During an extensive sampling trial in Ghana, a number of physico-chemical water quality problems have been identified. For example, pH values of the collected samples ranged from 3.69 to 8.88, while conductivity ranged from 10 to 45000 µS/cm and turbidity ranged from 0 to 542 NTU. Many water samples analysed breached the drinking water quality guidelines. High levels of heavy metals were found, and also locations high in sulphate and nitrate. In some regions, chemical contaminants such as fluoride occur naturally and result in a significant number of boreholes being capped. While such capping results in the protection of the population exposure to such chemicals, it may increase the risk for microbiological safety if surface water sources are used.

**Keywords:** chemical contaminants, heavy metals, water quality, Ghana, boreholes

### Materials and Methods

#### Sampling

Up to 20 samples were collected per day in 500 mL plastic bottles (see Figure 2). Bottles were transferred after initial analysis which was conducted as soon as practically possible, usually within 24 hours, into 25 mL sample vials. Where possible/relevant the name of the location, age of the bore or well and handpump, funding agency, water charge, money collection system, maintenance arrangements and proximity of other water sources in the area were registered. A photograph of the bore or well, or determine the depth of a bore. Surface waters (except wells) were sampled using gloves to avoid contamination.

#### Analysis

After collection all samples were filtered through a 0.45 µm syringe filter (Sartorius Minisart, non-pyrogenic CE) and stored in a 20 mL plastic vial. The remaining sample was analysed for pH, conductivity, temperature (Multiline P4 multimeter, WTW) and turbidity (Turbidimeter TN-100, Eutech Instruments). Filtered samples were stored at ambient temperature and airrified to the UK at the completion of the trial. Upon arrival samples were kept at 4°C, separated and one portion acidified to pH < 2 (concentrated Aristar HNO₃). Upon arrival samples were kept at 4°C, separated and one portion acidified to pH < 2 (concentrated Aristar HNO₃) for ICP-OES analysis whilst the other portion was kept untreated for IC analysis. Major cations of concentrations over 0.1 µg/L were detected by inductively coupled plasma-optical emission spectroscopy (ICP-OES) (Perkin Elmer Optima 5300 DV). Cations of concentrations down to 0.01 µg/L were analysed with inductively coupled plasma – mass spectrometry (ICP-MS). 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 ion chromatography (DIONEX, Sunnyvale, CA, USA). Limits of detection (LOD) as well as relevant drinking water quality guidelines are tabulated in Table 1.

Gold mining is one of the main industries in Ghana accounting for 44% of Ghana’s export earnings [12]. The large-scale extraction taking place in mainly Western and Ashanti region e.g. Bibiani and Obuasi, brings with it arsenic, mercury and sulphur contamination to water bodies, soil and even air pollution causing acid rain and degradation to the surrounding environment and impacts on human health [13-15]. Since legalisation of small-scale gold mining extraction in 1989, many people have a living through mining, employing extraction methods that release mercury into surrounding water sources [12, 16]. Although the major gold mining has taken place mainly in the south, exploration is now also taking place in the north, e.g. in the Upper East. Ghana is also one of the worlds largest exporters of manganese and is additionally exploring bauxite (Aluminium containing minerals) [12], in mainly in the south western part of the country [17, 18]. Arsenic, iron and manganese have also been found in elevated concentrations in water in Ghana. Iron is not a health concern in itself, however elevated levels of both iron and manganese affect the taste and quality of drinking water, leading to colouration of cooking utensils and food. This has caused hundreds of wells to be abandoned in favor of surface waters likely contaminated with surface microorganisms [5, 11]. Smalley found that many of the arsenic-rich stream waters had high colloidal iron content and were highly coloured, suggesting high iron and organic content. The high arsenic concentrations were probably being facilitated by the binding to these compounds. Surface waters were described as “almost universally brown”, rich in organic matter and colloidal iron [11]. Uranium content in Ghana is not well documented, Smalley [11] measured uranium concentrations of up to 7 µg/L in ground water by Obuasi. Gold can be enriched with uranium. Eugster [19] found up to 321 mg/kg when they analysed gold samples from various locations in the world and it may thus be released in conjunction with mining. Uranium has also been found in columbite-tantalite minerals mined in the Akim-Oda district in Ghana [20]. During the rainy season 2007 (July & August; in the rainy season immediately before the major flooding throughout the region) a sampling field trial was conducted collecting 230 samples mainly from boreholes (66% of the samples) but also wells (18%), surface waters (7%), piped (5%) and bottled water (3.5%) throughout Ghana. Extensive analysis of physico-chemical water quality was conducted and results are presented in this paper. The aim of this preliminary study was to determine likely hot spots of contamination for future treatment trials.

**Physico-Chemical Water Quality in Ghana: Prospects for Water Supply Technology Implementation**

A.I. Schäfer1, H.M.A. Rossiter1, P.A. Owusu2, B.S. Richards3, E. Awuah2

1 School of Engineering and Electronics, University of Edinburgh, Edinburgh, EH9 3JL, United Kingdom, email: Andrea.Schaef@ed.ac.uk
2 Department of Civil Engineering, Kwame Krнmuh University of Science and Technology, Kumasi, Ghana
3 School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, EH14 4AS, United Kingdom

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Figure 1: Map of Ghana with regions named and sampling sites indicated with circles.

Table 1: Ions analysed as well as typical detection limits for each method and the WHO drinking water guideline for reference.

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>METHOD</th>
<th>UNIT</th>
<th>LIMIT OF DETECTION</th>
<th>WHO GUIDELINE VALUE</th>
</tr>
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<tr>
<td>Boron</td>
<td>ICP-MS</td>
<td>µg/L</td>
<td>2.551</td>
<td>500</td>
</tr>
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<td>Vanadium</td>
<td>ICP-MS</td>
<td>µg/L</td>
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<td></td>
</tr>
<tr>
<td>Manganese</td>
<td>ICP-MS</td>
<td>µg/L</td>
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<tr>
<td>Cobalt</td>
<td>ICP-MS</td>
<td>µg/L</td>
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<td></td>
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<tr>
<td>Nickel</td>
<td>ICP-MS</td>
<td>µg/L</td>
<td>0.054</td>
<td>20</td>
</tr>
<tr>
<td>Copper</td>
<td>ICP-MS</td>
<td>µg/L</td>
<td>0.173</td>
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</tr>
<tr>
<td>Zink</td>
<td>ICP-MS</td>
<td>µg/L</td>
<td>1.591</td>
<td>3000*</td>
</tr>
<tr>
<td>Arsenic</td>
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<td>0.003</td>
<td>10</td>
</tr>
<tr>
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<td>10</td>
</tr>
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<td>10</td>
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<td>ICP-MS</td>
<td>µg/L</td>
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<td>15</td>
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<tr>
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<td>ICP-MS</td>
<td>µg/L</td>
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<td>300*</td>
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<tr>
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<td>mg/L</td>
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<td>0.2*</td>
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<tr>
<td>Magnesium</td>
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<tr>
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<tr>
<td>Sulphate</td>
<td>IC</td>
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<td>500*</td>
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<td>3</td>
</tr>
<tr>
<td>Nitrate</td>
<td>IC</td>
<td>mg/L</td>
<td>0.2</td>
<td>50</td>
</tr>
</tbody>
</table>

*not a health based value, but an aesthetic, taste or practical guideline
Results and Discussion

Common ions: Aluminium, calcium, potassium, magnesium and total sulphur
The common ions aluminium (Al), calcium (Ca), potassium (K), magnesium (Mg) and total sulphur (S) are reported in Figure 3. These compounds are not of great health concern and in consequence not regulated, although Al is a known neurotoxin as has been related by some studies to Alzheimer’s disease [21-23] and even bone fragility [24]. Due to the use of Al in water processes but also taking concerns over neurotoxicity into account, a practicable guideline value is recommended by the WHO as maximum 0.2 mg/L. Al concentrations in the samples ranged from the LOD to 68 mg/L with 199 samples (86% of samples) above that guideline value. The highest levels were found in various locations in the Volta Region and also in samples from Greater Accra. Consumers in Wassaw West complained about the hardness of water, but still use some boreholes for drinking. High levels were also found just south of Wa in the Upper West. Ca concentrations ranged from LOD to 275 mg/L, K from LOD to 30 mg/L, Mg from LOD to 144 mg/L, and total S from LOD to 116 mg/L. While those values are not as such a health concern, the presence of multivalent cations such as Al and Ca may have treatment implications for certain processes.

Turbidity
Turbidity is a major concern of surface waters in particular during the rainy season. Values of up to 542 NTU (see Figure 4) were measured in surface waters such as the Black (420 NTU), Red (310 NTU) and White (542 & 323 NTU) Volta Rivers, Oti River (345 NTU) and various surface ponds used to collect rainwater (422 & 376 NTU). Various wells also showed high turbidities of up to 176 NTU. While most bore waters showed turbidities < 2 NTU, some were as high as 266 NTU and such high values were often attributable to iron (85%). The turbidity of the surface/well water did have such a clear correlation and is likely to be due to larger particles such as organic matter and dissolved solids. Many of the high turbidity waters were difficult to filter; in particular those with an opaque white-yellow appearance (see Figure 5A). The turbidity can most likely be attributed to clays in surfaces waters while pathogens and bacteria are also measured in turbidity. The WHO has not set a health based guideline, but recommends that turbidity should ideally be below 0.1 NTU for effective disinfection. 87% of the samples were above this guideline.

Conductivity and total dissolved solids (TDS)
Electric conductivity is an indication of water salinity. TDS was calculated by adding the ions Conductivity range (mg/L) was contaminated by surface run off.

P H value
The pH values of the samples ranged from 3.7 to 8.9 (see Figure 7). A total of 115 samples (about 50%) were outside the guideline values of 6.5-8.5. While the health impacts of such non-compliance
Chloride, nitrate and sulphate
The ranges of chloride, sulphate and nitrate are displayed in Figure 8. Chloride (Cl) and sulphate (SO$_4^{2-}$) do not have health based guidelines, but may cause concern due to taste if found at too high levels. The WHO, suggest that Cl levels over 250 mg/L may decrease the acceptability of the water due to taste, as well as leading to corrosion of metals. Cl concentrations in the samples ranged from 0.14 mg/L to about 20 g/L, of which 7% of the total samples were above the taste guideline.

Sulphate does not have a health-based guideline value, however the WHO recommends that concentrations higher than 500 mg/L should be reported to “the health authorities” due to symptoms to the gastrointestinal tract [1]. Sources can be both natural and industrial. The concentrations of SO$_4^{2-}$ in the samples ranged from 0.14 to 2184 mg/L, where the highest value for chloride and sulphate corresponded to the highest TDS sample. Apart from in Adina on the east coast, the highest SO$_4^{2-}$ concentrations were found bore holes in the Northern Region. These results confirmed consumer complaints where the community actually used the well water rather than from that from the bore due to the high sulphate levels.

Nitrate (NO$_3$) is a contaminant that is regulated as it has significant health effects, especially on infants where nitrate is one of the causes of methaemoglobinaemia (or “blue-baby syndrome”) [27, 28]. Low levels of nitrate are naturally present in water, however high levels result from anthropogenic sources such as sewage or fertilisers. Nitrate concentrations ranged from LOD to 508 mg/L which is more than 10 times higher than the guideline value. Out of the total number of samples taken, 17% from both bores and wells in various locations in the country and were above the guideline value.

Fluoride
Fluoride (F) offers protection against dental caries at low concentrations but at higher levels causes serious problems such as dental and skeletal fluorosis. The levels of the samples taken across Ghana ranged from below the LOD to 19 mg/L (Figure 9), with 8% containing levels higher than the WHO guideline. As expected, most sources of high F levels were found in the Northern Region, in the Bongo district. Several water sources in this area had F levels over the guideline value, both wells and boreholes. The people there suffer visibly from teeth problems, and a number of organisations are trying to find a solution to the high F levels – especially as many boreholes are simply capped if the F levels are found to be too high [29]. However, high F levels were also found scattered in different locations of the country, such as just north of Obuasi, Mole National Park, Accra and some locations along the coast. The highest F level (19 mg/L) was found in a borehole in Adina on the coast of the Volta Region. Extremely high levels were found in the same sample also of other elements such as Al, Cs, Mg, S, B, Mn, Fe, Cl and SO$_4^{2-}$ indicating a serious contamination problem.

The conductivity of this water was thus high: 48.3 mS/cm and the water surrounding the pump was of intense red colour (see Figure 5B). This water source was understandably not used for drinking as it had a sulphurous smell and a salty taste, but the community members use it for washing.
disused due to the taste. High levels (up to 1000 µg/L) were also found in the Wassa West district around the town Bompieso. Despite high Mn levels this water was used for drinking. It was noted that some small scale mining was taking place close to the village, which might explain the high Mn levels found.

Arsenic, Lead and Uranium

Even though these elements are part of the earth's crust they are not essential to humans. Arsenic (As) is well known for the catastrophic mass poisoning it has caused in e.g. Bangladesh through tube wells [33]. Arsenic has also been found in the mining areas in Ghana [29]. Confirming findings by prior studies, elevated levels of As were found in Obuasi municipality (with a history of mining activity). The concentrations across the country ranged from below LOD to 28 µg/L (Figure 11), with one sample containing as much as 169 µg/L (Bolgatanga municipality in northern Ghana). A few water samples (1%) contained three times the set guideline value of 10 µg/L. In a bore hole by Lake Bosumtwi high Cl and NO₃ levels accompanied the As, which could indicate pollution from mining or agricultural activities. High levels of Fe and Mn were also found in this area, although it is interesting to note that the samples with high As do not necessarily contain high levels of Fe/Mn.

High levels Pb were also found. Overall the concentrations ranged from below the LOD up to 34 µg/L (Figure 11). 2% were found to be above the guideline value. The highest containing sample was taken from a borehole in the town Akrotom. The pH of the water was very acidic (pH 3.69), which would lead to a higher dissolution of heavy metals. This town is located south of Obuasi and thus may be subject to contamination from the mining activities in the area. High levels of Mn and NO₃ were also detected in this sample.

Uranium (U) is not commonly analysed when testing drinking water quality, but due to its chemical toxicity (let alone its radioactivity), the guideline value is set to 15 µg/L and 1% of the samples contained U over this level. These samples were found in a borehole in Odomo in the Volta Region, close to the border to Togo. This sample also measured high conductivity (1886 µS/cm) and worryingly contained F levels four times greater than the guideline value, NO₃ values 10 times the guideline value as well as high Cl. Another sample with high U was found in a well used for irrigation in the Western Region. The pH of the water was very acidic (pH 3.34). Yet another sample contained high U in the Asin North district. The water was used for drinking despite high Mn levels. A higher pH (pH 7.2) and high NO₃ (20 mg/L) were measured in this sample.

Conclusions

A wide variety of inorganic contaminants have been identified in different locations in Ghana. The variation is probably due to natural variations in geology and also human mining and industrial activities. High levels of Al were found to be quite widespread, along with Fe and Mn, especially in the Volta Region. Presence of F was not only found in the most northern regions but also in different locations in the southern part of the country. Water sources from the mining areas in Central and Eastern Region showed high levels of As, Pb and even some U. High levels of B were found in the Northern Region, especially west of Tamale. Seawater intrusion seems to be a problem in the coastal areas, which were rich in salts and pH values were found to be extreme in places. The lacking available data in a form such as a national database is problematic and regular sampling of bores as well as the coordination of bore installations would be useful. This study has provided a first overview of the chemical contamination issues of water sources from various locations throughout Ghana and will allow for more detailed investigations where necessary. It also provides a basis for evaluation of suitable water treatment technology, where de-centralised systems seem a sensible option. Areas with high levels of metals may require a relatively advanced treatment. A more detailed analysis of the contaminants is planned, together with compilation of the socio-economic data collected. Of interest would be to carry out more detailed sampling in areas of apparent high contamination and also to investigate how the water sources are affected by the dry season.

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