

Final author submission:

Science of the Total Environment 408 (2010) 2378–2386

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22

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

Helfrid M.A. Rossiter<sup>1</sup>, Peter A. Owusu<sup>2</sup>, Esi Awuah<sup>2</sup>, Alan M. MacDonald<sup>3</sup>, and Andrea I. Schäfer<sup>1\*</sup>

<sup>1</sup> School of Engineering, The University of Edinburgh,

Edinburgh, EH9 3JL, United Kingdom

<sup>2</sup> Department of Civil Engineering, Kwame Nkrumah University of

Science and Technology, Kumasi, Ghana

<sup>3</sup> British Geological Survey, Murchison House, West Mains Road,

Edinburgh, EH9 3LA, United Kingdom

\* Corresponding author phone: +44(0)131 650 7209, fax: +44(0)131 650 6781

Email: [Andrea.Schaefer@ed.ac.uk](mailto:Andrea.Schaefer@ed.ac.uk)

Submitted to

The Science of the Total Environment

17 November 2009

**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 ( $\text{NO}_3^-$ ) were found in 21% of the samples, manganese (Mn) and fluoride ( $\text{F}^-$ ) 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/ $\text{m}^3$ , many wells were free. Interestingly, the most expensive water (£2.9-3.5/ $\text{m}^3$ ) 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

54

55 **1. Introduction**

56 Approximately 880 million people still lack access to safe drinking water, the lowest coverage found in  
57 sub-Saharan Africa. Waterborne diseases, such as diarrhoea, cause 1.5 million deaths a year,  
58 prominently to children in developing countries (JMP, 2008). It is estimated that child mortality and  
59 could be significantly reduced and general health improved by providing access to safe potable water  
60 and improving sanitation and hygiene (WHO, 2004). This is the compelling motivation for  
61 governments and aid organisations to avoid acute problems of waterborne diseases by constructing  
62 boreholes and wells to improve coverage of safe water sources. However, these new sources, if not  
63 adequately monitored, may instead be a source of chronic health problems due to high concentrations  
64 of inorganic contaminants such as arsenic (As), fluoride (F<sup>-</sup>) and nitrate (NO<sub>3</sub><sup>-</sup>) (Bissen and Frimmel,  
65 2003a; Reimann and Banks, 2004)

66

67 Ghana, in West Africa, celebrated 50 years of independence from colonial rule in 2008, and is often  
68 hailed as an African economic and political success (Naylor, 2003). Yet, Ghana is still struggling to  
69 provide safe drinking water and sanitation to all its inhabitancy, especially in rural areas (UNICEF,  
70 2007). Although Ghana is doing better than its immediate neighbours (*e.g.* Côte d'Ivoire and Togo),  
71 nearly 12% of Ghanaian children die before they reach the age of five compared to *e.g.* 6% of children  
72 in South Africa and 0.6% of children in the UK (UNICEF, 2007). Access to safe water is an important  
73 factor to reduce the number of deaths. According to JMP (2008), 29% of the rural population rely on  
74 unimproved water sources. The majority of the improved sources in rural Ghana are boreholes and  
75 protected wells.

76

77 Ghana has 10 administrative regions: Western Region, Eastern Region, Central Region, Greater Accra,  
78 Volta Region, Ashanti Region, Brong-Ahafo, Northern Region, Upper West and Upper East. The

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

100

101 Studies on the water quality in particular problem areas in Ghana have been conducted, such as the  
102 northern parts (Pelig-Ba *et al.*, 1991; Pelig-Ba, 1998; Pelig-Ba *et al.*, 2001, 2004), along the coast (Gill,  
103 1996) and in mining areas (Smedley, 1996; Pelig-Ba *et al.*, 2001; Ahmad *et al.*, 2004; Asante *et al.*,

104 2007; Buamah *et al.*, 2008; Kortatsi *et al.*, 2008b). In these mining areas, elevated concentrations of Fe,  
105 Mn, As, F<sup>-</sup>, Pb, Hg and Cr have been found in water sources, soil and air (Kortatsi, 1994;  
106 AmonooNeizer *et al.*, 1996; Golow *et al.*, 1996; Obiri *et al.*, 2006; Kortatsi *et al.*, 2008b). Elevated  
107 concentrations of NO<sub>3</sub><sup>-</sup> have also been found (Kortatsi *et al.*, 2009), but further study is needed to  
108 establish the NO<sub>3</sub><sup>-</sup> distribution in Ghana (British Geological Survey, 2000). Gill (1996) reported  
109 brackish water and high concentrations of Fe, Mn, Cl and NO<sub>3</sub><sup>-</sup> in boreholes and wells in the Volta and  
110 Upper and Northern regions.

111

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

## 116 2. Materials and methods

### 117 2.1. Sample collection in Ghana

118

119 A total of 230 samples were collected out of which 199 were from improved drinking water sources,  
120 mainly boreholes and wells but also some standpipes and trucked water during the 2007 rainy season  
121 (July/August) from different regions throughout Ghana. In this paper we analyze the samples from the  
122 improved drinking water sources. Where possible the name of the location, age of the water source and  
123 pump, funding agency, water charge, money collection system, maintenance arrangements and  
124 proximity of other water sources in the area were registered. Difficulties arose when trying to  
125 distinguish between boreholes and wells with hand pumps as information on the depth of the source  
126 was usually not available. However, the type of pump installed was used as an indication (see Asklund  
127 and Eldvall (2005) for a detailed discussion on this problem). Samples were collected from the source  
128 in 500 mL plastic bottles (washed three times with the sample water prior to collection), 20 mL of it

129 filtered through a 0.45 µm syringe filter (Sartorius Minisart, non-pyrogenic CE) and stored in a 20 mL  
130 polypropylene vial. The pH of the remaining sample was checked upon collection and measured again  
131 at the end of the day as was conductivity (Multiline P4 multimeter, WTW) and turbidity (Turbidimeter  
132 TN-100, Eutech Instruments). Drinking water was likely to be exposed to the atmosphere before  
133 consumption as it was carried back in open basins and buckets and thus this reflects the pH which  
134 would be consumed. Filtered samples were stored at ambient temperature and airlifted to the UK at the  
135 completion of the data collection.

136

## 137 2.2. *Chemical analysis*

138

139 The samples were kept at 4°C and separated into two portions. One portion was acidified to pH < 2  
140 (concentrated Aristar HNO<sub>3</sub>) and left to equilibrate at for at least 3 days before ICP analysis. The other  
141 portion was kept untreated at 4°C for ion chromatography (IC) analysis. Laboratory blanks were prepared  
142 by using MilliQ water and treating it in the same way as the samples. Major cations (> 0.1 mg/L) were  
143 detected by inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Perkin Elmer Optima  
144 5300 DV, USA). Cations of concentrations as low as 0.01 µg/L were analysed with inductively coupled  
145 plasma – mass spectroscopy (ICP-MS) (Agilent 7500ce, Japan). Calibrations were verified by a standard  
146 reference material (ICP Multi Element Standard Solution VI CertiPUR) and a reference water (SRM  
147 1640). Anions were analysed using IC (Dionex, CA, USA).

## 148 3. Results and discussion

### 149 3.3. *Physico-chemical water quality*

150 The results from the chemical analysis (mean, minimum median, lower inter-quartile range (Q1),  
151 median, higher inter-quartile range (Q3) and maximum values) are displayed in Table 1. The number of  
152 samples analysed (N), the applicable WHO drinking water guidelines and the percentage of samples  
153 with concentrations out with the guideline values are also presented. The following elements do

154 currently not have a WHO guideline value: bromium (Br), calcium (Ca), magnesium (Mg), potassium  
155 (K), sulphur (S), vanadium (V) and cobalt (Co). The following elements did not exceed the WHO  
156 guideline value in any location: cadmium (Cd), selenium (Se), Copper (Cu), zinc (Zn), cobalt (Co) and  
157 chromium (Cr). The following elements exceeded the health-based WHO guideline value in at least  
158 one location: boron (B), manganese (Mn), iron (Fe), arsenic (As), lead (Pb), uranium (U), fluoride ( $F^-$ ),  
159 nitrate ( $NO_3^-$ ), sulphate ( $SO_4^{2-}$ ) and nickel (Ni). The most widespread parameters exceeding a health  
160 based WHO guideline, were  $NO_3^-$  (21%), Mn (11%) and  $F^-$  (6.7%). Numerous samples exceeded the  
161 recommended guidelines based on water treatment considerations or taste for Al (95%) and Cl (5.7%).  
162 Turbidity and pH were also outside the recommended range for 90% and 53% of the samples,  
163 respectively.

164  
165  
166  
167

(Table 1)

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

173

174

(Figure 1)

175

176 As can be seen in Figure 1, several water sources across the country contain concentrations of  
177 inorganic contaminants above the WHO drinking water guideline. Many of the water sources along the  
178 coast had elevated TDS, due to proximity to the sea. High concentrations of NaCl are expected to some  
179 extent due to seawater influence. Other ions such as  $F^-$ , Mn, Fe and  $NO_3^-$  were also above the WHO  
180 guideline along the coast. Further inland, a variety of elements exceeded the guideline value, in

181 particular in the Western, Central, Ashanti and Upper East Regions, where  $F^-$  and  $NO_3^-$  concentrations  
182 exceeded the guideline. Overall 38% of the samples exceeded the health-based WHO drinking water  
183 guidelines for a minimum of one parameter. The graphs of pH, cumulative frequency versus  
184 concentration for TDS, conductivity, turbidity and the main inorganic parameters of interest are  
185 displayed in Figure 2 to 5. This shows the range of the concentrations found and the percentage of  
186 samples found within a certain concentration. The dotted lines mark the WHO drinking water  
187 guidelines, where applicable. A more detailed discussion of the individual contaminants found in the  
188 waters sources follows.

189

190 There is no health based guideline for pH, although a range of 6.5-8.5 is often used suggested because  
191 aquatic life is negatively affected below pH 6.0 (Mason, 1990). Additionally at low pH, the water is  
192 corrosive and can cause wear to equipment. About 50% of the samples fell outside the recommended  
193 pH range, with the majority being too acidic (Figure 2). Acidity is more prominent in environments  
194 with granite based rocks with low buffering capacity (Mason, 1990). Of particularly high acidity (pH  
195 3.7) was a borehole close to the mining town Obuasi in the Ashanti Region. The borehole also had high  
196 concentrations of Al, Mn, Pb and  $NO_3^-$ , indicating contamination from mining. Other acidic waters (pH  
197 4-5.5) were found in the Ashanti, Western and Central Region. Some had high concentrations of Al,  
198 Mn or Pb, indicating contamination from mining. These regions are also subject to much mining on  
199 both small and large scale. The Western, Central and Ashanti regions would be naturally more acidic  
200 both due to their geology (British Geological Survey, 2000) and due to forest coverage (Gill, 1996).  
201 Forests are naturally expected to be somewhat acidic, both due to the organic acids from the breakdown  
202 of organic matter and the higher precipitation they receive (Spiro and Stigliani, 1996). This same area  
203 also receives the highest rainfall in the country (1500-2200 mm/yr, compared to 700-1000 mm/yr in the  
204 northern parts and east coast) (Gill, 1996).

205

206

(Figure 2)

207

208 Turbidity does not have a health based guideline, but it is recommended that it should ideally be below  
209 0.1 NTU for effective disinfection (World Health Organisation, 2006). Ninety percent of the samples  
210 were above this guideline (Figure 3) and the turbidity was generally highest in surface waters, although  
211 high values (up to 266 NTU) were also found in boreholes. Ghana has set a guideline for a newly  
212 drilled bore holes at 5 NTU; and about 80% of the water sources sampled complied with this value.

213

214

(Figure 3)

215

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

219

#### 220 3.4. *Parameters of health concern*

221

222 The elements analysed for in this study that exceeded a WHO health based guideline value were As,  
223 Pb, U, B, F<sup>-</sup> and NO<sub>3</sub><sup>-</sup>.

224

225 The WHO guideline value for arsenic (As) is 10 µg/L. Concentrations exceeding this guideline were  
226 found in the Ashanti Region, around Obuasi, in the north of the Volta Region and the Upper East  
227 (Figure 4). The highest As concentration was in a borehole in Bolgatanga (170 µg/L). Smedley (1996)  
228 and Kinniburgh (Smedley, 1996; Smedley and Kinniburgh, 2002) give a detailed description of As  
229 geochemistry and its mobility due to weathering conditions. As can for instance be mobilised by  
230 flooding and the reduction and mobilisation of As-containing Fe oxides, or by oxidation of

231 arsenopyrates, which is the case in the gold mining areas of Ghana (Smedley and Kinniburgh, 2002).  
232 Similarly high As concentrations were measured by Asante (2007) in the Tarkwa gold mining region  
233 (Western Region). Bolgatanga is an active mining area, and may thus release naturally occurring As.  
234 Asante *et al.* (2007) measured As concentrations in human urine samples of inhabitants of Tarkwa,  
235 concluding that the concentrations were similar to those of concentrations found in *e.g.* Bangladesh and  
236 India, although they could not ascertain a link to drinking water. As concentrations in rivers were  
237 higher than boreholes, indicating air-borne contamination (Smedley, 1996). Kortatsi *et al.* (2008b)  
238 found that 21% of the boreholes in the Offin basin (Ashanti Region) contain As concentrations above  
239 the WHO guideline. Interestingly, Amonoo-Neizer and Amekor (1993) showed that crops grown close  
240 to Obuasi often had double As contents compared to the same crop types grown around Kumasi  
241 indicating the release of high concentrations of As in mining areas. Kortatsi (2008a) also identified a  
242 number of samples with As concentrations above the drinking water guideline in the Central, Greater  
243 Accra and Volta Region. From the results of this study, it does not appear that As is a widespread  
244 problem in Ghana, however, it is still important to monitor and regulate contamination from mining  
245 activities as very high localised concentrations occur.

246

247

(Figure 4)

248

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

255

256 Concentrations of uranium (U) above the provisional WHO guideline (15  $\mu\text{g/L}$ ) were found in the  
257 Central Region and the Volta Region. The Volta Region sample also had high concentrations of  $\text{NO}_3^-$   
258 (508 mg/L, ten times the WHO guideline value),  $\text{F}^-$  (4.24 mg/L, nearly three times the guideline value)  
259 and Cl (500 mg/L, double the taste guideline value). The borehole containing most U (267  $\mu\text{g/L}$ ) was in  
260 the Central Region. It did not contain other chemical pollutants. Other boreholes in that area also  
261 contained U, although below the drinking water guideline value. U was previously found by Dampare  
262 (2005). Concentrations below the drinking water guideline were also found in found in the Upper East,  
263 indicating that while U might not be a widespread concern, it may be worth monitoring as it is a natural  
264 part of the geology. As well as being naturally radioactive, U is chemically toxic and when ingested  
265 may target bones or damage the kidney (The Royal Society, 2002; Kurttio *et al.*, 2005).

266

267 Boron (B) was found at levels up to 2034  $\mu\text{g/L}$  (the WHO guideline value is 500  $\mu\text{g/L}$ ) in the Northern  
268 Region. The highest B concentrations corresponded with alkaline pH. Speciation models of the water  
269 (using Minteq 2.53, results not shown), showed B to exist mainly as boric acid ( $\text{H}_3\text{BO}_3$ ) over the acidic  
270 to neutral pH range, and borate ( $\text{H}_2\text{BO}_3^-$ ) above pH 8.5. Sources of boron include seawater (unlikely in  
271 this situation), coal burning and industrial sources as well as borate-containing fertilizers, which may  
272 be the most likely source in this case as there is agricultural activity in the region.

273

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

280

281

(Figure 5)

282

283 Nitrate ( $\text{NO}_3^-$ ) has a WHO guideline value of 50 mg/L and exceeded this concentration in 21% of the  
284 samples (Figure 5). The highest concentration was 508 mg/L. The locations were widespread but  
285 mostly found in the Western, Ashanti, southern Volta, Northern region and Upper East.  $\text{NO}_3^-$  is  
286 regulated as it is one of the causes of methaemoglobinaemia (or “blue-baby syndrome”) in infants  
287 (Manassaram *et al.*, 2006) as well as a potential risk of stomach cancer (Abrahams, 2002). Forty-seven  
288 percent of the well waters had concentrations above the guideline, compared to 16% of the borehole  
289 waters (Figure 6). The concentrations of  $\text{NO}_3^-$  were also higher in wells than in surface water (results  
290 not shown). This indicates a widespread problem of elevated  $\text{NO}_3^-$  in shallow groundwater –probably a  
291 result of poor sanitation and latrine construction (MacDonald and Calow, 2009). High levels can also  
292 be caused by fertilizer use. The results of Pelig-Ba (2004) confirm those of this study and report a mean  
293 of 93.3 mg/L of  $\text{NO}_3^-$  and a maximum of 511 mg/L in groundwater in the Upper West. The WHO  
294 guideline value for nitrite ( $\text{NO}_2^{2-}$ ) is 0.2 mg/L. Unfortunately  $\text{NO}_2^{2-}$  needs to be determined within 48  
295 hours, which was not possible due to the logistics. Thus the  $\text{NO}_3^-$  values reported in this paper, include  
296 any  $\text{NO}_2^{2-}$  which may have been originally present.

297

298

(Figure 6)

299

### 300 3.5. *Aesthetic parameters*

301

302 Parameters analysed for in this study with non-*health* based WHO guidelines were Al, Fe, Mn, Cl and  
303  $\text{SO}_4^{2-}$ . Despite not being a health concern, high concentrations affect the quality of water, leading to bad  
304 taste and colouration of cooking utensils and food. This has caused hundreds of wells to be abandoned in

305 favour of surface waters likely contaminated with harmful micro-organisms (Smedley, 1996; Gyau-  
306 Boakye and Dapaah-Siakwan, 1999).

307

308 The most widespread pollutant was aluminium (Al). The health effects from Al remain unclear, however,  
309 Al does have a practicable non-health based WHO guideline value of 0.2 mg/L (stated as an achievable  
310 level for small water treatment facilities. This takes into consideration the health concerns but also the  
311 benefits from using Al in water treatment (World Health Organisation, 2006)). Ninety-five percent of the  
312 samples measured were above the recommended guideline value (Figure 5), several more than ten-fold,  
313 with the maximum concentration at 67 mg/L. Areas of particularly high Al concentration were in the  
314 Volta Region (regional average of 27 mg/L) where Nkwanta district, Asuogyaman, Hohoe, Keta and  
315 Ketu districts had especially high concentrations (average of 30, 42, 28, 55 and 44 mg/L respectively).  
316 The Western Region also had locations containing high Al concentrations, with an average of 13 mg/L in  
317 the Wassa West district. Al may leach from soils unable to buffer acidic precipitation and from minerals  
318 such as kaolinite and gibbsite (Langmuir, 1997). Some researchers find high Al concentrations in  
319 association with particles (Reimann *et al.*, 2003), in our study however, Al showed no correlation with  
320 turbidity. Al concentrations were found to be highest around neutral pH, where Al normally is less  
321 soluble. The high Al in the samples may possibly be associated with colloids smaller than the 0.45 µm  
322 filter. Pelig-Ba (2004) also found higher Al concentrations in water at neutral pH and explained it by  
323 presence of chelating agents such as soil organic matter raising the Al solubility. In Pelig-Ba's study from  
324 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  
325 Northern Region.

326

327 A number of samples had very high sulphate ( $\text{SO}_4^{2-}$ ) concentrations (>500 mg/L) (Figure 5). One was  
328 found in a relatively new borehole in the Northern Region, probably due to mudstone geology. In this  
329 sample high Mn concentrations were also found. Due to the taste, consumers preferred to drink water

330 from the nearby shallow well, which contained low  $\text{SO}_4^{2-}$  and Mn concentrations but possible  
331 microbiological contamination. This illustrates how poor chemical water quality of new deeper  
332 groundwater sources may drive people back to shallow contaminated sources. Another borehole from  
333 the same region contained similar  $\text{SO}_4^{2-}$  and TDS levels, but no Mn, and people were happy to drink  
334 the water.

335

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

343

344 Iron (Fe) concentrations below 2000  $\mu\text{g/L}$  are described as safe by the WHO (Figure 4), although taste  
345 is affected above 300  $\mu\text{g/L}$ . This taste based value is used by many studies when reporting Fe. Up to  
346 4257  $\mu\text{g/L}$  was measured. As can be seen from the map (Figure 1), high Fe concentrations were found  
347 in a variety of locations along the coast, inland in forested areas and the Northern Region. Most  
348 samples (97.4%) fall below 300  $\mu\text{g/L}$  and 99% are below the guideline value 2000  $\mu\text{g/L}$  (Figure 4).  
349 Most of the sources containing very high Fe concentrations were found in boreholes. The chemistry of  
350 naturally occurring Fe is controlled by the redox conditions of the water (not measured due to lack of  
351 equipment), where Fe is mobilised under reducing conditions, indicating that the environment of these  
352 boreholes was reducing.

353

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

359

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

368

369 In summary, the water quality from the different sources in Ghana displayed a wide range of chemical  
370 water quality, with many sources containing concentrations above the drinking water guidelines. In  
371 boreholes high concentrations of  $\text{NO}_3^-$ ,  $\text{F}^-$ , B, Pb, As, U, Cl, Fe, Mn and  $\text{SO}_4^{2-}$ , and high levels turbidity  
372 were found. In wells  $\text{NO}_3^-$ , Fe and turbidity were common problems, as well as some instances of As,  
373 Mn, Cl and  $\text{F}^-$ .

374

### 375 3.6. *Current rural water sources, costs and ability to pay*

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

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

380

381 About 25% of the communities visited had an annual user fee per household ranging from 5000 to  
382 40000 cedis (£0.3-£21, August 2007). About 33% of the water supplies had a water collection charge  
383 based on quantity of water collected (Figure 7). Surface and many well waters were often free of  
384 charge while boreholes, piped and especially truck-delivered water attracted the highest charges. The  
385 cost per bucket (18L) for boreholes and piped water ranged from 25 to 250 cedis (£0.07 to £0.7/m<sup>3</sup>,  
386 based on 62 communities) and the cost per basin (40L) ranged from 50 to 500 cedis (£0.07 to £0.7/m<sup>3</sup>,  
387 based on 47 communities). Where water was trucked in, the cost was 1000-1200 cedis per bucket  
388 (£2.9-3.5/m<sup>3</sup>, based on two communities). An appointed water vendor from the WatSan committee was  
389 often situated at the water source to directly collect the payment from the users. Understandably some  
390 households choose to use cheaper or free water sources for washing and bathing, increasing the risk of  
391 contact with diseases transmitted by surface water. Surface water is often used during the rainy season  
392 due to availability while in dry seasons they may be used if borehole re-charge is low (Iten and  
393 McCarron, 2006). 13% of the communities visited did not have an operational payment system in  
394 place. Many communities were therefore struggling to raise between 1.5-2.5 million cedis (about £80-  
395 £130) in order to pay for repairs or spare parts of pumps, broken a couple of years earlier. When this  
396 proved to be a major hurdle and pumps would remain disused or even abandoned. Another problem  
397 encountered in some communities was that there was no payment system for the trained community  
398 members to get paid for maintenance services, which meant that they were unwilling to assist.  
399 Organising maintenance and collecting payment for repairs is further complicated by the dynamic  
400 movement of people between different communities and even parts of the country (Iten and McCarron,  
401 2006). In some cases pumps were ill designed, causing unaffordable chronic failure of parts.

402

403  
404  
405  
406

(Figure 7)

407 3.7. *Is water treatment a suitable option for sources of poor chemical quality?*

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

428

429 Treatment methods which target chemical contaminants combine processes such as adsorption or  
430 coagulation with ultrafiltration or sandfiltration processes (Brandhuber and Amy, 2001; Johnston and  
431 Heijnen, 2001; Chakravarty *et al.*, 2002). Issues of handling, cost of chemicals, sanitation and  
432 regeneration of the adsorption materials are a concern. Ultrafiltration systems are available at an  
433 investment cost of about £2000 (20 m<sup>3</sup>/day capacity), and are maintained by a daily washing. Low-cost  
434 As removal for communities in developing countries have been investigated (Bissen and Frimmel,  
435 2003b; Malik *et al.*, 2009) and wells can even be constructed to allow re-circulation of oxidised water  
436 back into the source, thus oxidising and immobilising Fe and As before it is with-drawn (van Halem *et*  
437 *al.*, 2009). This method still requires further development and testing, however, and the resulting  
438 concentrations depend on concentrations originally present. The need to remove a variety of chemical  
439 contaminants from existing water sources persists and long-term studies are lacking. The issue of F<sup>-</sup>  
440 removal from drinking water in the northern regions of Ghana, for example, is unresolved (CWSA,  
441 2007). In such situations membrane technologies have unique potential due to their physical separation.  
442 Nanofiltration or reverse osmosis are well adapted in developed countries for water desalination, reuse  
443 and removal of dissolved contaminants while application in developing countries has not yet widely  
444 progressed. Investment cost into single tap reverse osmosis has been estimated to £190-£380 (Peter-  
445 Varbanets *et al.*, 2009) which may be an option if it could be developed for boreholes. A solar powered  
446 community-based membrane system was field tested by Schäfer *et al.* (2007) and found to perform  
447 well in terms of potable water production. The system had a specific energy consumption of 1.2  
448 kWh/m<sup>3</sup>. Investment and maintenance costs into a solar powered electro dialysis systems have been  
449 calculated as £0.15-0.28/m<sup>3</sup>, with an initial investment of at least £5400 (Ortiz *et al.*, 2008). However,  
450 the long-term integration of operation and maintenance of such systems into communities requires  
451 solid strategies at a local level.

452

453 3.8. *Sustainability of treatment systems*

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

472

473 **4. Conclusions**

474 It was found in this study that 38% of the wells and boreholes in Ghana had high concentrations of  
475 inorganic contaminants. Major problems identified were that of high turbidity, low pH, high  
476 concentrations of  $\text{NO}_3^-$ ,  $\text{F}^-$ , Al and Cl and in localised areas As, Pb, B and U. The importance of regular

477 monitoring of groundwater sources is emphasized. While some ‘low-cost’ treatment technologies to  
478 remove, for instance, As and F<sup>-</sup> exist, the long-term sustainability and management of such  
479 technologies is yet to be proven for a wide range of chemical contaminants and how performance (in  
480 particular contaminant breakthrough) can be monitored. The maintenance costs of systems could  
481 potentially be incorporated in the maintenance costs currently paid by community members (up to  
482 £0.7/m<sup>3</sup>), especially if government and NGO’s were willing to invest in the capital costs. This could be  
483 worthwhile, considering the cost of unsuccessful boreholes. About 58% of the communities had a  
484 payment system in place to recover basic maintenance costs.

485

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

496

## 497 **5. Acknowledgements**

498 UNESCO Scotland are thanked for project funding, the Royal Society and the Royal Academy of  
499 Engineering for travel support. A studentship from EPSRC and ESRC was provided for H.M.A. Rossiter.  
500 Mr. Samuel Ansere is thanked for his superb local guidance in Ghana as the driver of the team during the

501 field trip in summer 2007 and KNUST for the provision of a vehicle. Tanya Peshkur and Dr Peter  
502 Anderson assisted with IC analysis, and Dr Lorna Eades for assistance with ICP-MS (all University of  
503 Edinburgh).

504 Prof. Bryce Richards (Heriot Watt University) is thanked for his active participation in the sampling  
505 trip, while Björn Schulte-Herbrüggen as well as Kofi Awuah who provided some remote samples.

506 Faustina Atipoka (CWSA, Bongo district), Osmund Ansa-Ansare (WRI, Accra), Hajo Schäfer (IGIP  
507 Consulting Engineers, Kumasi) are thanked for helpful discussions in conjunction with field trip  
508 logistics. Gloria Addicio (University of Hull) provided the map modified for the paper. Prof.

509 Menachem Elimelech (Yale University) has critically reviewed the manuscript and Annalisa DeMunari  
510 and Laura Richards (University of Edinburgh) are thanked for critical proof reading.

511

## 512 **References**

513

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

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

517 Ahmad K, Dampare SB, Adomako D, Opata NN, Quagraine RE. The use of neutron activation analysis  
518 in gold prospecting in small-scale mining in Ghana. *J Radioanal Nucl Chem* 2004; 260: 653-  
519 658.

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

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

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

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

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

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

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

- 535 British Geological Survey. 2000. Groundwater quality: Ghana.  
536 [www.bgs.ac.uk/downloads/start.cfm?id=1281](http://www.bgs.ac.uk/downloads/start.cfm?id=1281), 2009, November  
537 Buamah R, Petrusevski B, Schippers JC. Presence of arsenic, iron and manganese in groundwater  
538 within the gold-belt zone of Ghana. *Journal of Water Supply Research and Technology-Aqua*  
539 2008; 57: 519-529.
- 540 Chakravarty S, Dureja V, Bhattacharyya G, Maity S, Bhattacharjee S. Removal of arsenic from  
541 groundwater using low cost ferruginous manganese ore. *Water Research* 2002; 36: 625-632.
- 542 CWSA. Summary of the fluoride issues in the northern region, 2007.
- 543 Dampare SB, Nyarko BJB, Osae S, Akaho EHK, Asiedu DK, Serfor-Armah Y, et al. Simultaneous  
544 determination of tantalum, niobium, thorium and uranium in placer columbite-tantalite deposits  
545 from the Akim Oda District of Ghana by epithermal instrumental neutron activation analysis. *J*  
546 *Radioanal Nucl Chem* 2005; 265: 53-59.
- 547 Gill HE. A groundwater Reconnaissance of the Republic of Ghana, with description of geohydrolic  
548 provinces. *US Geol Surv Water Supply Pap* 1996; 1757-k.
- 549 Golow AA, Schlueter A, AmihereMensah S, Granson HLK, Tetteh MS. Distribution of arsenic and  
550 sulphate in the vicinity of Ashanti Goldmine at Obuasi, Ghana. *Bull Environ Contam Toxicol*  
551 1996; 56: 703-710.
- 552 Government of Ghana. National Water Policy. In: Ministry of Water Resources WaH, editor, 2007.
- 553 Gyau-Boakye P, Dapaah-Siakwan S. Groundwater: Solution to Ghana's Rural Water Supply Industry?  
554 the *Ghana Engineer* 1999; May.
- 555 Hoque BA, Hoque MM, Ahmed T, Islam S, Azad AK, Ali N, et al. Demand-based water options for  
556 arsenic mitigation: an experience from rural Bangladesh. *Public Health* 2004; 118: 70-77.
- 557 Hunter PR. Household water treatment in developing countries: comparing different intervention types  
558 using meta-regression. *Environ. Sci. Technol.* in press.
- 559 Hunter PR, Zmirou-Navier D, Hartemann P. Estimating the impact on health of poor reliability of  
560 drinking water interventions in developing countries. *Sci Total Environ* 2009; 407: 2621-2624.
- 561 Iten S, McCarron P. Buried in Boreholes. Department of Environment, Technology and Social Studies  
562 2006; M.Sc. Technological and Socio-Economic Planning: 306.
- 563 JMP. Progress on drinking water and sanitation: special focus on sanitation WHO, Geneva and  
564 UNICEF, New York, World Health Organisation and United Nations Childre's Fund Joint  
565 Monitoring Programme for Water Supply and Sanitation (JMP), 2008.
- 566 Johnston R, Heijnen H. Safe water technology for arsenic removal. International workshop on  
567 technologies for arsenic removal from drinking water, Bangladesh University of Engineering  
568 and Technology, Dhaka, India, 2001.
- 569 Kortatsi BK. Groundwater Utilization in Ghana. *Future Groundwater Resources at Risk* 1994: 149-156.
- 570 Kortatsi BK. Hydrochemical characterization of groundwater in the Accra plains of Ghana. *Environ*  
571 *Geol* 2006; 50: 299-311.
- 572 Kortatsi BK, Anku YSA, Anornu GK. Characterization and appraisal of facets influencing  
573 geochemistry of groundwater in the Kulpawn sub-basin of the White Volta Basin, Ghana.  
574 *Environ Geol* 2009; 58: 1349-1359.
- 575 Kortatsi BK, Asigbe J, Dartey GA, Tay CK, Anornu G, Hayford E. Reconnaissance survey of arsenic  
576 concentration in groundwater in south-eastern Ghana. *West Afr J Appl Ecol* 2008a; 13.
- 577 Kortatsi BK, Tay CK, Anornu G, Hayford E, Dartey GA. Hydrogeochemical evaluation of  
578 groundwater in the lower Offin basin, Ghana. *Environ Geol* 2008b; 53: 1651-1662.
- 579 Kurttio P, Komulainen H, Leino A, Salonen L, Auvinen A, Saha H. Bone as a possible target of  
580 chemical toxicity of natural uranium in drinking water. *Environ Health Perspect* 2005; 113: 68-  
581 72.
- 582 Langmuir D. *Aqueous Environmental Geochemistry*. Upper Saddle River, Prentice Hall, 1997, 600.

- 583 MacDonald AM, Calow RC. Developing groundwater for secure rural water supplies in Africa.  
584 Desalination 2009; 248: 546-556.
- 585 Malik AH, Khan ZM, Mahmood Q, Nasreen S, Bhatti ZA. Perspectives of low cost arsenic remediation  
586 of drinking water in Pakistan and other countries. J Hazard Mater 2009; 168: 1-12.
- 587 Manassaram DM, Backer LC, Moll DM. A review of nitrates in drinking water: Maternal exposure and  
588 adverse reproductive and developmental outcomes. Environ Health Perspect 2006; 114: 320-  
589 327.
- 590 Mason CF. Biological aspects of freshwater pollution. In: Harrison RM, editor. Pollution: causes,  
591 effects and control. the Royal Society of Chemistry, Cambridge, 1990, pp. 108-111.
- 592 Montgomery MA, Bartram J, Elimelech M. Increasing Functional Sustainability of Water and  
593 Sanitation Supplies in Rural Sub-Saharan Africa. Environ Eng Sci 2009; 26: 1017-1023.
- 594 Naylor R. Ghana An Oxfam Country Profile. Oxford, Oxfam, 2003.
- 595 Nyarko KB, Awuah E, Ofori D. Local initiative in community water supply: Case study in Ashanti  
596 Region, Ghana. Desalination 2009; 248: 650-657.
- 597 Nyarko KB, Oduro-Kwarteng S, Adama I. Cost recovery of community-managed piped water systems  
598 in Ashanti region, Ghana. Water and Environment Journal 2007; 21: 92-99.
- 599 Obiri S, Doodoo DK, Okai-Sam F, Essumang DK. Cancer health risk assessment of exposure to arsenic  
600 by workers of AngloGold Ashanti-Obuasi gold mine. Bull Environ Contam Toxicol 2006; 76:  
601 195-201.
- 602 Ortiz JM, Exposito E, Gallud F, Garcia-Garcia V, Montiel V, Aldaz A. Desalination of underground  
603 brackish waters using an electrodialysis system powered directly by photovoltaic energy. Solar  
604 Energy Materials and Solar Cells 2008; 92: 1677-1688.
- 605 Packham RF. Water quality and health. In: Harrison RM, editor. Pollution: causes, effects and control.  
606 the Royal Society of Chemistry, Cambridge, 1990, pp. 83-97.
- 607 Pelig-Ba KB. Trace elements in groundwater from some crystalline rocks in the Upper Regions of  
608 Ghana. Water Air Soil Pollut 1998; 103: 71-89.
- 609 Pelig-Ba KB, Biney CA, Antwi LA. Trace-Metal Concentrations in Borehole Waters from the Upper  
610 Regions and the Accra Plains of Ghana. Water Air Soil Pollut 1991; 59: 333-345.
- 611 Pelig-Ba KB, Parker A, Price M. Elemental contamination of rainwater by airborne dust in Tamale  
612 Township area of the northern region of Ghana. Environ Geochem Health 2001; 23: 333-346.
- 613 Pelig-Ba KB, Parker A, Price M. Trace element geochemistry from the Birrimian metasediments of the  
614 Northern Region of Ghana. Water Air Soil Pollut 2004; 153: 69-93.
- 615 Peter-Varbanets M, Zurbruegg C, Swartz C, Pronk W. Decentralized systems for potable water and the  
616 potential of membrane technology. Water Research 2009; 43: 245-265.
- 617 Reimann C, Banks D. Setting action levels for drinking water: Are we protecting our health or our  
618 economy (or our backs!)? Sci Total Environ 2004; 332: 13-21.
- 619 Reimann C, Bjorvatn K, Frengstad B, Melaku Z, Tekle-Haimanot R, Siewers U. Drinking water quality  
620 in the Ethiopian section of the East African Rift Valley I - data and health aspects. Sci Total  
621 Environ 2003; 311: 65-80.
- 622 Schäfer AI, Broeckmann A, Richards BS. Renewable energy powered membrane technology 1.  
623 development and characterisation of a photovoltaic hybrid membrane system. Environmental  
624 Science and Technology 2007; 41: 998-1003.
- 625 Schmidt W-P, Cairncross S. Household water treatment in poor populations: Is there enough evidence  
626 for scaling up now? Environ. Sci. Technol. in press.
- 627 Smedley PL. Arsenic in rural groundwater in Ghana. J Afr Earth Sci 1996; 22: 459-470.
- 628 Smedley PL, Kinniburgh DG. A review of the source, behaviour and distribution of arsenic in natural  
629 waters. Appl Geochem 2002; 17: 517-568.
- 630 Smedley PL, Nkotagu H, Pelig-Ba KB, MacDonald AM, Tyler-Whittle R, Whitehead EJ, et al.  
631 Fluoride in groundwater from high-fluoride areas of Ghana and Tanzania 'Minimising fluoride

- 632 in drinking water in problem aquifers' R8033. Phase I Final Report. Keyworth, Nottingham,  
633 British Geological Survey 2002, 1-72.
- 634 Sobsey MD, Stauber CE, Casanova LM, Brown JM, Elliott MA. Point of use household drinking water  
635 filtration: A practical, effective solution for providing sustained access to safe drinking water in  
636 the developing world. *Environmental Science & Technology* 2008; 42: 4261-4267.
- 637 Spiro TG, Stigliani WM. *Chemistry of the Environment*. Upper Saddle River, New Jersey, Prentice  
638 Hall, 1996.
- 639 The Royal Society. The health effects of depleted uranium munitions: a summary. *Journal of*  
640 *Radiological Protection* 2002; 22: 131-139.
- 641 UNICEF. *The State of the World's Children 2008: Child Survival*. New York, USA, 2007.
- 642 van Halem D, Heijman SGJ, Amy GL, van Dijk JC. Subsurface arsenic removal for small-scale  
643 application in developing countries. *Desalination* 2009; 248: 241-248.
- 644 von der Heyden CJ, New MG. Groundwater pollution on the Zambian Copperbelt: deciphering the  
645 source and the risk. *Sci Total Environ* 2004; 327: 17-30.
- 646 WHO. *Guidelines for Drinking Water Quality*, 2004.
- 647 World Health Organisation. *Guidelines for drinking water quality: first addendum to third edition*.  
648 Geneva, 2006, 515.
- 649  
650  
651

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

Parameter	Unit	N	Mean	Min	Q1	Median	Q3	Max	WHO guideline	% outwith guideline
Al	mg/L	192	11.87	<0.020	<b>3.927</b>	<b>8.500</b>	<b>14.60</b>	<b>66.69</b>	0.2*	95
As	µg/L	195	1.930	<0.003	<0.003	0.073	0.532	<b>169.5</b>	10	0.5
B	µg/L	195	61.11	<2.551	5.820	10.08	27.14	<b>2034</b>	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	<b>597.2</b>	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 <sup>-</sup>	mg/L	193	0.470	<0.100	0.044	0.209	0.45	<b>4.238</b>	1.5	6.7
Fe	µg/L	195	84.73	<0.001	5.446	17.78	46.16	<b>4257</b>	2000 <sup>a</sup> (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	<b>2051</b>	400	11
Ni	µg/L	195	0.579	<0.054	<0.054	<0.054	0.436	<b>29.59</b>	20	0.5
NO <sub>3</sub> <sup>-</sup>	mg/L	193	34.01	<0.200	0.514	6.394	31.52	<b>507.7</b>	50	21
Pb	µg/L	195	1.526	<0.006	0.489	0.946	1.517	<b>34.94</b>	10	1.5
PO <sub>4</sub> <sup>2-</sup>	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 <sub>4</sub> <sup>2-</sup>	mg/L	193	34.69	<0.200	1.648	5.236	23.75	<b>931.4</b>	500 <sup>b</sup>	1.0
U	µg/L	195	1.988	<0.001	0.049	0.114	0.410	<b>266.6</b>	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	-
Conductivity	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	<b>1454</b>	1200*	1.0
Turbidity	NTU	199	14.30	0	<b>0.237</b>	<b>0.793</b>	<b>3.303</b>	<b>629.7</b>	0.1*	90
pH		199	<b>6.32</b>	<b>3.69</b>	<b>5.67</b>	<b>6.43</b>	6.98	<b>8.88</b>	6.5- 8.5*	53

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

<sup>a</sup>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.

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

655

656

657 **List of Figures**

658 Figure 1 Map of Ghana with regions and sample points marked. Locations tested that did not exceed  
659 the WHO guideline value for As, B, Cl, F<sup>-</sup>, Fe, Mn, NO<sub>3</sub><sup>-</sup>, Pb or U were marked with an open circle,  
660 locations exceeding the WHO guideline were marked according to the legend in the map.

661

662 Figure 2 Cumulative frequency (%) versus pH. The dotted lines mark the recommended pH range.

663

664 Figure 3 Cumulative frequency (%) versus turbidity (NTU), conductivity (μS/cm) and TDS (mg/L).

665

666 Figure 4 Cumulative frequency (%) versus concentration (μg/L) on log axis for Pb, As and U (top) and

667 Fe, Mn, B and F<sup>-</sup> (below). The dotted line indicates the WHO guideline.

668

669 Figure 5 Cumulative frequency (%) versus concentration (mg/L) on log axis for Al (top); then Cl, NO<sub>3</sub><sup>-</sup>

670 and SO<sub>4</sub><sup>2-</sup> (middle) and finally Ca, K, Mg and S (bottom). The dotted line indicates the WHO guideline

671 where available.

672

673 Figure 6 Comparison between boreholes (BH) and wells: percentage of source type with samples above

674 the WHO guideline for Mn, Fe, F<sup>-</sup>, Cl, NO<sub>3</sub><sup>-</sup> and turbidity.

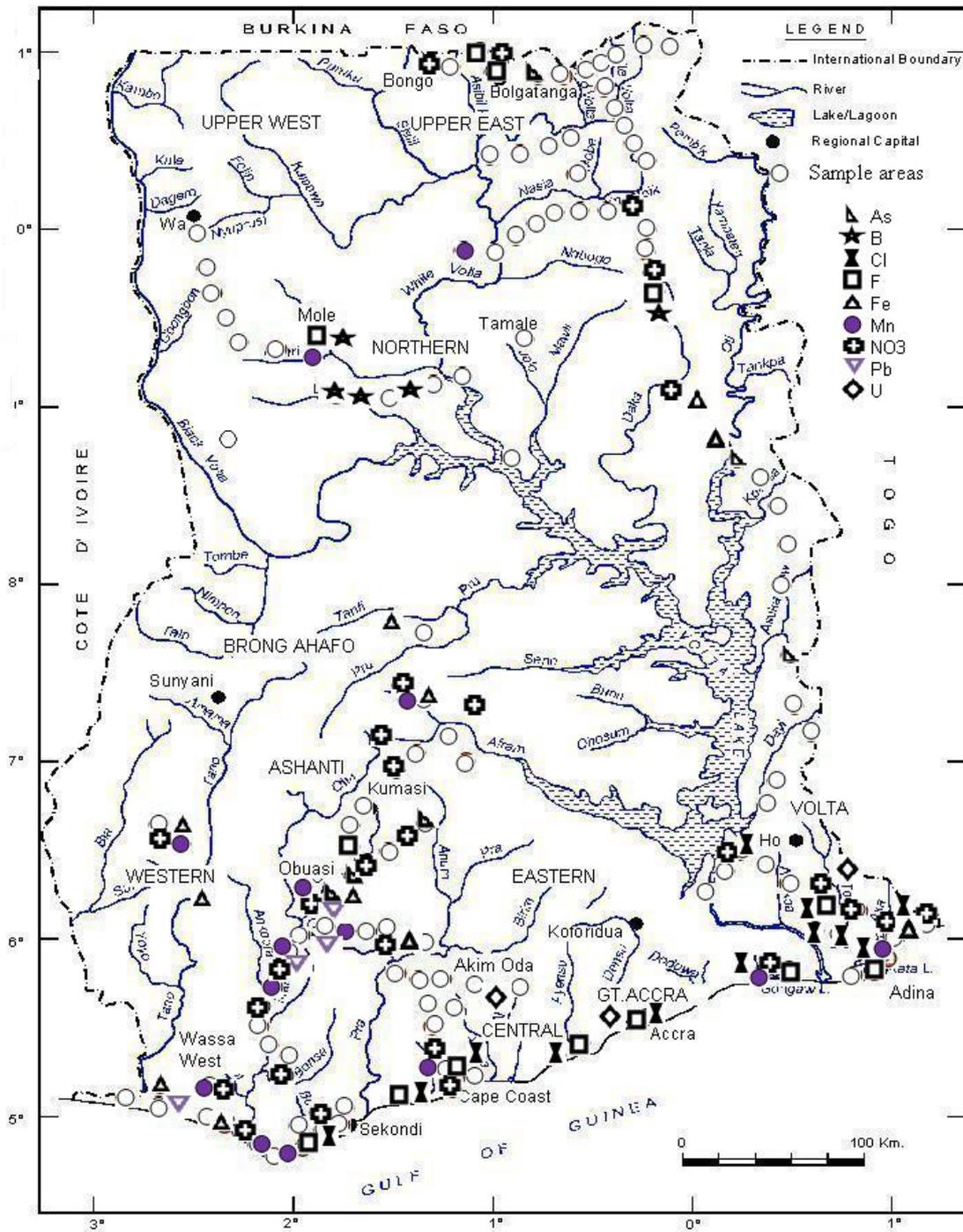
675

676 Figure 7 Distribution of water charge systems (charge based on water usage, annual charge, no charge)

677 out of the 220 water sources visited.

678

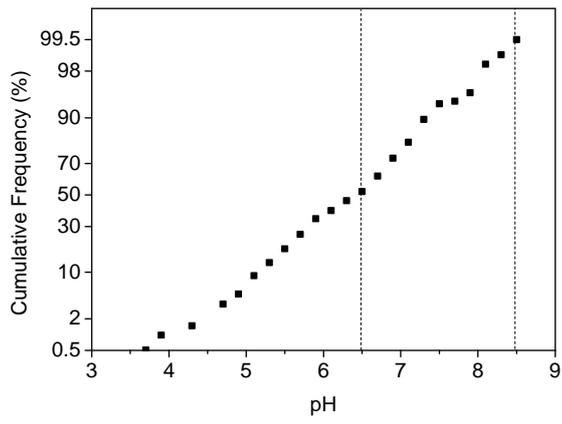
679



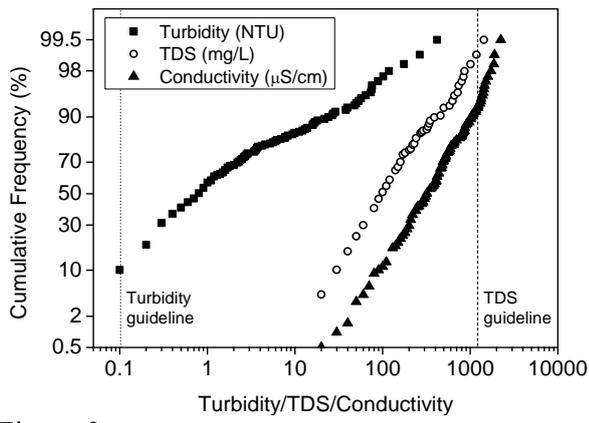
680

681 Figure 1

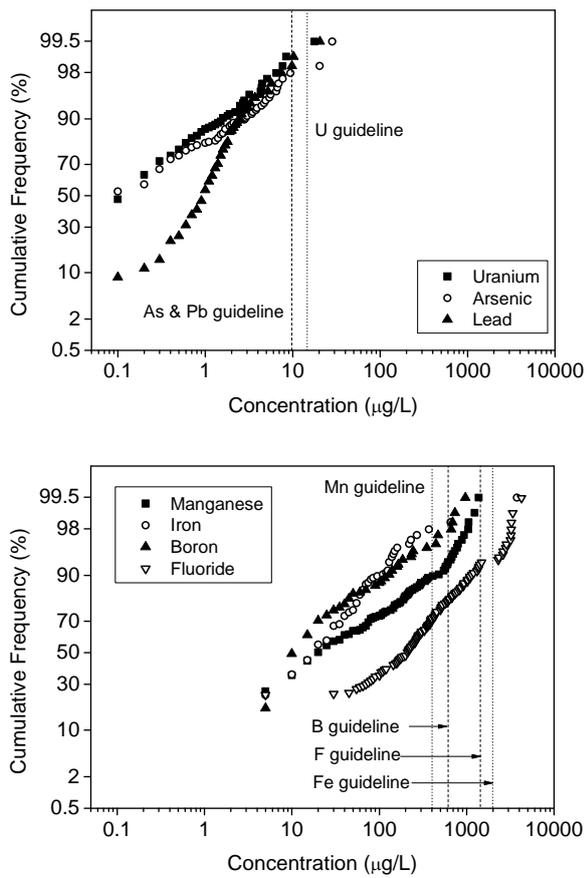
682



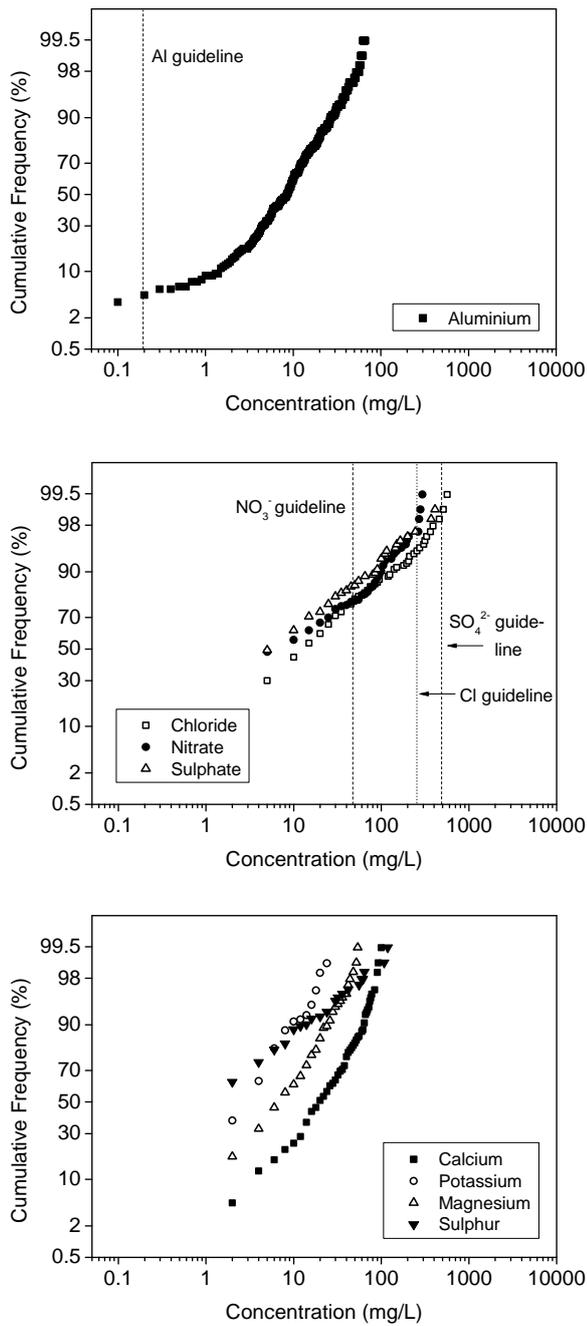
683  
684 Figure 2  
685



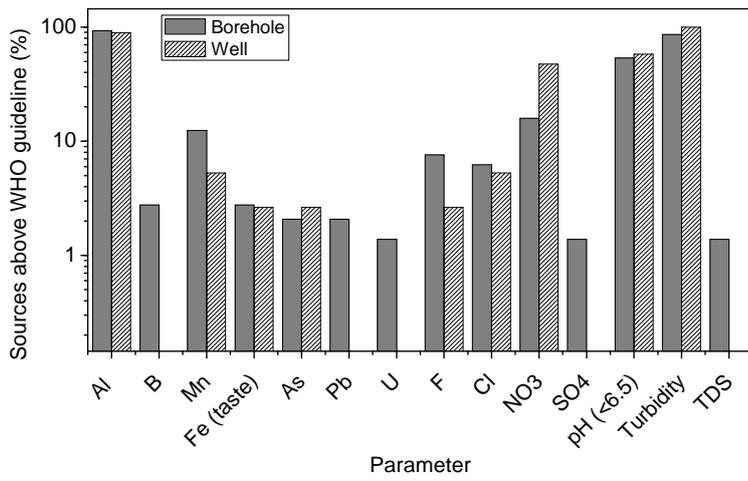
686  
687 Figure 3  
688



689  
690 Figure 4

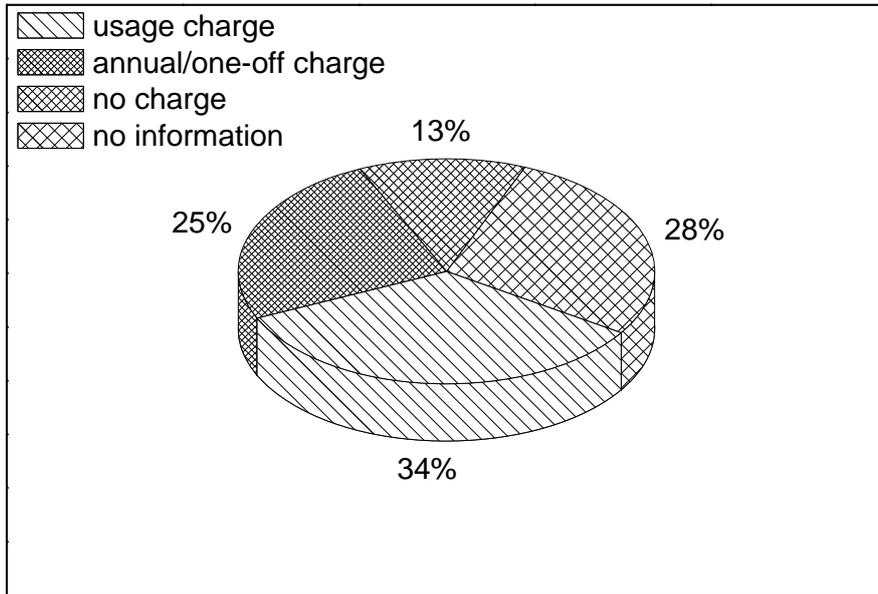


691  
692 Figure 5  
693



694  
 695 Figure 6  
 696

697  
698



699  
700

Figure 7