set a guideline for a newly drilled bore holes at 5 NTU; and about 80% of the water sources sampled complied with this value.

(Figure 3)

Conductivity is an indication of the total dissolved solids (TDS), both organic and inorganic found in the water. There is no health-based guideline. The WHO guideline value of 1200 mg/L for TDS is based on taste rather than health. High TDS may cause corrosion of equipment such as hand pumps.

3.4. Parameters of health concern

The elements analysed for in this study that exceeded a WHO health based guideline value were As, Pb, U, B, F^- and NO_3^-.

The WHO guideline value for arsenic (As) is 10 µg/L. Concentrations exceeding this guideline were found in the Ashanti Region, around Obuasi, in the north of the Volta Region and the Upper East (Figure 4). The highest As concentration was in a borehole in Bolgatanga (170 µg/L). Smedley (1996) and Kinniburgh (Smedley, 1996; Smedley and Kinniburgh, 2002) give a detailed description of As geochemistry and its mobility due to weathering conditions. As can for instance be mobilised by flooding and the reduction and mobilisation of As-containing Fe oxides, or by oxidation of arsenopyrates, which is the case in the gold mining areas of Ghana (Smedley and Kinniburgh, 2002). Similarly high As concentrations were measured by Asante (2007) in the Tarkwa gold mining region (Western Region). Bolgatanga is an active mining area, and may thus release naturally occurring As. Asante *et al.* (2007) measured As concentrations in human urine samples of inhabitants of Tarkwa, concluding that the concentrations were similar to those of concentrations found in *e.g.* Bangladesh and India, although they could not ascertain a link to drinking water. As concentrations in rivers were higher than boreholes, indicating air-borne contamination (Smedley, 1996). Kortatsi *et al.* (2008b) found that 21% of the boreholes in the Offin basin (Ashanti Region) contain As concentrations above the WHO guideline. Interestingly, Amonoo-Neizer and Amekor (1993) showed that crops grown close to Obuasi often had double As contents compared to the same crop types grown around Kumasi indicating the release of high concentrations of As in mining areas. Kortatsi (2008a) also identified a number of samples with As concentrations above the drinking water guideline in the Central, Greater Accra and Volta Region. From the results of this study, it does not appear that As is a widespread problem in Ghana, however, it is still important to monitor and regulate contamination from mining activities as very high localised concentrations occur.

(Figure 4)

High concentrations of lead (Pb), above the WHO guideline value 10 µg/L, were found in the Ashanti region, as well as on the coast. The highest concentration determined was 35 µg/L. Concentrations of Pb above the WHO guideline in wells and boreholes imply that groundwater sources are not necessarily safe from pollution from industrial activities. The high Pb concentrations found at very low pH, and south of Obuasi, indicating acid mine drainage or other mining contamination as a possible source.

Concentrations of uranium (U) above the provisional WHO guideline (15 µg/L) were found in the Central Region and the Volta Region. The Volta Region sample also had high concentrations of NO_3^- (508 mg/L, ten times the WHO guideline value), F^- (4.24 mg/L, nearly three times the guideline value) and Cl (500 mg/L, double the taste guideline value). The borehole containing most U (267 µg/L) was in the Central Region. It did not contain other chemical pollutants. Other boreholes in that area also contained U, although below the drinking water guideline value. U was previously found by Dampare (2005). Concentrations below the drinking water guideline were also found in found in the Upper East, indicating that while U might not be a widespread concern, it may be worth monitoring as it is a natural part of the geology. As well as being naturally radioactive, U is chemically toxic and when ingested may target bones or damage the kidney (The Royal Society, 2002; Kurttio *et al.*, 2005).

Boron (B) was found at levels up to 2034 µg/L (the WHO guideline value is 500 µg/L) in the Northern Region. The highest B concentrations corresponded with alkaline pH. Speciation models of the water (using Minteq 2.53, results not shown), showed B to exist mainly as boric acid (H_3BO_3) over the acidic to neutral pH range, and borate ($H_2BO_3^-$) above pH 8.5. Sources of boron include seawater (unlikely in this situation), coal burning and industrial sources as well as borate-containing fertilizers, which may be the most likely source in this case as there is agricultural activity in the region.

About 6.7% of the samples contained fluoride (F^-) concentrations above the WHO guideline value (1.5 mg/L) (Figure 4). High concentrations of F^- were found in the north, but also in many locations along the coast, mainly in wells and boreholes. In the Upper East about 17% of the samples contained F^- concentrations above the guideline. Boreholes near the coast in the Volta Region contained F^- concentrations of above 4 mg/L, which can cause skeletal fluorosis. Kortatsi (2008b) also found F^- concentrations of 11 mg/L in the Offin Basin (Ashanti Region).

(Figure 5)

Nitrate (NO_3^-) has a WHO guideline value of 50 mg/L and exceeded this concentration in 21% of the samples (Figure 5). The highest concentration was 508 mg/L. The locations were widespread but mostly found in the Western, Ashanti, southern Volta, Northern region and Upper East. NO_3^- is regulated as it is one of the causes of methaemoglobinaemia (or "blue-baby syndrome") in infants (Manassaram *et al.*, 2006) as well as a potential risk of stomach cancer (Abrahams, 2002). Forty-seven percent of the well waters had concentrations above the guideline, compared to 16% of the borehole waters (Figure 6). The concentrations of NO_3^- were also higher in wells than in surface water (results not shown). This indicates a widespread problem of elevated NO_3^- in shallow groundwater –probably a result of poor sanitation and latrine construction (MacDonald and Calow, 2009). High levels can also be caused by fertilizer use. The results of Pelig-Ba (2004) confirm those of this study and report a mean of 93.3 mg/L of NO_3^- and a maximum of 511 mg/L in groundwater in the Upper West. The WHO guideline value for nitrite (NO_2^{2-}) is 0.2 mg/L. Unfortunately NO_2^{2-} needs to be determined within 48 hours, which was not possible due to the logistics. Thus the NO_3^- values reported in this paper, include any NO_2^{2-} which may have been originally present.

(Figure 6)

3.5. Aesthetic parameters

Parameters analysed for in this study with non-*health* based WHO guidelines were Al, Fe, Mn, Cl and SO_4^{2-}. Despite not being a health concern, high concentrations affect the quality of water, leading to bad taste and colouration of cooking utensils and food. This has caused hundreds of wells to be abandoned in favour of surface waters likely contaminated with harmful micro-organisms (Smedley, 1996; Gyau-Boakye and Dapaah-Siakwan, 1999).

The most widespread pollutant was aluminium (Al). The health effects from Al remain unclear, however, Al does have a practicable non-health based WHO guideline value of 0.2 mg/L (stated as an achievable level for small water treatment facilities. This takes into consideration the health concerns but also the benefits from using Al in water treatment (World Health Organisation, 2006)). Ninety-five percent of the samples measured were above the recommended guideline value (Figure 5), several more than ten-fold, with the maximum concentration at 67 mg/L. Areas of particularly high Al concentration were in the Volta Region (regional average of 27 mg/L) where Nkwanta district, Asuogyaman, Hohoe, Keta and Ketu districts had especially high concentrations (average of 30, 42, 28, 55 and 44 mg/L respectively). The Western Region also had locations containing high Al concentrations, with an average of 13 mg/L in the Wassa West district. Al may leach from soils unable to buffer acidic precipitation and from minerals such as kaolinite and gibbsite (Langmuir, 1997). Some researchers find high Al concentrations in association with particles (Reimann *et al.*, 2003), in our study however, Al showed no correlation with turbidity. Al concentrations were found to be highest around neutral pH, where Al normally is less soluble. The high Al in the samples may possibly be associated with colloids smaller than the 0.45 μm filter. Pelig-Ba (2004) also found higher Al concentrations in water at neutral pH and explained it by presence of chelating agents such as soil organic matter raising the Al solubility. In Pelig-Ba's study from the Upper Regions (1998) the Al range was reported as up to 47 mg/L, with a mean of 4.4 mg/L in the Northern Region.

A number of samples had very high sulphate (SO_4^{2-}) concentrations (>500 mg/L) (Figure 5). One was found in a relatively new borehole in the Northern Region, probably due to mudstone geology. In this sample high Mn concentrations were also found. Due to the taste, consumers preferred to drink water from the nearby shallow well, which contained low SO_4^{2-} and Mn concentrations but possible microbiological contamination. This illustrates how poor chemical water quality of new deeper groundwater sources may drive people back to shallow contaminated sources. Another borehole from the same region contained similar SO_4^{2-} and TDS levels, but no Mn, and people were happy to drink the water.

Around 5.7% of the waters sampled contain more chloride (Cl) than the recommended value (250 mg/L) (Figure 5). This value is based on taste, but waters of these Cl concentrations are also more corrosive. As can be seen from the map in Figure 1, much of the high Cl concentrations are found in the Volta delta and along the coast. Gill *et al.* (1996) also reported high Cl concentrations in the Keta district and found similar evidence of seawater intrusion. A study conducted by Kortatsi (2006) in the Accra plains similarly found high concentrations of Cl and concluded that 75% of the boreholes in the area were brackish (TDS range 1000-10000 mg/L), with Na and Cl as the dominating ions.

Iron (Fe) concentrations below 2000 µg/L are described as safe by the WHO (Figure 4), although taste is affected above 300 µg/L. This taste based value is used by many studies when reporting Fe. Up to 4257 µg/L was measured. As can be seen from the map (Figure 1), high Fe concentrations were found in a variety of locations along the coast, inland in forested areas and the Northern Region. Most samples (97.4%) fall below 300 µg/L and 99% are below the guideline value 2000 µg/L (Figure 4). Most of the sources containing very high Fe concentrations were found in boreholes. The chemistry of naturally occuring Fe is controlled by the redox conditions of the water (not measured due to lack of equipment), where Fe is mobilised under reducing conditions, indicating that the environment of these boreholes was reducing.

Concentrations of manganese (Mn) above the WHO drinking water guideline value (400 µg/L) were found mainly the Western and Ashanti region and along the coast (Figure 1). The highest concentrations were found in boreholes (Figure 6). Similarly to Fe, Mn chemistry is also redox controlled. High concentrations of Fe and Mn corresponded in some samples, but for the majority of them high Mn concentrations were not accompanied by high Fe concentrations.

High concentrations of calcium (Ca), magnesium (Mg) and potassium (K) (Figure 5) are generally not a health concern and thus do not have guideline values set by the WHO, but are important nutrients. Studies have shown an inverse relationship between cardiovascular disease and water hardness, with increased risk occurring with Ca concentrations <60mg/L of Ca (Packham, 1990). In fact the water sources in Ghana were relatively soft and the concentrations of the samples in the third percentile were below 15 mg/L for Mg and 40 mg/L for Ca (Table 1). In large concentrations however, they may affect the taste of the water by contributing to high TDS, which will also affect practical water usage (washing with soap).

In summary, the water quality from the different sources in Ghana displayed a wide range of chemical water quality, with many sources containing concentrations above the drinking water guidelines. In boreholes high concentrations of NO_3^-, F^-, B, Pb, As, U, Cl, Fe, Mn and SO_4^{2-}, and high levels turbidity were found. In wells NO_3^-, Fe and turbidity were common problems, as well as some instances of As, Mn, Cl and F^-.

3.6. Current rural water sources, costs and ability to pay

The Ghana Water Policy advocates provision of demand driven basic water and sanitation services for communities that contribute towards capital cost, operation, maintenance and repairs (Government of

Ghana, 2007). Non-government organisations often support the communities by paying up to 95% of the borehole cost, while the community raises 5% of the borehole cost (Government of Ghana, 2007).

About 25% of the communities visited had an annual user fee per household ranging from 5000 to 40000 cedis (£0.3-£21, August 2007). About 33% of the water supplies had a water collection charge based on quantity of water collected (Figure 7). Surface and many well waters were often free of charge while boreholes, piped and especially truck-delivered water attracted the highest charges. The cost per bucket (18L) for boreholes and piped water ranged from 25 to 250 cedis (£0.07 to £0.7/m^3, based on 62 communities) and the cost per basin (40L) ranged from 50 to 500 cedis (£0.07 to £0.7/m^3, based on 47 communities). Where water was trucked in, the cost was 1000-1200 cedis per bucket (£2.9-3.5/m^3, based on two communities). An appointed water vendor from the WatSan committee was often situated at the water source to directly collect the payment from the users. Understandably some households choose to use cheaper or free water sources for washing and bathing, increasing the risk of contact with diseases transmitted by surface water. Surface water is often used during the rainy season due to availability while in dry seasons they may be used if borehole re-charge is low (Iten and McCarron, 2006). 13% of the communities visited did not have an operational payment system in place. Many communities were therefore struggling to raise between 1.5-2.5 million cedis (about £80-£130) in order to pay for repairs or spare parts of pumps, broken a couple of years earlier. When this proved to be a major hurdle and pumps would remain disused or even abandoned. Another problem encountered in some communities was that there was no payment system for the trained community members to get paid for maintenance services, which meant that they were unwilling to assist. Organising maintenance and collecting payment for repairs is further complicated by the dynamic movement of people between different communities and even parts of the country (Iten and McCarron, 2006). In some cases pumps were ill designed, causing unaffordable chronic failure of parts.

(Figure 7)

3.7. Is water treatment a suitable option for sources of poor chemical quality?

The problems encountered in the survey were those of high turbidity, high concentrations of F^-, NO_3^-, Al, Mn, Fe and localised contamination of Pb, As, B and U. Overall, 38% of the sources analysed exceeded a *health*-based WHO guideline for chemical parameters. Installation costs of boreholes and wells are about £3800 and £1800, respectively. Many boreholes fail due to the high chemical content of for example F^- (Smedley *et al.*, 2002) and up to 64% of the boreholes in the north of Ghana fail based on water flow, re-charge and chemical quality (Iten and McCarron, 2006). Thus for the actual costs of developing ground water the number of unsuccessful boreholes drilled need to be taken into account. To reduce this cost in areas of complex geology, investment in initial hydrogeological investigations is important to improve success (MacDonald and Calow, 2009). An alternative option to capping existing boreholes and drilling new, potentially unsuccessful boreholes would be to treat the water. Suitable treatment options in developing countries can be provided as centralised, community based or point-of-use/household based approaches. For economic and infrastructural reasons, community based or point-of-use treatments are considered preferable to centralised treatment for rural communities (Peter-Varbanets *et al.*, 2009). This also applies to rural areas of Ghana where boreholes or wells may already exist while access to a centralised supply does not. Treatment technologies considered suitable for developing countries, such as sand filtration, UV disinfection (SODIS), ceramic filters and chlorination mainly remove or destroy microbial pathogens and turbidity (Sobsey *et al.*, 2008; Peter-Varbanets *et al.*, 2009) and could potentially be used to disinfect surface waters of good chemical quality, but do not effectively remove chemical contaminants. Importantly, over 90% of the samples had a turbidity of more than 0.1 NTU, which must be reduced before disinfection can be effective.

Treatment methods which target chemical contaminants combine processes such as adsorption or coagulation with ultrafiltration or sandfiltration processes (Brandhuber and Amy, 2001; Johnston and Heijnen, 2001; Chakravarty *et al.*, 2002). Issues of handling, cost of chemicals, sanitation and regeneration of the adsorption materials are a concern. Ultrafiltration systems are available at an investment cost of about £2000 (20 m^3/day capacity), and are maintained by a daily washing. Low-cost As removal for communities in developing countries have been investigated (Bissen and Frimmel, 2003b; Malik *et al.*, 2009) and wells can even be constructed to allow re-circulation of oxidised water back into the source, thus oxidising and immobilising Fe and As before it is with-drawn (van Halem et al., 2009). This method still requires further development and testing, however, and the resulting concentrations depend on concentrations originally present. The need to remove a variety of chemical contaminants from existing water sources persists and long-term studies are lacking. The issue of F^- removal from drinking water in the northern regions of Ghana, for example, is unresolved (CWSA, 2007). In such situations membrane technologies have unique potential due to their physical separation. Nanofiltration or reverse osmosis are well adapted in developed countries for water desalination, reuse and removal of dissolved contaminants while application in developing countries has not yet widely progressed. Investment cost into single tap reverse osmosis has been estimated to £190-£380 (Peter-Varbanets *et al.*, 2009) which may be an option if it could be developed for boreholes. A solar powered community-based membrane system was field tested by Schäfer *et al.* (2007) and found to perform well in terms of potable water production. The system had a specific energy consumption of 1.2 kWh/m^3. Investment and maintenance costs into a solar powered electrodialysis systems have been calculated as £0.15-0.28/m^3, with an initial investment of at least £5400 (Ortiz *et al.*, 2008). However, the long-term integration of operation and maintenance of such systems into communities requires solid strategies at a local level.

3.8. Sustainability of treatment systems

The effectiveness and sustainability of point-of-use and small-scale water treatment technology remains to be seen as contentious (see for example Hunter (in press), Hunter *et al.* (2009) and Schmidt and Cairncross (in press)). Three components of sustainability for engineered solutions in developing countries were identified by Montgomery *et al.* (2009) as 1) effective community demand, 2) local financing and cost recovery, and 3) dynamic operation and maintenance. The importance of local ownership of both the technology development (local sourcing and production) as well as the resulting systems should be emphasized. Failure to incorporate these components into a water source and potential water treatment reduce the likelihood of its long-term functionality. Cost recovery of five community managed water systems in the Ashanti Region was investigated by Nyarko *et al.* (2007), who found that neither of the communities recovered their full capital and operational costs, while four out of five recovered their operation and maintenance costs. Interview results showed that there was not an understanding amongst the community members of the full costs involved, while some preferred to use free untreated water sources when the prices were too high. The importance of demand-driven appropriate water treatment was high-lighted in a study by Hoque *et al.* (2004). They found that household treatment systems often were abandoned after a short period, while community based systems proved more sustainable. For this reason it is important to understand the willingness (and ability) to pay for water provision in such communities as well as elucidating the most suitable treatment option.

4. Conclusions

It was found in this study that 38% of the wells and boreholes in Ghana had high concentrations of inorganic contaminants. Major problems identified were that of high turbidity, low pH, high concentrations of NO_3^-, F^-, Al and Cl and in localised areas As, Pb, B and U. The importance of regular monitoring of groundwater sources is emphasized. While some 'low-cost' treatment technologies to remove, for instance, As and F^- exist, the long-term sustainability and management of such technologies is yet to be proven for a wide range of chemical contaminants and how performance (in particular contaminant breakthrough) can be monitored. The maintenance costs of systems could potentially be incorporated in the maintenance costs currently paid by community members (up to £0.7/m^3), especially if government and NGO's were willing to invest in the capital costs. This could be worthwhile, considering the cost of unsuccessful boreholes. About 58% of the communities had a payment system in place to recover basic maintenance costs.

In areas of high chemical contamination more advanced inorganic removal treatment such as nanofiltration and reverse osmosis may be necessary. This would require extensive training in operation and maintenance, but while initial investment would increase, it may facilitate maintenance and potentially reduce long-term costs in particular if renewable energy is used as a power supply. Given that renewable energy powered ground water pumps are rapidly penetrating the market and water charges for trucked water is comparable to membrane treatment costs this is a most viable option. Any form of improved water supply requires community ownership and commitment by local and national authorities to ensure that long-term needs are met. Research into ensuring long-term sustainability in terms of community demand, cost recovery, failure management, maintenance of water sources and treatment needed is timely and of critical importance.

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References

Abrahams PW. Soils: their implications to human health. Sci Total Environ 2002; 291: 1-32.

Agyeman K. Privatization of water in Ghana: stopped in its tracks or a strategic pause? Int J Environ Stud 2007; 64: 525-536.

Ahmad K, Dampare SB, Adomako D, Opata NN, Quagraine RE. The use of neutron activation analysis in gold prospecting in small-scale mining in Ghana. J Radioanal Nucl Chem 2004; 260: 653-658.

AmonooNeizer EH, Amekor EMK. Determination of Total Arsenic in Environmental-Samples from Kumasi and Obuasi, Ghana. Environ Health Perspect 1993; 101: 46-49.

AmonooNeizer EH, Nyamah D, Bakiamoh SB. Mercury and arsenic pollution in soil and biological samples around the mining town of Obuasi, Ghana. Water Air Soil Pollut 1996; 91: 363-373.

Asante KA, Agusa T, Subramanian A, Ansa-Asare OD, Biney CA, Tanabe S. Contamination status of arsenic and other trace elements in drinking water and residents from Tarkwa, a historic mining township in Ghana. Chemosphere 2007; 66: 1513-1522.

Asklund R, Eldvall B. Contamination of water resources in Tarkwa mining area of Ghana. Department of Engineering Geology 2005; M.Sc.: 57.

Bissen M, Frimmel FH. Arsenic - a review. - Part 1: Occurrence, toxicity, speciation, mobility. Acta Hydroch Hydrob 2003a; 31: 9-18.

Bissen M, Frimmel FH. Arsenic - a review. Part II: Oxidation of arsenic and its removal in water treatment. Acta Hydroch Hydrob 2003b; 31: 97-107.

Brandhuber P, Amy G. Arsenic removal by a charged ultrafiltration membrane-influences of membrane operating conditions and water quality on arsenic rejection. Desalination 2001; 140: 1-14.

British Geological Survey. 2000. Groundwater quality: Ghana. www.bgs.ac.uk/downloads/start.cfm?id=1281, 2009, November

Buamah R, Petrusevski B, Schippers JC. Presence of arsenic, iron and manganese in groundwater within the gold-belt zone of Ghana. Journal of Water Supply Research and Technology-Aqua 2008; 57: 519-529.

Chakravarty S, Dureja V, Bhattacharyya G, Maity S, Bhattacharjee S. Removal of arsenic from groundwater using low cost ferruginous manganese ore. Water Research 2002; 36: 625-632.

CWSA. Summary of the fluoride issues in the northern region, 2007.

Dampare SB, Nyarko BJB, Osae S, Akaho EHK, Asiedu DK, Serfor-Armah Y, et al. Simultaneous determination of tantalum, niobium, thorium and uranium in placer columbite-tantalite deposits from the Akim Oda District of Ghana by epithermal instrumental neutron activation analysis. J Radioanal Nucl Chem 2005; 265: 53-59.

Gill HE. A groundwater Reconnaissance of the Republic of Ghana, with description of geohydrolic provinces. US Geol Surv Water Supply Pap 1996; 1757-k.

Golow AA, Schlueter A, AmihereMensah S, Granson HLK, Tetteh MS. Distribution of arsenic and sulphate in the vicinity of Ashanti Goldmine at Obuasi, Ghana. Bull Environ Contam Toxicol 1996; 56: 703-710.

Government of Ghana. National Water Policy. In: Ministry of Water Resources WaH, editor, 2007.

Gyau-Boakye P, Dapaah-Siakwan S. Groundwater: Solution to Ghana's Rural Water Supply Industry? the Ghana Engineer 1999; May.

Hoque BA, Hoque MM, Ahmed T, Islam S, Azad AK, Ali N, et al. Demand-based water options for arsenic mitigation: an experience from rural Bangladesh. Public Health 2004; 118: 70-77.

Hunter PR. Household water treatment in developing countries: comparing different intervention types using meta-regression. Environ. Sci. Technol. in press.

Hunter PR, Zmirou-Navier D, Hartemann P. Estimating the impact on health of poor reliability of drinking water interventions in developing countries. Sci Total Environ 2009; 407: 2621-2624.

Iten S, McCarron P. Buried in Boreholes. Department of Environment, Technology and Social Studies 2006; M.Sc. Technological and Socio-Economic Planning: 306.

JMP. Progress on drinking water and sanitation: special focus on sanitation WHO, Geneva and UNICEF, New York, World Health Organisation and United Nations Childre's Fund Joint Monitoring Programme for Water Supply and Sanitation (JMP), 2008.

Johnston R, Heijnen H. Safe water technology for arsenic removal. International workshop on technologies for arsenic removal from drinking water, Bangladesh University of Engineering and Technology, Dhaka, India, 2001.

Kortatsi BK. Groundwater Utilization in Ghana. Future Groundwater Resources at Risk 1994: 149-156.

Kortatsi BK. Hydrochemical characterization of groundwater in the Accra plains of Ghana. Environ Geol 2006; 50: 299-311.

Kortatsi BK, Anku YSA, Anornu GK. Characterization and appraisal of facets influencing geochemistry of groundwater in the Kulpawn sub-basin of the White Volta Basin, Ghana. Environ Geol 2009; 58: 1349-1359.

Kortatsi BK, Asigbe J, Dartey GA, Tay CK, Anornu G, Hayford E. Reconnaissance survey of arsenic concentration in groundwater in south-eastern Ghana. West Afr J Appl Ecol 2008a; 13.

Kortatsi BK, Tay CK, Anornu G, Hayford E, Dartey GA. Hydrogeochemical evaluation of groundwater in the lower Offin basin, Ghana. Environ Geol 2008b; 53: 1651-1662.

Kurttio P, Komulainen H, Leino A, Salonen L, Auvinen A, Saha H. Bone as a possible target of chemical toxicity of natural uranium in drinking water. Environ Health Perspect 2005; 113: 68-72.

Langmuir D. Aqueous Environmental Geochemistry. Upper Saddle River, Prentice Hall, 1997, 600.

MacDonald AM, Calow RC. Developing groundwater for secure rural water supplies in Africa. Desalination 2009; 248: 546-556.
Malik AH, Khan ZM, Mahmood Q, Nasreen S, Bhatti ZA. Perspectives of low cost arsenic remediation of drinking water in Pakistan and other countries. J Hazard Mater 2009; 168: 1-12.
Manassaram DM, Backer LC, Moll DM. A review of nitrates in drinking water: Maternal exposure and adverse reproductive and developmental outcomes. Environ Health Perspect 2006; 114: 320-327.
Mason CF. Biological aspects of freshwater pollution. In: Harrison RM, editor. Pollution: causes, effects and control. the Royal Society of Chemistry, Cambridge, 1990, pp. 108-111.
Montgomery MA, Bartram J, Elimelech M. Increasing Functional Sustainability of Water and Sanitation Supplies in Rural Sub-Saharan Africa. Environ Eng Sci 2009; 26: 1017-1023.
Naylor R. Ghana An Oxfam Country Profile. Oxford, Oxfam, 2003.
Nyarko KB, Awuah E, Ofori D. Local initiative in community water supply: Case study in Ashanti Region, Ghana. Desalination 2009; 248: 650-657.
Nyarko KB, Oduro-Kwarteng S, Adama I. Cost recovery of community-managed piped water systems in Ashanti region, Ghana. Water and Environment Journal 2007; 21: 92-99.
Obiri S, Dodoo DK, Okai-Sam F, Essumang DK. Cancer health risk assessment of exposure to arsenic by workers of AngloGold Ashanti-Obuasi gold mine. Bull Environ Contam Toxicol 2006; 76: 195-201.
Ortiz JM, Exposito E, Gallud F, Garcia-Garcia V, Montiel V, Aldaz A. Desalination of underground brackish waters using an electrodialysis system powered directly by photovoltaic energy. Solar Energy Materials and Solar Cells 2008; 92: 1677-1688.
Packham RF. Water quality and health. In: Harrison RM, editor. Pollution: causes, effects and control. the Royal Society of Chemistry, Cambridge, 1990, pp. 83-97.
Pelig-Ba KB. Trace elements in groundwater from some crystalline rocks in the Upper Regions of Ghana. Water Air Soil Pollut 1998; 103: 71-89.
Pelig-Ba KB, Biney CA, Antwi LA. Trace-Metal Concentrations in Borehole Waters from the Upper Regions and the Accra Plains of Ghana. Water Air Soil Pollut 1991; 59: 333-345.
Pelig-Ba KB, Parker A, Price M. Elemental contamination of rainwater by airborne dust in Tamale Township area of the northern region of Ghana. Environ Geochem Health 2001; 23: 333-346.
Pelig-Ba KB, Parker A, Price M. Trace element geochemistry from the Birrimian metasediments of the Northern Region of Ghana. Water Air Soil Pollut 2004; 153: 69-93.
Peter-Varbanets M, Zurbruegg C, Swartz C, Pronk W. Decentralized systems for potable water and the potential of membrane technology. Water Research 2009; 43: 245-265.
Reimann C, Banks D. Setting action levels for drinking water: Are we protecting our health or our economy (or our backs!)? Sci Total Environ 2004; 332: 13-21.
Reimann C, Bjorvatn K, Frengstad B, Melaku Z, Tekle-Haimanot R, Siewers U. Drinking water quality in the Ethiopian section of the East African Rift Valley I - data and health aspects. Sci Total Environ 2003; 311: 65-80.
Schäfer AI, Broeckmann A, Richards BS. Renewable energy powered membrane technology 1. development and characterisation of a photovoltaic hybrid membrane system. Environmental Science and Technology 2007; 41: 998-1003.
Schmidt W-P, Cairncross S. Household water treatment in poor populations: Is there enough evidence for scaling up now? Environ. Sci. Technol. in press.
Smedley PL. Arsenic in rural groundwater in Ghana. J Afr Earth Sci 1996; 22: 459-470.
Smedley PL, Kinniburgh DG. A review of the source, behaviour and distribution of arsenic in natural waters. Appl Geochem 2002; 17: 517-568.
Smedley PL, Nkotagu H, Pelig-Ba KB, MacDonald AM, Tyler-Whittle R, Whitehead EJ, et al. Fluoride in groundwater from high-fluoride areas of Ghana and Tanzania ‘Minimising fluoride

in drinking water in problem aquifers' R8033. Phase I Final Report. Keyworth, Nottingham, British Geological Survey 2002, 1-72.

Sobsey MD, Stauber CE, Casanova LM, Brown JM, Elliott MA. Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. Environmental Science & Technology 2008; 42: 4261-4267.

Spiro TG, Stigliani WM. Chemistry of the Environment. Upper Saddle River, New Jersey, Prentice Hall, 1996.

The Royal Society. The health effects of depleted uranium munitions: a summary. Journal of Radiological Protection 2002; 22: 131-139.

UNICEF. The State of the World's Children 2008: Child Survival. New York, USA, 2007.

van Halem D, Heijman SGJ, Amy GL, van Dijk JC. Subsurface arsenic removal for small-scale application in developing countries. Desalination 2009; 248: 241-248.

von der Heyden CJ, New MG. Groundwater pollution on the Zambian Copperbelt: deciphering the source and the risk. Sci Total Environ 2004; 327: 17-30.

WHO. Guidelines for Drinking Water Quality, 2004.

World Health Organisation. Guidelines for drinking water quality: first addendum to third edition. Geneva, 2006, 515.

Table 1 Distribution of measured parameters in the samples. The minimum, mean, maximum and median values are given along with the WHO guideline values and the percentage of samples which exceeded the guideline value.

Parameter	Unit	N	Mean	Min	Q1	Median	Q3	Max	WHO guide-line	% outwith guide-line
Al	mg/L	192	11.87	<0.020	**3.927**	**8.500**	**14.60**	**66.69**	0.2*	95
As	µg/L	195	1.930	<0.003	<0.003	0.073	0.532	**169.5**	10	0.5
B	µg/L	195	61.11	<2.551	5.820	10.08	27.14	**2034**	500	2.6
Br	mg/L	193	0.029	<0.200	<0.200	<0.200	<0.200	1.116	-	-
Ca	mg/L	192	28.59	0.091	10.411	19.70	39.61	169.4	-	-
Cd	µg/L	195	0.025	<0.001	<0.001	<0.001	0.013	1.755	3	-
Cl	mg/L	193	49.44	<0.200	3.711	13.27	41.22	**597.2**	250*	5.7
Co	µg/L	195	0.262	<0.051	<0.051	<0.051	0.077	11.62	-	-
Cr	µg/L	195	0.199	<0.068	<0.068	<0.068	0.151	9.290	50	-
Cu	µg/L	195	2.774	<0.173	<0.173	<0.173	0.715	83.10	2000	-
F^-	mg/L	193	0.470	<0.100	0.044	0.209	0.45	**4.238**	1.5	6.7
Fe	µg/L	195	84.73	<0.001	5.446	17.78	46.16	**4257**	2000[a] (300*)	1.0 (2.6)
K	mg/L	187	4.382	0.241	1.475	2.564	5.511	29.65	-	-
Mg	mg/L	192	10.52	<0.030	2.586	6.459	14.55	66.20	-	-
Mn	µg/L	195	134.8	0.030	4.447	19.21	117.9	**2051**	400	11
Ni	µg/L	195	0.579	<0.054	<0.054	<0.054	0.436	**29.59**	20	0.5
NO_3^-	mg/L	193	34.01	<0.200	0.514	6.394	31.52	**507.7**	50	21
Pb	µg/L	195	1.526	<0.006	0.489	0.946	1.517	**34.94**	10	1.5
PO_4^{2-}	mg/L	193	0.058	<0.100	<0.10	<0.100	<0.100	1.214	-	-
S	mg/L	192	6.905	<0.200	0.372	1.150	4.091	235.4	-	-
Se	µg/L	195	0.434	<0.306	<0.306	<0.306	0.598	6.175	10	
SO_4^{2-}	mg/L	193	34.69	<0.200	1.648	5.236	23.75	**931.4**	500[b]	1.0
U	µg/L	195	1.988	<0.001	0.049	0.114	0.410	**266.6**	15	1.0
V	µg/L	195	2.380	<0.011	<0.011	<0.011	0.891	45.37	-	-
Zn	µg/L	195	9.305	<1.591	<1.591	<1.591	<1.591	454.8	3000	-
Conduc-tivity	µS/cm	199	457.1	15.00	178.0	314.0	549.0	2280	-	-
TDS	mg/L	198	176.2	4.963	51.77	98.42	178.2	**1454**	1200*	1.0
Turbidity	NTU	199	14.30	0	**0.237**	**0.793**	**3.303**	**629.7**	0.1*	90
pH		199	**6.32**	**3.69**	**5.67**	**6.43**	6.98	**8.88**	6.5-8.5*	53

*Recommendation based on aesthetic considerations such as taste and colour.

[a]Taste is often affected (at 300 µg/L) before WHO health guideline is reached, which is why many prefer to use the taste guideline value.

[b]No health based guideline value is set, however values less than 500 mg/L are recommended due to damage to gastrointestinal effects.

List of Figures

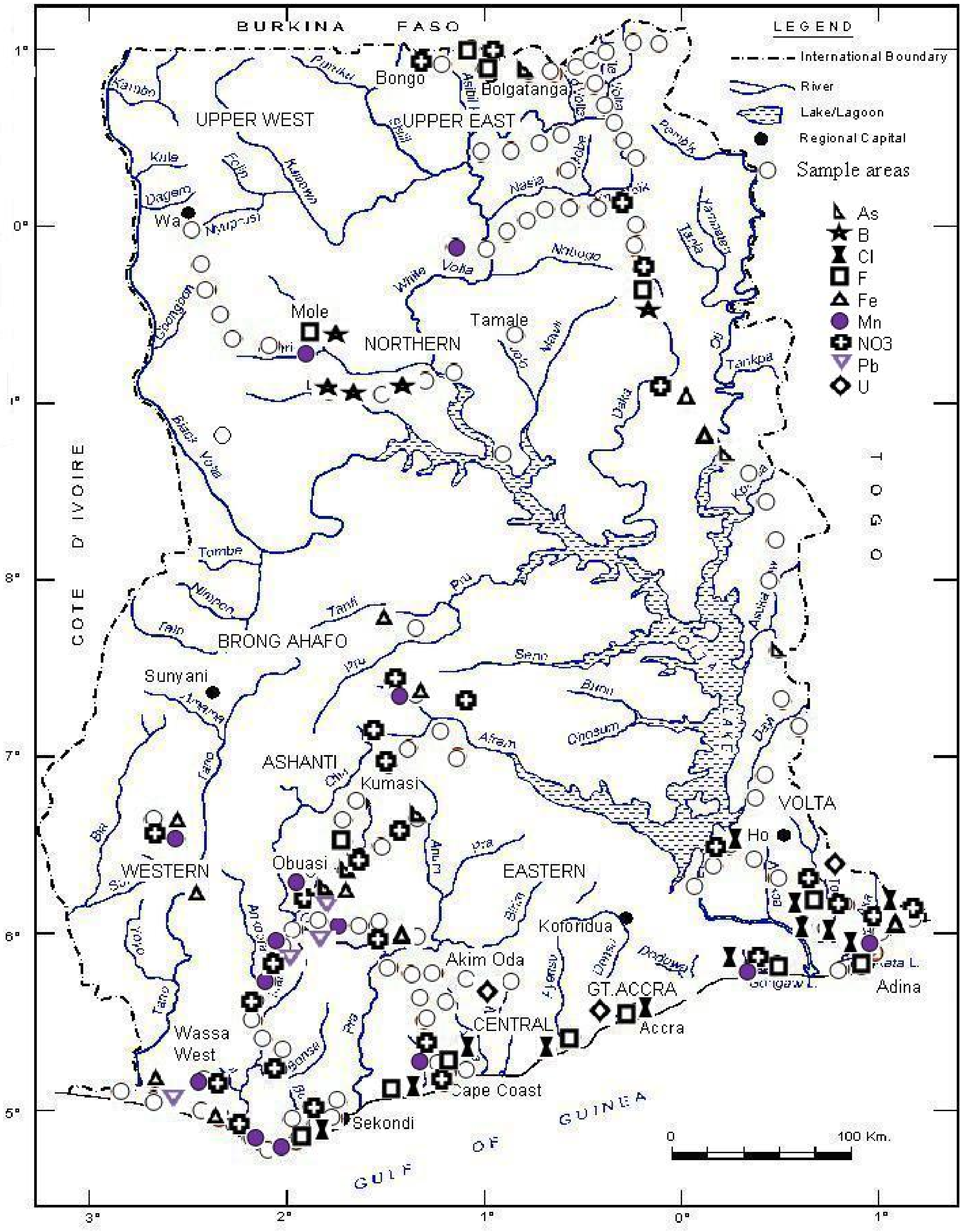

BURKINA FASO
LEGEND
International Boundary
River
Lake/Lagoon
Regional Capital
Sample areas
As
B
Cl
F
Fe
Mn
NO3
Pb
U
UPPER WEST
UPPER EAST
NORTHERN
BRONG AHAFO
ASHANTI
WESTERN
EASTERN
CENTRAL
GT.ACCRA
VOLTA
COTE D' IVOIRE
TOGO
GULF OF GUINEA
Bongo
Bolgatanga
Wa
Mole
Tamale
Sunyani
Kumasi
Obuasi
Koforidua
Akim Oda
Accra
Ho
Adina
Wassa West
Cape Coast
Sekondi
0
100 Km.
3°
2°
1°
0°
1°
5°
6°
7°
8°

Figure 1

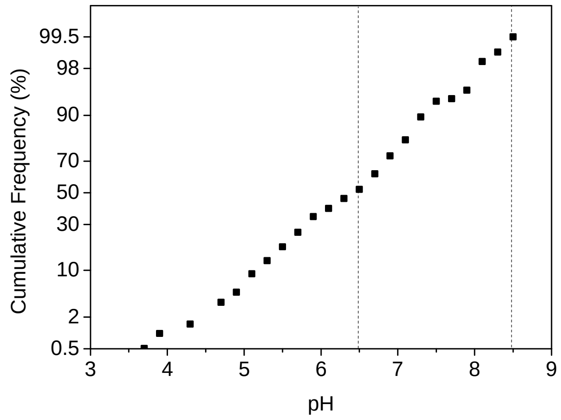


Figure 2

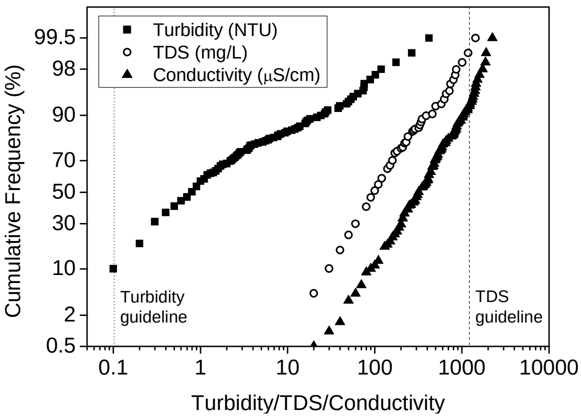
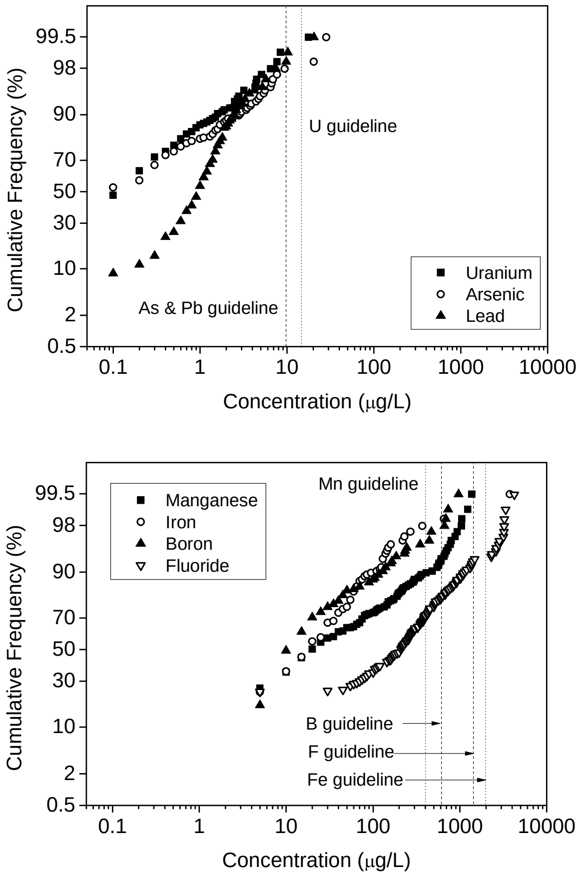

Turbidity (NTU)
TDS (mg/L)
Conductivity (μS/cm)
Cumulative Frequency (%)
99.5
98
90
70
50
30
10
2
0.5
Turbidity
guideline
TDS
guideline
0.1
1
10
100
1000
10000
Turbidity/TDS/Conductivity

Figure 3



689
690 Figure 4

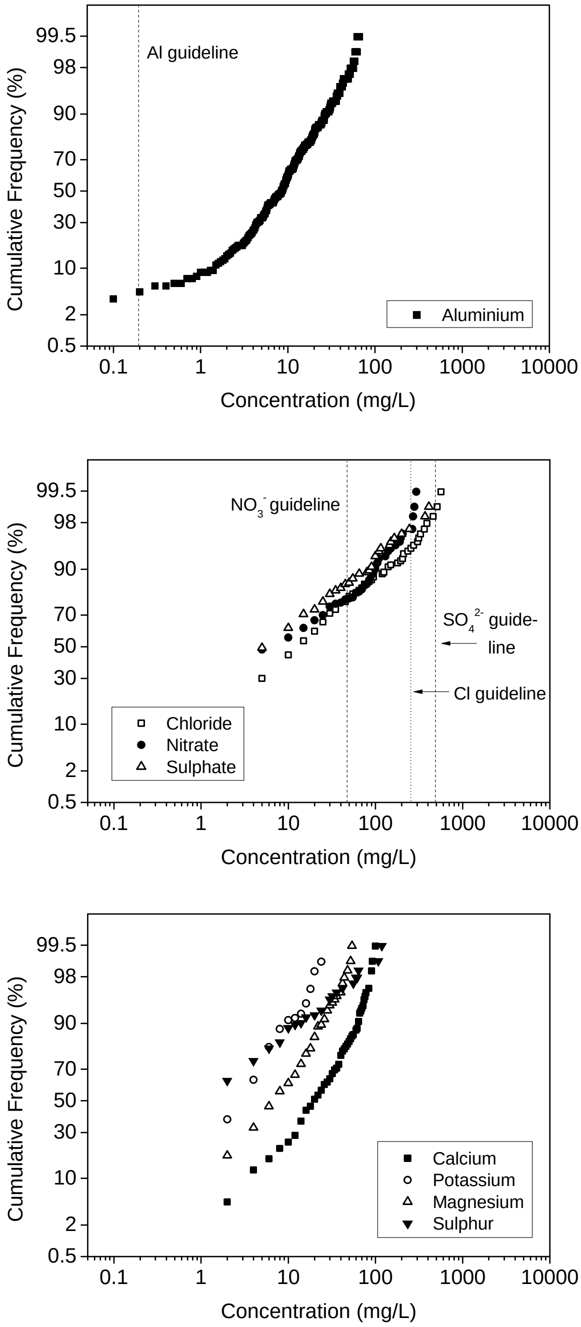

Al guideline
Aluminium
Cumulative Frequency (%)
Concentration (mg/L)
NO3- guideline
SO42- guide-line
Cl guideline
Chloride
Nitrate
Sulphate
Calcium
Potassium
Magnesium
Sulphur

Figure 5

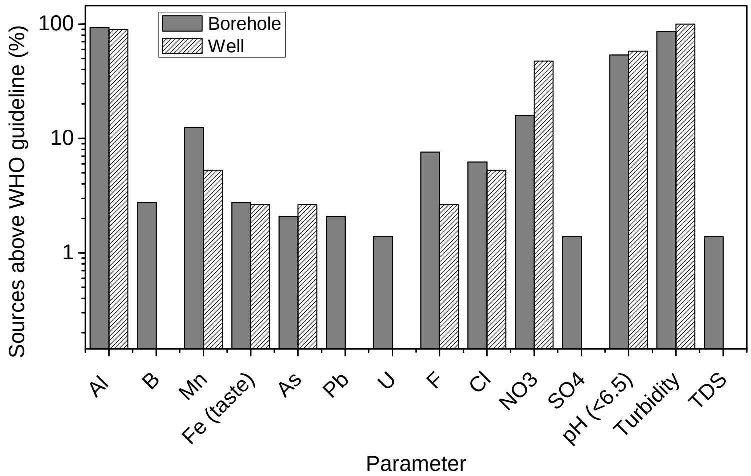

Borehole
Well
Sources above WHO guideline (%)
100
10
1
Al
B
Mn
Fe (taste)
As
Pb
U
F
Cl
NO3
SO4
pH (<6.5)
Turbidity
TDS
Parameter

Figure 6

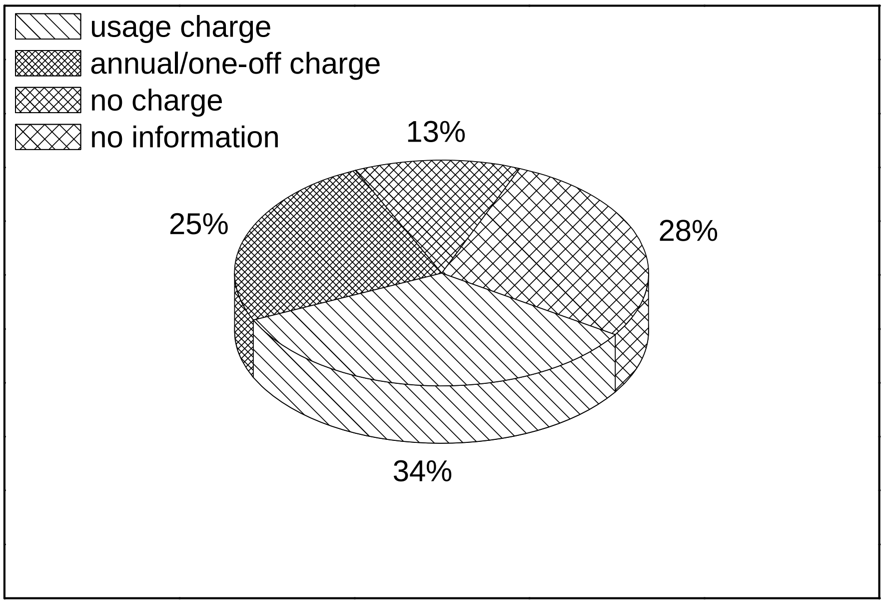

usage charge
annual/one-off charge
no charge
no information
13%
25%
28%
34%

Figure 7