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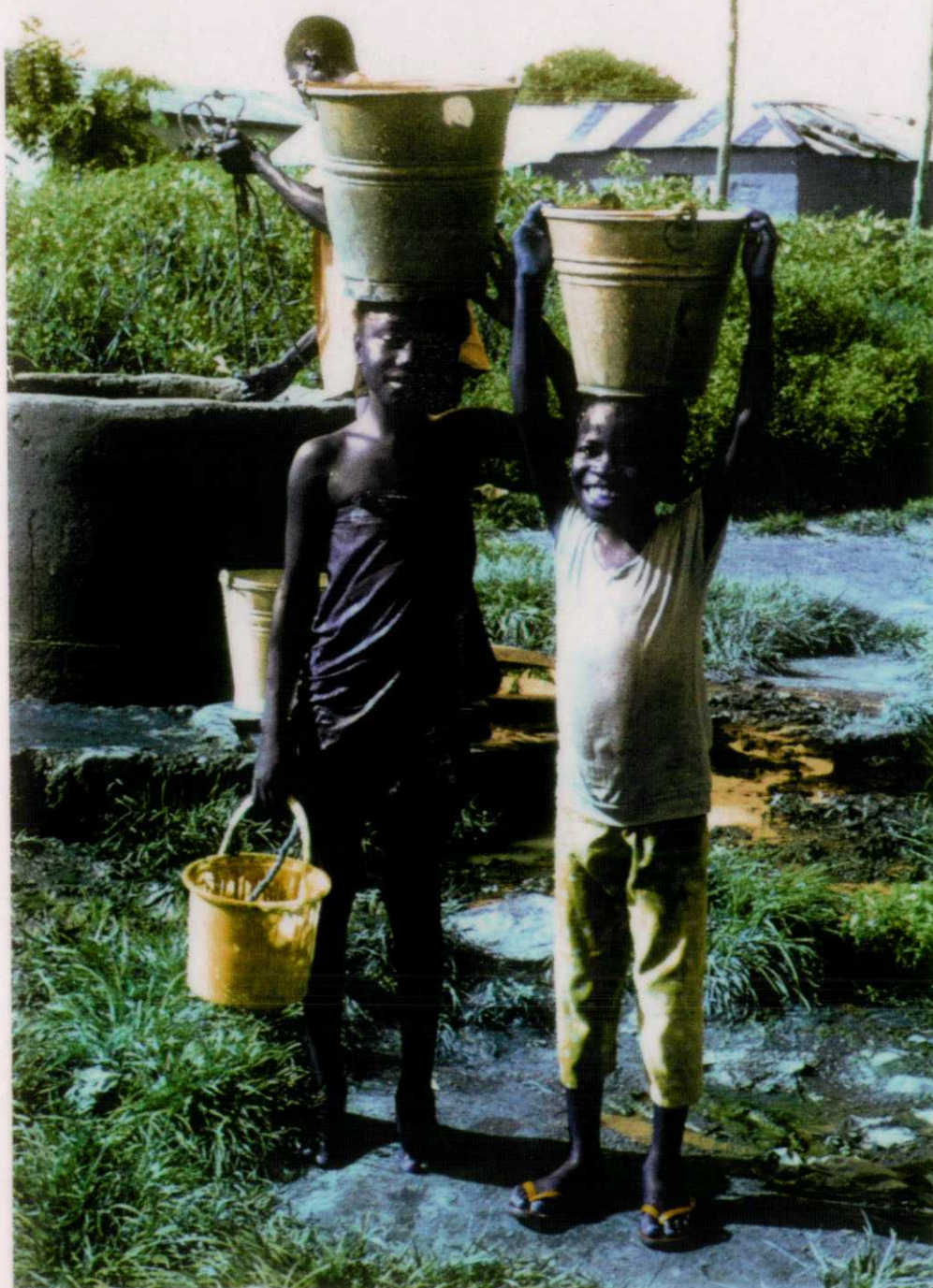
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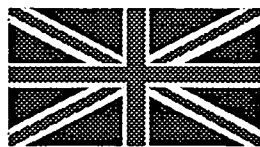
Vulnerability of Shallow Groundwater Quality due to
Natural Geochemical Environment

2 HEALTH PROBLEMS RELATED TO GROUNDWATER IN THE OBUASI AND BOLGATANGA AREAS, GHANA

P L SMEDLEY, W M EDMUNDS, J M WEST, S J GARDNER AND K B PELIG-BA

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British Geological Survey

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Overseas Geology Series

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Children collecting shallow well water, Bolgatanga, Ghana

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PREFACE

This report forms one in a series of three concerning the relationship between water quality resulting from natural processes of water-rock interaction and human health. The first report provides an overview of the constituents in groundwater which at certain concentrations may be detrimental to human health, including arsenic, aluminium, fluorine, iodine, selenium, barium, manganese and beryllium, their health consequences and the geochemical modes of mobilisation in the groundwater environment. The other two reports are the result of field investigations on rural groundwaters in Ghana and Sri Lanka and focus on the particular problems of arsenic, iodine and fluoride in water supplies in parts of these countries. The research has been funded by the British Overseas Development Administration as part of the Technology Development and Research Programme (Project R5552) and the reports represent the culmination of three years research. The research programmes were carried out in collaboration with Ghanaian and Sri Lankan research workers from the Water Resources Research Institute, Accra and the Institute of Fundamental Studies, Kandy respectively.

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EXECUTIVE SUMMARY

Two areas in Precambrian (Birimian) basement aquifers in Ghana have been chosen for an investigation of the relationships between water quality derived by natural processes of water-rock interaction and human health. The Obuasi area in Ashanti Region (southern Ghana) has long been associated with gold mining and the ore is in many places As-rich. Arsenic is therefore of specific interest in this study area. In the Bolgatanga area of Upper East Region (north-eastern Ghana) endemic goitre is a particular problem, although dental fluorosis has also been identified recently in localised districts. Iodine and F are therefore of particular interest in this study area. Other trace elements of health significance as well as microbial populations have also been investigated and geochemical processes of element mobilisation are discussed.

Arsenic in drinking water from streams, shallow wells and boreholes in the Obuasi gold-mining area of Ghana range between <2 and $175 \mu\text{g l}^{-1}$. The main sources are mine pollution and natural oxidation of sulphide minerals, predominantly arsenopyrite (FeAsS). Streamwaters have been most affected by mining activity and contain some of the highest As concentrations observed. They are also of poor bacteriological quality. Some of the streams have a high As(III) content ($\text{As(III)}/\text{As}_{\text{total}} > 0.5$), probably as a result of methylation and reduction reactions mediated by bacteria and algae. Concentrations of As in groundwaters reach up to $64 \mu\text{g l}^{-1}$, being highest in deeper (40–70 m) and more reducing (220–250 mV) waters. The As is thought to build up as a result of the longer residence times undergone by groundwaters in the deeper parts of the aquifer. The proportion of As present as As(III) is also higher in the deeper groundwaters. Deep mine exploration boreholes (70–100 m) have relatively low As contents of $5\text{--}17 \mu\text{g l}^{-1}$, possibly due to sorption of As onto precipitating ferric oxyhydroxides or to localised low As concentrations of sulphide minerals.

Microbial populations of Obuasi groundwaters are generally high, total counts (by epifluorescence) reaching up to $42700 \text{ bacteria ml}^{-1}$, although these are not necessarily detrimental to health. The presence of carbon (organic C or HCO_3^-) appears to be the main control on their numbers as this acts as an energy or nutrient source. Microbial numbers are much higher than in the Bolgatanga study area further north (up to $2500 \text{ bacteria ml}^{-1}$), probably due to the higher organic-carbon content of soils in the Obuasi area. Estimates of total heterotrophic bacteria in Obuasi groundwaters from plate counting using CPS medium gave much lower populations than by direct counting, suggesting that the populations comprise significant numbers of non-heterotrophic bacteria. Although the populations were not characterised, it is likely that they include significant numbers of autotrophic bacteria, including Fe and S oxidisers. Sulphide oxidation in the Obuasi area may therefore be catalysed by microbial activity.

Median concentrations of inorganic urinary As from sample populations in two villages, one a rural streamwater-drinking community and the other a suburb of Obuasi using groundwater for potable supply, were $42 \mu\text{g l}^{-1}$ and $18 \mu\text{g l}^{-1}$ respectively. The value for the community drinking groundwater is typical of background concentrations of urinary As. The slightly higher value for the streamwater-drinking community probably reflects different provenance of foodstuffs and higher As concentrations of water sources local to the village. The low value obtained for the inhabitants of the Obuasi suburb, living close to and abstracting groundwater from the area of major mining activity, suggests that groundwater can form a useful potable supply of good inorganic quality provided that deep, long-residence-time sources are avoided.

In the Bolgatanga study area, endemic goitre is a regional, widespread problem. Two areas in the Upper East surveyed by the University of Ghana in 1993 found goitre prevalence in school children and women of child-bearing age of 59% and 77% respectively in Sekoti district and 77% and 64% respectively in Builsa district. Further studies would help to elucidate the extent of the problem in other districts of northern Ghana. Dietary I deficiency is taken to be the principal cause. Analyses of groundwaters and soils in the Bolgatanga area show a general deficiency in I: the median I concentration in the groundwaters sampled was $3.2 \mu\text{g l}^{-1}$ and soil-I concentrations were 3.7 mg kg^{-1} or less. Rocks are granitic, granodioritic, metasedimentary and metabasic rocks which usually also have low I concentrations, typically less than 5 mg kg^{-1} . Environmental concentrations of I are therefore low and considered insufficient for dietary intake. Claimed goitrogens such as Ca, Mg, Co, Zn, Mo and As do not appear to be important for development of the disease in the Bolgatanga area but the impact of other suspected goitrogens such as high F in drinking water and thiocyanate in foodstuffs cannot be ruled out. Poor diet is also considered an important contributory factor. It is however, considered that I deficiency is the single most important factor in development of endemic goitre in the area.

There is little apparent variation in I concentration in groundwater from different depths or lithologies, most sources being low in I. There is therefore little to be gained from drilling boreholes to different depths, resiting boreholes or exploiting alternative local aquifer lithologies. The problem of goitre can be tackled best by dietary-I supplementation. This is already being carried out by a district programme of iodised oil and vitamin A administration. However, lack of public awareness of the causes of goitre and treatment available have hampered the progress of its eradication. Further public health information in the rural areas of Ghana would improve the situation considerably.

Unlike goitre, dental fluorosis is an endemic problem restricted to populations abstracting groundwater from specific rock types: the Bongo Granite and Sekoti Granodiorite. These are amphibole- and biotite-rich rocks with abundant accessory apatite, sphene and occasional fluorite. Concentrations of F in the groundwater reach up to 3.8 mg l^{-1} . There is some evidence that F concentration increases with increasing borehole depth, or groundwater residence time, especially in the Bongo Granite. Shallow wells in this aquifer have F concentrations less than 0.4 mg l^{-1} . Future borehole-installation programmes in vulnerable aquifers such as granitic rocks and amphibole-, biotite- and apatite-rich assemblages should include consideration of aquifer lithology and analysis of F in groundwater before borehole completion. Shallow boreholes tapping short-residence-time waters are more likely to have F concentrations within acceptable limits than boreholes tapping deeper horizons. However, the bacteriological quality of such shallow sources is also of great importance to health: many of the shallow-well waters in the Bolgatanga area have very high coliform counts as a result of poor sanitary practice. Use of shallow wells in F-vulnerable areas should be made with strict regard to hygiene and the maintenance of a clean and safe water supply.

1 INTRODUCTION

Although the main drinking-water quality problem facing developing countries is undoubtedly water-borne disease from microbiological contaminants, a number of quality problems also arise from inorganic constituents arising either through natural processes of water-rock interaction or from human pollution. Quality problems and resultant health problems may either arise due to element excess (F, As, Al, Cd, Se, Be, Mn) or deficiency (e.g. Ca, Mg, I). The most important of these health problems in rural areas of developing countries are associated with As and F excess and I deficiency and resultant chronic arsenosis, fluorosis and goitre respectively are known to affect many millions of people in endemic populations throughout the developing world.

Groundwaters in hard-rock aquifers are known to be particularly vulnerable to quality problems that may have an impact on human health: such rocks are typically carbonate-poor and give rise to poorly-buffered, acidic waters which may encourage dissolution of elements such as Al, Mn, Be and Fe from host minerals. Deficiency of Ca in solution may also allow potentially harmful concentrations of dissolved F to build up, particularly in groundwaters in acid-igneous rocks where late-stage F-rich minerals may be abundant. Many hard-rock aquifers contain sulphide minerals, typically in vein complexes, which may include high concentrations of other toxic metals such as As, Sb, Pb and Ba. Oxidation of these may release high concentrations into solution and render groundwater supplies potentially dangerous. Also, igneous and metamorphic rocks are known to be I-poor and rock dissolution processes may yield groundwater with I concentrations which are insufficiently high for health requirements. Processes leading to element excess may affect surface waters but groundwaters are far more vulnerable because of the greater contact times for mineral reactions to take place. Although groundwaters are of much better quality from a microbiological perspective, quality with respect to inorganic constituents must also be considered before groundwaters can be considered safe for potable supply.

Despite the much lower concentrations of pollution-derived pathogenic organisms in groundwaters, populations of naturally-occurring microbes may still be considerable. These rarely represent a health hazard but many may play an important role in a number of geochemical processes, particularly redox processes. Microbes have been detected in a wide range of geological environments (e.g. Pederson et al., 1991; Amy et al., 1992) and to considerable depths (e.g. up to 2 km depth in the Paris Basin, Daumas et al., 1986). An integrated investigation of both geochemical and microbiological processes should therefore give greater insight into the major mechanisms of mobilisation of constituents of health concern in groundwaters used for potable supply.

This report considers the quality of drinking waters from two areas in Ghana with respect to their potential effects on human health. Precambrian basement rocks (principally metasediment, greenstone, metaigneous and granitic rocks) comprise about 40% of the area of Ghana (Figure 1.1) and a large rural population depends entirely on groundwater abstracted from them. The quality of the groundwater is therefore crucial to human health. Two typical areas, the Obuasi and Bolgatanga areas in Ashanti and Upper East Regions (Figure 1.1), have been chosen for investigation of regional water quality and its controlling geochemical and microbiological processes as well as its impacts on the health of local rural populations.

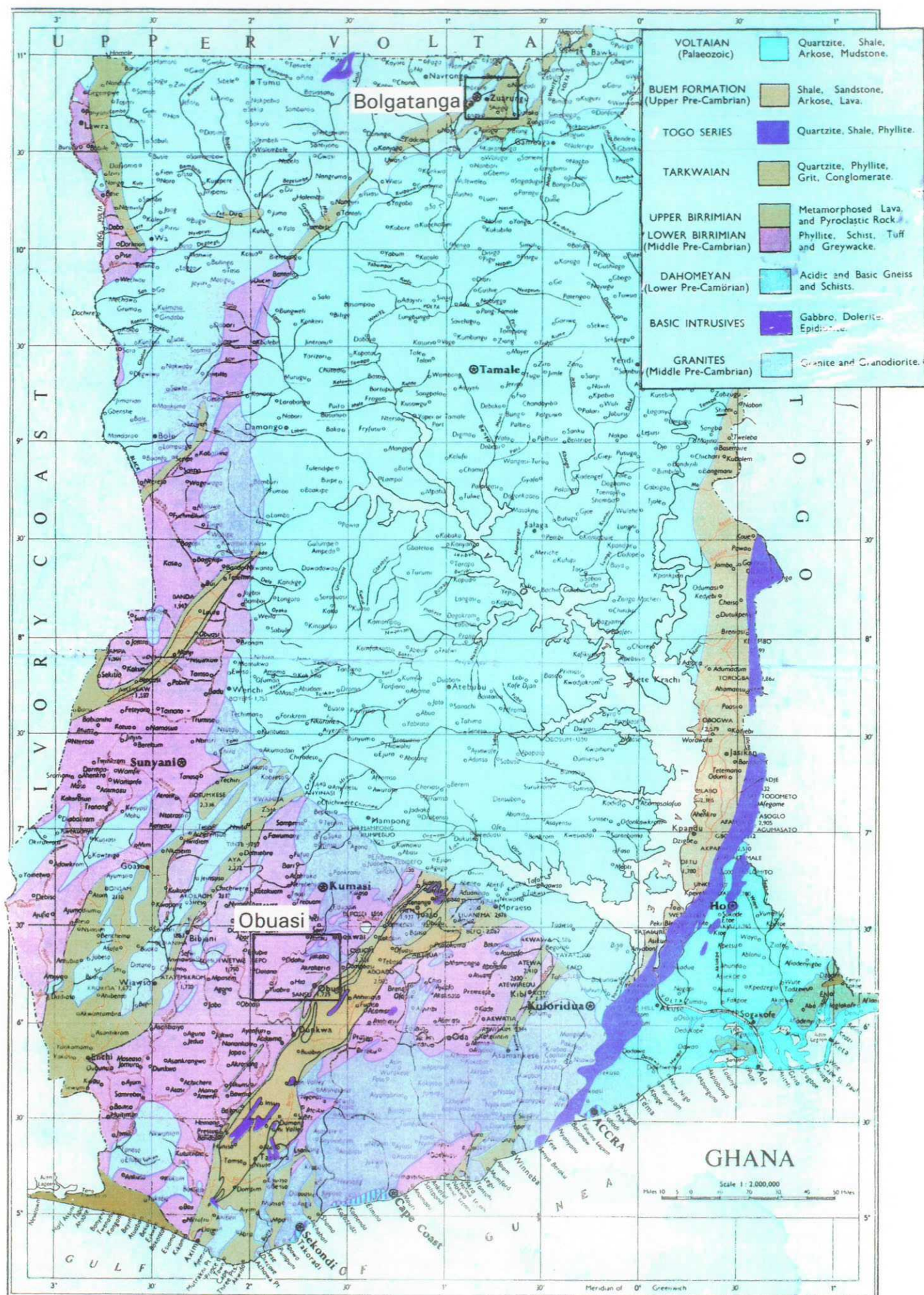


Figure 1.1. Geological map of Ghana showing the two study areas: Obuasi (Ashanti Region) and Bolgatanga (Upper East Region). After Survey of Ghana 1:2,000,000 map (1969).

2 ARSENIC AND RELATED ELEMENTS IN DRINKING WATERS FROM THE OBUASI AREA, ASHANTI REGION

2.1 Introduction

Arsenic has long been recognised as a toxin and carcinogen. A relatively high incidence of skin and other cancers has been noted in populations ingesting water with high As concentrations (WHO, 1993) and other disorders, especially some dermatological (e.g. Bowen's disease, hyperkeratosis, hyperpigmentation), cardiovascular (Blackfoot disease, Raynaud's syndrome), neurological and respiratory diseases are linked to arsenic ingestion and exposure (e.g. Gorby, 1994). Recent epidemiological evidence has led WHO to decrease its recommended maximum value for As in drinking water from $50 \mu\text{g l}^{-1}$ to $10 \mu\text{g l}^{-1}$ (WHO, 1993) in recognition of its potential health risks, although many regulatory bodies such as the EU and US-EPA have not yet followed suit. Arsenic is a relatively common trace element in the environment and this guideline maximum is frequently exceeded in drinking-water supplies. Many cases of chronic and acute endemic As poisoning from drinking water have been documented, notably cases in Taiwan (Tseng et al., 1968, Chen et al., 1994), Argentina (Astolfi, 1971), Chile (Zaldivar, 1974), China (Wang and Huang, 1994) and Mexico (Cebrián et al., 1994). Wang and Huang (1994) claimed that no morbidity cases were found where drinking-water concentrations were less than $100 \mu\text{g l}^{-1}$, but that morbidity increased exponentially as aqueous As increased. Mild As poisoning was observed between 100 and $200 \mu\text{g l}^{-1}$.

The average concentration of As in the earth's crust is $1.5\text{--}2 \text{ mg kg}^{-1}$ (National Academy of Sciences, 1977). It occurs in many geological materials including shales, phosphorites and iron and manganese ores, but is found in highest concentrations in sulphide minerals, especially arsenopyrite, as well as realgar (AsS), orpiment (As_2S_3) and in solid solution in pyrite (FeS_2). Terrains rich in sulphide-bearing strata can therefore have high concentrations of dissolved As in rivers and groundwaters derived by sulphide oxidation. In south-west Taiwan for example, water from artesian wells in sulphide-rich black shales has concentrations of As as high as 1.8 mg l^{-1} . Here, a clear dose-response relationship has been found between As ingestion and occurrences of endemic skin cancer, hyperpigmentation, keratosis and Blackfoot disease (Tseng et al., 1968).

Mining of sulphide ore bodies can pose a particular problem of As pollution and many ore smelting operations are well known to release large quantities of As into the environment (e.g. Díaz-Barriga et al., 1993; Lagerkvist and Zetterlund, 1994). Concentrations of As up to $240 \mu\text{g l}^{-1}$ have been found in polluted river water draining a tin-mining area in south-west England (Hunt and Howard, 1994). Wilson and Hawkins (1978) found concentrations of As ranging from $5 \mu\text{g l}^{-1}$ up to 1.2 mg l^{-1} in streamwaters draining the Fairbanks gold-mining district of Alaska. Acidic waters draining a gold-mining area in Zimbabwe were reported to contain up to 72 mg l^{-1} of As (Williams and Smith, 1994) and high As contents have also been reported in lake sediments affected by former gold mining in the Waverley area of Nova Scotia (Mudroch and Clair, 1986).

The town of Obuasi (Ashanti Region) in Ghana has been the centre of large-scale gold-mining activity since the late 19th century. The main gold-bearing ore is arsenopyrite. Mining activity is known to have given rise to substantial airborne As pollution from the ore-roasting chimney in the town as well as riverborne As pollution derived from nearby tailings dams. Some studies of As exposure of mine workers in Obuasi have been carried out (Amasa, 1975)

but little information is available about the concentrations of As and other potentially toxic metals in the drinking water of rural communities around the town, both as a result of pollution from the mining activity and from natural processes of water-rock interaction and sulphide oxidation. This paper investigates the concentrations of As in drinking water from streams, shallow dug wells and boreholes in a 40 x 40 km area around the town as well as the composition of deep groundwaters (70–100 m depth) from mine-exploration boreholes and mining effluent. Arsenic has also been determined in urine samples from volunteers in two selected villages. The main processes of As mobilisation in the natural groundwater environment of the Obuasi region and the impact of As on the health of local rural communities are assessed.

2.2 Hydrogeochemistry and biogeochemistry of arsenic

Arsenic can occur in the environment in several oxidation states (-3 to +5) but in natural waters is mostly found as an oxyanion in trivalent (arsenite) or pentavalent (arsenate) form. Equilibrium speciation of As has been described in detail by Ferguson and Gavis (1972) and Brookins (1988). In oxidising environments, arsenate is the dominant form: under acidic conditions (pH less than about 6.9), H_2AsO_4^- may be stabilised, whilst at higher pH, HAsO_4^{2-} will be more stable (H_3AsO_4 and AsO_4^{3-} may be present in extremely acidic and alkaline conditions respectively). Under reducing conditions at pH less than about 9.2, the arsenite species H_3AsO_3^0 should predominate (Brookins, 1988). Arsenic can therefore be stable in dissolved form over a wide range of Eh and pH conditions. However, under reducing conditions in the presence of sulphur, As concentrations are limited by the low solubility of As sulphide minerals, such as realgar and orpiment. Little information is available about the rates of As reactions in natural waters and specific rate constants are largely unknown. At near-neutral pH, the rate of oxidation of As(III) to As(V) is known to be very slow, but may proceed faster (order of days) under more extreme pH conditions (Ferguson and Gavis, 1972).

Water pH has an important impact on As release rates from minerals. Leaching experiments on river sediments contaminated by mine waste have shown that As release to solution is lowest at near-neutral pH; release is enhanced under both acidic and alkaline aqueous conditions (Mok and Wai, 1989; 1990; Howell, 1994).

Most of the As in waters is present in inorganic form (e.g. Cebrián et al., 1994). However, organic arsenicals are also known to be stabilised by methylation reactions involving bacteria and algae (Mok and Wai, 1994). Monomethylarsonic acid (MMAA) and dimethylarsinic acid (DMAA) have for example been observed, albeit in small quantities, in some river waters and porewaters by biotransformation of inorganic As compounds (e.g. Faust et al., 1987). Demethylation reactions are also known to occur in water.

Mobility of As in water is limited by sorption onto ferric oxyhydroxide, humic substances and clays (e.g. Mok and Wai, 1994). Wauchop (1975) showed that sorption of As species onto sediments was in the order: arsenate > MMAA > arsenite > DMAA and Howell (1994) found that sorption onto Fe oxyhydroxide and oxide minerals was in the order $\text{As(V)} > \text{DMAA} = \text{MMAA} > \text{As(III)}$ at pH values less than 7, the degree of sorption being greater on amorphous oxyhydroxide (goethite) than on crystalline Fe oxide (haematite). Arsenic should therefore be less mobile in oxidising environments, firstly because of the greater tendency for sorption of As(V) than As(III) and secondly, the lower solubility of ferric oxyhydroxide under

such conditions (Peterson and Carpenter, 1986). Dissolved arsenic is therefore more commonly found in reducing waters, often correlating well with dissolved Fe concentrations.

Arsenic toxicity is dependent on both its oxidation state and partitioning between organic and inorganic phases. Reduced forms tend to be more toxic than oxidised forms and inorganic species more toxic than organic, though toxicity of reduced organic forms such as trimethylarsine is relatively high. Toxicity decreases from arsine (-3) through arsenite (inorganic trivalent), arsenoxides (organic trivalent), arsenate (inorganic pentavalent), arsonium compounds to native arsenic (Morton and Dunette, 1994). Arsenic(III) is known to be up to 60 times more toxic than As(V) due to its reactivity with, and inhibition of, sulphhydryl-bearing enzymes in human metabolism (Squibb and Fowler, 1983). However, some *in vivo* reduction of As(V) to As(III) may take place (Vahter and Envall, 1983).

The most common sources of ingested As (in the absence of direct pollution sources) are drinking water and food. Some foodstuffs are known to contain high concentrations of As, especially seafood (up to $40 \mu\text{g g}^{-1}$, National Academy of Sciences, 1977), although this contains As almost entirely in organic form as arsenobetaine ($(\text{CH}_3)_3\text{As}^+\text{CH}_2\text{CO}_2^-$) and to a lesser extent as arsenocholine ($(\text{CH}_3)_3\text{As}^+\text{CH}_2\text{CH}_2\text{OH}$), both of which are of very low toxicity. Most other foodstuffs contain As (in either organic or inorganic form) in the range $0.1\text{--}1.0 \mu\text{g g}^{-1}$. Since the most common species in water are inorganic, this represents potentially the most detrimental source of As in the human diet, especially if present in reduced form.

Arsenic tends not to accumulate in the body but is readily excreted via the kidneys (e.g. Vahter and Lind, 1986). Urine is therefore a good indicator of environmental As exposure and many studies of populations exposed to airborne As from smelters have been reported. Since seafood is known to be a major source of As (in organic form), most studies report both inorganic and organic (seafood-derived) As content.

Background concentrations of inorganic As in urine are largely reported in the range $10\text{--}23 \mu\text{g l}^{-1}$ (Braman and Foreback, 1973; Bencko and Symon, 1977; Vahter and Lind, 1986; Pan et al., 1993). Lin et al. (1985) quoted a somewhat higher background value of $63.4 \mu\text{g l}^{-1}$ although the proportion of As present in inorganic form is not known.

Concentrations of As in urine from smelter workers exposed to airborne As are higher: Kodama et al. (1976) reported a value of $56 \mu\text{g l}^{-1}$ and Lagerkvist and Zetterlund (1994) gave a mean value of $61 \mu\text{g l}^{-1}$ in urine from smelter workers. Concentrations of As in urine of people having recently eaten seafood can reach up to $1000 \mu\text{g l}^{-1}$ (Pinto et al., 1976), mostly as arsenobetaine.

2.3 Obuasi: local environment and geology

Ashanti region is in the tropical rainforest belt of southern Ghana. It receives a high annual rainfall (about 1580 mm) with a pronounced wet season from March to November and a diurnal temperature range of $20\text{--}30^\circ\text{C}$. Evaporation is also high, about 1260 mm yr^{-1} although rainfall exceeds evaporation for about 8 months of the year (March to October). Much of the Ashanti region comprises natural forest, although many places have been cleared for cocoa and food-crop production. River flows in the region are mainly from north-east to south-west and are dominated by two rivers, the Oda and the Gyimi rivers, separated by the Sansu-Moinsu

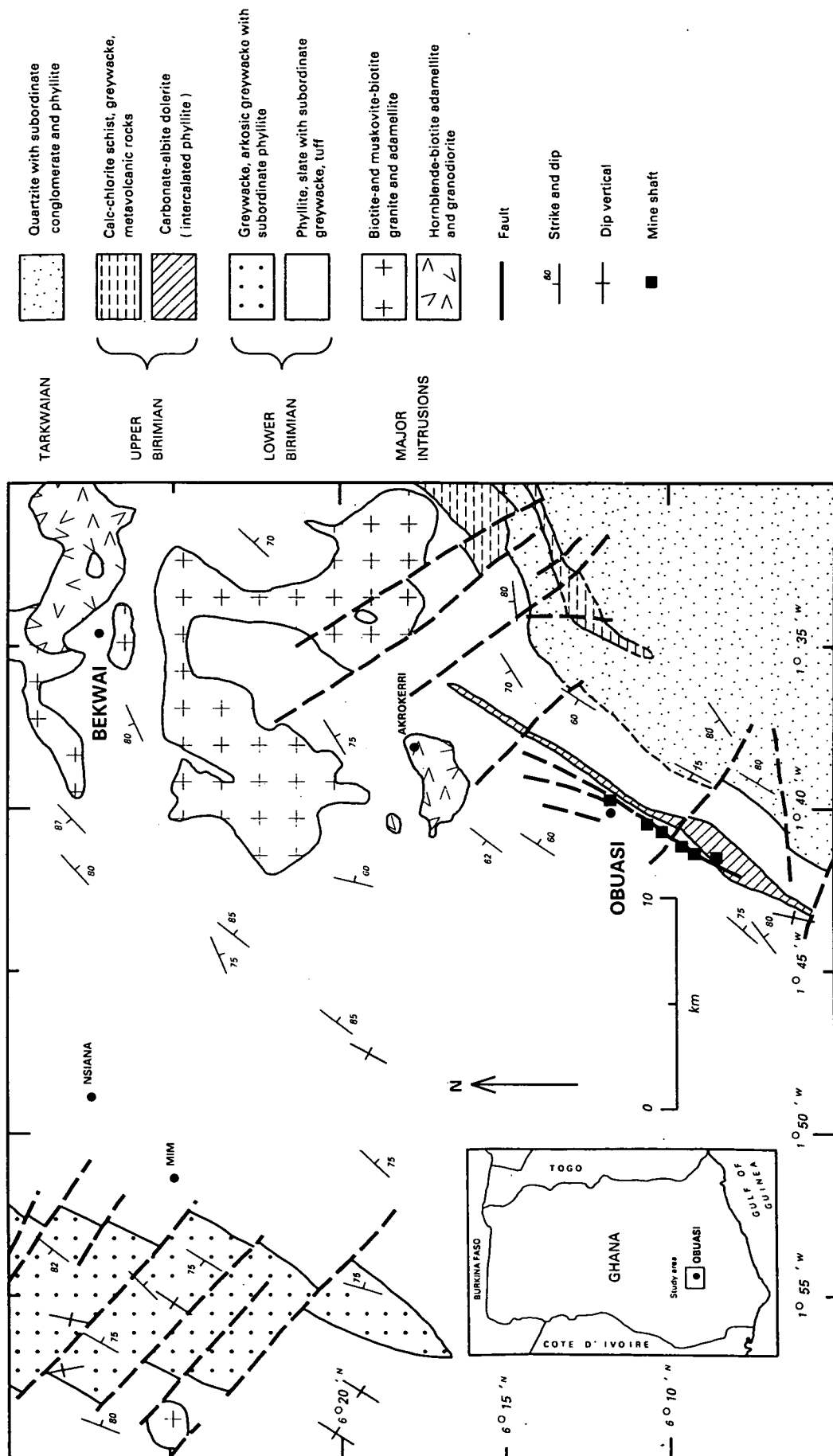


Figure 2.1. Geological map of the Obuasi area showing mine shafts (after Ghana Geological Survey 1:62.5K maps; Bowell, 1992). Location of the study area is indicated in the inset map.

hill range (maximum height around 600 m).

The geology of the area is summarised in Figure 2.1. Underlying bedrocks are of Birimian (Proterozoic) metasediment and metavolcanic rocks, the Lower Birimian comprising mainly schist, phyllite and metagreywacke as well as granite and the Upper Birimian comprising mainly metavolcanic rocks (Kesse, 1985; Figure 2.1). These were subjected to intensive folding and faulting and metamorphosed to greenschist grade during the Eburnian orogeny (1830–2030 Ma).

Gold mining has been the major industry in the Ashanti region since the late 19th century. Ore deposits occur in a major shear zone with a proven lateral extent of 8 km and depth of 1600 m (Amanor and Gyapong, 1988). Numerous shafts and surface operations occur along the shear zone in the vicinity of Obuasi (Figure 2.1). The gold is present as both disseminated grains in quartz reefs and in association with sulphide minerals, particularly arsenopyrite (Bowell, 1992).

Processing of the gold ore is carried out at the Pompora Treatment Plant (PTP; Plate 2.1) in Obuasi where the ore is crushed, roasted and extracted by a cyanide complexation process. Spent ore is collected in nearby tailings dams and although the liquid effluent from the dams is now recycled in the gold-extraction process, at the time of field investigation it was discharged directly into a local stream, the Kwabrafo (Plate 2.2). This stream flows southerly on the east side of the town, joining the Pompo River 5 km south-east of Obuasi and thereafter flowing into the Gyami River. The effluent is known to contain large quantities of dissolved As, SO_4 and CN from the extraction and concentration process and as a result has caused serious pollution of the stream waters downstream of the input point. Additional discharges from the mine workings occur from tailings-dam overflows, pumping of minewater drainage into local streams (Plate 2.3) and runoff from slime dams during periods of heavy rainfall.

Arsenic (as arsenic trioxide, As_2O_3) and sulphur (SO_2) were also emitted into the atmosphere via the PTP chimney until the recent installation of an As scrubber which reduced the levels of As emissions considerably (Ashanti Goldfields Corporation Environmental Laboratory, pers. commun. 1993). The prevailing wind direction is northerly and as a result of long-term emissions from the chimney, vegetation on the northerly slopes adjacent to the chimney has been killed or badly damaged. Defoliation as a result of both airborne arsenic and sulphur contamination has been observed up to 8 km north of Obuasi (Amasa, 1975). This has resulted in severe erosion of bare slopes by high rainfall.

High As concentrations in hair samples of workers from the PTP attest to the former high incidence of airborne As pollution from the mining activity. Amasa (1975) found that hair samples from workers at the PTP ranged between $196 \pm 7 \mu\text{g g}^{-1}$ and $1940 \pm 62 \mu\text{g g}^{-1}$. Arsenic concentrations of soils and vegetation were also found to be high (up to $148 \mu\text{g g}^{-1}$ and $4700 \mu\text{g g}^{-1}$ respectively). Amasa (1975) noted that residents of villages 8–10 km north of the town claimed to have suffered eye inflammations as a result of mine emissions.

Soils in the Obuasi region are leached kaolinite-muscovite laterites with average thicknesses of 1–3 m, although the thickness depends on underlying saprolite lithology, topography and drainage (Bowell, 1993). Bowell (1993) studied soil profiles 40 km east of Obuasi and noted that As was concentrated in the upper A horizon of the soils, in association with the higher content of organic matter in this layer. Concentrations of As were noted to be very low at

0.2–0.3 mg kg⁻¹ in the A horizon of profiles not contaminated by mining activity, decreasing to an even lower value of 0.01 mg kg⁻¹ in the argillaceous (B) horizon below. Soil As in the Ashanti concession has much higher concentrations of between 1 and 1530 mg kg⁻¹ (mean 41.2 mg kg⁻¹; N. Bailie, pers. commun., 1993). Saprolite thickness is variable but is mostly in the range 10–20 m (Gibb and Partners, 1992). In much of the saprolite, arsenopyrite appears to have been replaced by secondary As- and Fe-bearing minerals, including scorodite (FeAsO₄·2H₂O), haematite, arsenolite, amorphous iron oxides and arsenates (Bowell, 1992).

Groundwater flow in the Birimian aquifer is predominantly via fracture zones, mostly along quartz veins. Rest-water levels in the Obuasi area are mainly in the range 2.5–7.5 m below ground level with a seasonal variation of several metres (Gibb and Partners, 1992) although the piezometric surface for the whole area studied is believed to reflect the surface topography closely. Groundwater flow direction is principally from north-east to south-west.

2.4 Health aspects

Many rural communities in the Obuasi area have either never had access to groundwater, or boreholes drilled over the last few years have fallen into disrepair through lack of maintenance. Use of surface waters for potable and domestic supply is therefore common. Education on the relationship between water quality and health is generally poor. As a result, water-borne diseases such as bilharzia and dysentery are common among streamwater and well-water drinkers. Bilharzia is spread particularly during the dry season since stream flow rates are very low and favourable for development of the parasite in snail hosts. Guinea worm is rare though present in parts and occasional cholera outbreaks occur, especially during the wet season (J. Ansah, AGC Hospital, Obuasi, pers. commun. 1993). Such water-borne diseases usually have much lower prevalence among communities using groundwater.

Despite the occasional incidence of skin mottling (depigmentation) and rashes, no diseases that could be unequivocally attributed to As ingestion were observed among the rural communities in the study area.

2.5 Sampling and analysis

Water samples from a 40 x 40 km area around Obuasi (Figure 2.2) were collected in January 1993, towards the end of the dry season. It was intended to collect samples from boreholes as well as a few hand-dug wells in the area. However, many rural water-supply boreholes had been abandoned due to lack of ability or willingness to pay maintenance costs and many communities have therefore resorted to surface-water sources which are generally highly coloured (humic substances) with high suspended-solids and poor bacteriological quality. Since such water sources constituted the drinking water of many communities, these too were sampled. In all, 65 boreholes, 13 shallow wells and 26 streams used for drinking water were sampled in our study.

On-site analysis comprised temperature, specific electrical conductance (SEC, corrected to 25°C), HCO₃ (measured as total alkalinity), pH, Eh (temperature-corrected) and dissolved oxygen, the last three of which were measured in an anaerobic flow-through cell attached in-line to borehole water outlets. Boreholes were pumped until stable readings for these parameters were obtained (usually 15–20 minutes). Streams and shallow wells were not pumped and so pH and dissolved oxygen were measured either at source or from a collected



Plate 2.1. Obuasi mine complex and the ore-roasting chimney. Hill slopes to the north of the chimney (prevailing wind direction) have been stripped bare of vegetation by historic atmospheric emissions of arsenic trioxide (and sulphur dioxide) from the plant.



Plate 2.2. Tailings effluent from a nearby tailings dam being pumped directly into the Kwabrafo stream. Tailings effluent is now recycled rather than discharged.

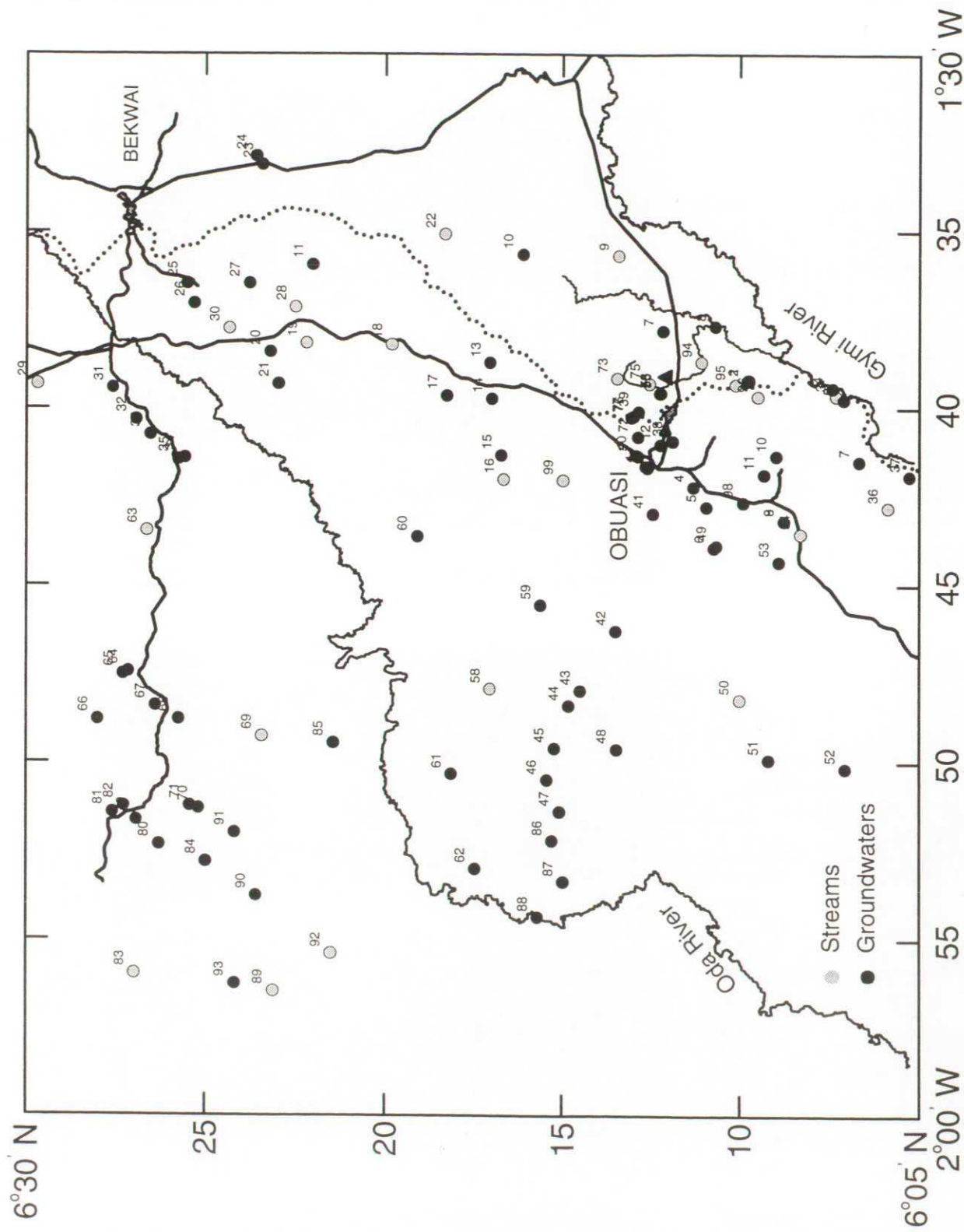


Figure 2.2. Map of the Obuasi area showing sampling sites (streams and groundwaters). Roads are shown in solid black, railway in dotted black. Rivers are also shown.

sample (on-site); no Eh readings were taken at these sites. Filtered (0.45 μm) samples were also collected in acid-washed polyethylene bottles for subsequent laboratory analysis. Samples for major-cation, SO_4 and trace-element analysis were acidified to 1% HNO_3 (v/v, Aristar), unacidified samples were collected for anion analysis and separate HCl-acidified aliquots were collected for As(III) and total As analysis. Samples were stabilised at ca. pH 4 for As(III) analysis and subsequently acidified to 2% HCl (v/v Aristar) for As_{total} analysis.

Major cations, SO_4 , Si, Al, P, V, Fe_{total} , Mn, Sr and Ba were analysed by ICP-AES using an ARL 34000C optical emission spectrometer; Cl, N species, I and F by automated colorimetry, other trace elements by ICP-MS (Fison's PQ1 instrument) and As by hydride-generation ICP-AES (using an ARL 341 hydride generator). Total As was analysed by pre-reduction of all As(V) to As(III) in samples 24 hours before analysis using 5% KI (2.5 ml 20% KI in 7.5 ml sample solution), followed by on-line hydride generation using 1% w/v NaBH_4 in 0.1% w/v NaOH (Trafford, 1986). Arsenic(III) was analysed using a modified version of the method given by Driehaus and Jekel (1992). Arsenic(III) was reduced to arsine by NaBH_4 at pH > 3.5 using 0.5 M acetic acid as buffer solution (to prevent As(V) also being reduced at lower pH; Driehaus and Jekel, 1992). The acetic-acid method has the limitation that it fails to separate As(III) from DMAA (Anderson et al., 1984) and therefore analyses quoted in this paper for As(III) are strictly for the two species. However, since methylated As species usually have very low concentrations in natural waters, the values listed are probably dominated by As(III). The As(III) method used is known to suffer from suppression of the As(III) signal by high concentrations (order of 1 mg l^{-1} and above) of Fe, Cu and Ni (e.g. Driehaus and Jekel, 1992). All samples except one of mine-tailings effluent had very low concentrations of Cu and Ni and suppression from these elements is thought to be insignificant. Suppression of the As(III) signal by Fe at the concentrations found in most samples should also be negligible except in some of the minewaters which have up to 20 mg l^{-1} Fe. The As(III) data for these, together with the single tailings-effluent sample, may have suffered serious suppression of the As(III) signal and must therefore be taken as minimum values (Appendix 1B).

Eighty per cent of samples analysed had ionic charge imbalances of less than 5%. Charge imbalances were poorer for some samples due to low TDS concentrations. The accuracy of ICP-AES and ICP-MS analyses was periodically checked using international reference standards. Mean analyses and 1σ standard deviations for the National Research Council of Canada standard SLRS1 analysed by ICP-AES just prior to the Obuasi samples included (certified values in parentheses; mg l^{-1}): Na: 9.7 ± 0.2 (10.4 ± 0.6), K: 1.30 ± 0.07 (1.30 ± 0.20), Ca: 29.0 ± 0.7 (25.1 ± 0.9), Mg: 5.8 ± 0.1 (5.99 ± 0.28), Ba: 0.020 ± 0.002 (0.022 ± 0.001), Fe: 0.036 ± 0.006 (0.031 ± 0.002) and Sr: 0.137 ± 0.003 mg l^{-1} (0.136 ± 0.003 ; $n=14$). Precision of ICP-AES data is typically of the order of 2% RSD (Fe: 5%). Mean concentrations for the National Institute of Standards and Technology standard 1643C obtained by ICP-MS during the course of sample analysis were: Al: 119 ± 67 (certified value: 114 ± 5.1), Cr: 20.4 ± 1.3 (19.0 ± 0.6), Co: 25.8 ± 1.5 (23.5 ± 0.8), Ni: 63.0 ± 3.7 (60.6 ± 7.3), Cu: 22.6 ± 1.3 (22.3 ± 2.8), Zn: 70 ± 11 (73.9 ± 0.9), Sr: 269 ± 8 (263.6 ± 2.6), Mo: 111 ± 3 (104.3 ± 1.9), Cd: 11.7 ± 0.2 (12.2 ± 1.0), Ba: 50.9 ± 0.9 (49.6 ± 3.1), Pb: 35.5 ± 1.3 $\mu\text{g l}^{-1}$ (35.3 ± 0.9 ; $n=3$) and Rb: 12.1 ± 0.2 $\mu\text{g l}^{-1}$ (11.4 ± 0.2 ; $n=4$). The mean concentration for total As in 1643C by ICP-AES hydride during the course of sample analysis was 75.5 ± 6 $\mu\text{g l}^{-1}$ ($n=4$, certified value 82.1 ± 1.2 $\mu\text{g l}^{-1}$) and SPEX standard EP8 gave a value of 10.5 ± 0.4 $\mu\text{g l}^{-1}$ ($n=4$, certified value 10.0 $\mu\text{g l}^{-1}$). Detection limits are quoted as 3σ about the variation of the blank concentration although precision is poorer at these low levels. Detection limits are given as 6σ for As_{total} and As(III) analyses.



Plate 2.3. Iron-rich water derived from the Obuasi mine complex causing contamination of local streams.



Plate 2.4. Fenaso stream (sampling point 50) showing typical enrichment in colloidal iron and organic matter of surface waters in the Obuasi area.

Microbial numbers in Obuasi waters were evaluated using two methods: spread-plate technique with solid agar using CPS medium was used to measure numbers of aerobic heterotrophic bacteria and total bacterial counts were measured on selected samples using epifluorescence microscopy. Spread plates were inoculated with water sample in the field and colonies counted 10-20 hours later. Epifluorescence analysis was carried out at BGS laboratories, Keyworth. Full analytical details are given in West et al. (1995).

Urine samples were collected from sample populations in two villages (30 volunteers in each) in the Obuasi area. Samples were collected in 30 ml sterile containers and frozen before analysis. Each represented a single casual, rather than 24-hour bulked sample. Records were made of villagers' age, occupation, sex, general health and dietary intake over the previous 24 hours. Sample digestion for reducible As was achieved by adding 4 ml concentrated HCl to 2 ml of urine and refluxing in an air condenser for 2-3 hours. Condensers were then washed down and the wash added to the sample; 1 ml 20% KI was added and the sample made up to 20 ml using deionised water. The reducible fraction is strictly inorganic As(III), As(V) and the methylated metabolite MMAA but the method does not quantitatively reduce DMAA. Since MMAA is usually a minor constituent of urine (Naqvi et al., 1994), the reducible fraction can be taken mainly to represent the concentration of inorganic As species. Digestion for total As involved mixing 2 ml of urine with 1 ml of a concentrated HNO_3 - HClO_4 - H_2SO_4 solution in the ratio 20:10:1. Samples were heated from 150°C to 300°C in steps of 30°C every 15-20 minutes and the resultant salt residue then dissolved in 5 ml deionised water and 4 ml HCl. Finally, 1 ml of KI was added to each sample and made up to 20 ml using deionised water. All solutions were heated to 90°C for 20 minutes prior to analysis to ensure total reduction of all As to As(III). Both total As and reducible As were analysed by the National Poisons Unit, Guy's Hospital, London by hydride-generation atomic absorption spectrometry.

2.6 Results and Discussion

2.6.1 Mine-effluent discharge

Chemical data given by Gibb and Partners (1992) for tailings effluent from the Obuasi mine reveal it to be a highly toxic cocktail of chemicals including especially As and CN derived from the roasting and extraction process. These are discharged directly to nearby streams with no prior treatment or control. One sample taken during this study of the effluent being pumped directly into the Kwabrafo stream on the east side of Obuasi (Appendices 1A-1C) showed this to be an alkaline solution (pH 8.45) incorporating a range of toxic substances including dissolved As of 1.8 mg l^{-1} , SO_4 of 1750 mg l^{-1} and CN of 30 mg l^{-1} (CN analysed for this study by Ashanti Goldfields Corporation laboratory). Concentrations of NH_4 , P, B, Co, Ni, Cu, Zn, I, Sr, Rb, Mo, Sb, Ag, Au and W are also very high in this effluent (Appendices 1A-1C). The As(III) content of the sample is only $50 \text{ } \mu\text{g l}^{-1}$ and suggests that most of the As in the effluent is present as oxidised As(V). However, for reasons stated above, the low As(III) value may be an artefact of the analytical method and the ratio of As(III) to As_{total} may be higher than that quoted. The high concentrations of dissolved solutes in the effluent are most likely due to the formation of CN⁻ complexes.

The concentration of As in the Kwabrafo stream just a few metres downstream of the effluent discharge point (sample collected January 1993) was 7.9 mg l^{-1} and SO_4 1130 mg l^{-1} . Concentrations of P, B, I, Ni, Co, Mo, Ag and Sb were 1.4 mg l^{-1} , $740 \text{ } \mu\text{g l}^{-1}$, $533 \text{ } \mu\text{g l}^{-1}$,

62 $\mu\text{g l}^{-1}$, 68 $\mu\text{g l}^{-1}$, 7.2 $\mu\text{g l}^{-1}$, 0.24 $\mu\text{g l}^{-1}$ and 10 $\mu\text{g l}^{-1}$ respectively. A sample of Kwabrafo streamwater taken at the same time from several hundred metres upstream of the effluent-discharge point also revealed a high total As concentration (though much lower than the effluent; 0.35 mg l^{-1}), probably as a result of wash-in of pollutants to the stream from various points upstream in the mine area.

The quality of the Pompo and Gympi river systems downstream of the mine complex has not been investigated in this study although it is thought to have been seriously impaired over a distance of many kilometres. Concentrations of CN are expected to diminish downstream (and in groundwaters) due to degradation in the aerobic environment. This may lead to decreased trace-metal mobilisation as CN complexes break down but will result in increased concentrations in stream sediments. However, mobilisation of many trace elements, including As, may persist in the streams by binding to organic matter and colloids.

2.6.2 Regional water quality

Representative chemical data for streams, wells and boreholes are given in Appendices 1A-D and median values are summarised in Table 2.1. Waters are usually acidic, median values for streams, wells and boreholes being 6.4, 5.4, and 5.8 respectively. Total-dissolved-solids contents (TDS) are also low, but are highest in the borehole waters (streams, wells and boreholes have median values of 70, 52 and 101 mg l^{-1} respectively; Table 2.1). The low overall TDS concentrations suggest that the waters have had short contact times with host rock materials and that rock dissolution has been relatively small, the borehole waters having undergone the greatest amounts of reaction. Most major elements and some trace elements (e.g. F, Sr, Si) have correspondingly higher concentrations in the borehole waters (Table 2.1). Maps of Ca, Mg, Na and F distribution for streams and groundwaters are given as examples in Figure 2.3. Mineral sources of these elements include particularly feldspar, clay minerals and micas, but some F may also be derived from apatite. All waters sampled are undersaturated with respect to calcite and reflect the general paucity of carbonate in the aquifer, although carbonate is present as a gangue mineral in the auriferous shear zones (Leube et al., 1990). The waters are saturated with respect to quartz, reflecting the dominance of silicate-water interaction processes.

The surface waters are almost universally brown, being rich in organic matter and colloidal Fe (Plate 2.4). Bacterial counts are also usually high in surface and shallow-well waters but are generally much lower in groundwater from hand-pumped boreholes (section 2.6.6).

Most of the groundwaters are oxidising with Eh values between ≥ 300 and 500 mV but some deeper waters have lower redox potentials of around 220–250 mV. These are relatively high values for reducing waters but reflect the low pH of the sources investigated.

Dissolved SO_4 concentrations are usually very low in the Obuasi waters, median values for streams, wells and boreholes being 1.5, 1.1 and 0.4 mg l^{-1} respectively (Table 2.1). All drinking-water sources are undersaturated with respect to barite. Iron contents are variable, the median values for streams being 0.5 mg l^{-1} , wells 0.07 mg l^{-1} and boreholes 0.2 mg l^{-1} .

Three groundwater samples collected from exploration boreholes penetrating to 70–100 m depth at the mine complex have compositions distinct from other groundwaters with much higher TDS values of 500–800 mg l^{-1} . They are moderately reducing with Eh values of

Table 2.1. Median values for major elements and parameters of health significance in Obuasi drinking waters (streams, wells and boreholes). WHO (1993) guideline maximum values are also given for comparison (values in parentheses are for elements for which no recommended guideline maximum is given, but the value represents the limit above which taste problems might occur). TDS: total dissolved solids.

		Streams	Wells	Boreholes	WHO maximum
n		26	13	65	
Temperature	°C	24.3	25.2	26.3	
Well depth	m		3.5	48	
pH		6.42	5.37	5.84	
Ca	mg l ⁻¹	4.8	3.9	7.0	
Mg	mg l ⁻¹	3.1	0.82	3.9	
Na	mg l ⁻¹	8.5	6.6	13.8	(200)
K	mg l ⁻¹	1.4	1.1	0.55	
HCO ₃	mg l ⁻¹	41	21	67	
SO ₄	mg l ⁻¹	1.5	1.1	0.44	500
Cl	mg l ⁻¹	6.2	6.2	6.0	(250)
NO ₃ -N	mg l ⁻¹	<0.2	0.3	<0.2	10
NO ₂ -N	µg l ⁻¹	<5	<5	<5	910
NH ₄ -N	mg l ⁻¹	<0.01	<0.01	<0.01	(1000)
TDS	mg l ⁻¹	70	52	101	
Si	mg l ⁻¹	8.7	8.0	21.3	
Al	mg l ⁻¹	0.03	<0.02	<0.02	0.2
Fe _{total}	mg l ⁻¹	0.5	0.07	0.2	0.3
Mn	mg l ⁻¹	0.03	0.03	0.08	0.5
Sr	µg l ⁻¹	44	38	94	
Ba	µg l ⁻¹	19	29	16	700
As(III)	µg l ⁻¹	<3	<3	<3	
As _{total}	µg l ⁻¹	7	<2	<2	10
Cd	µg l ⁻¹	<0.2	<0.2	<0.2	3
Cu	µg l ⁻¹	1.3	1.5	3.7	
Ni	µg l ⁻¹	1.0	2.2	3.4	
Co	µg l ⁻¹	0.34	1.55	1.33	
Zn	µg l ⁻¹	3.9	27	18	
Sb	µg l ⁻¹	<0.04	<0.04	<0.04	5
Ag	µg l ⁻¹	<0.02	<0.02	<0.02	
Pb	µg l ⁻¹	0.09	0.11	0.06	10
F	µg l ⁻¹	65	50	70	1500
I	µg l ⁻¹	9.1	10.1	6.7	

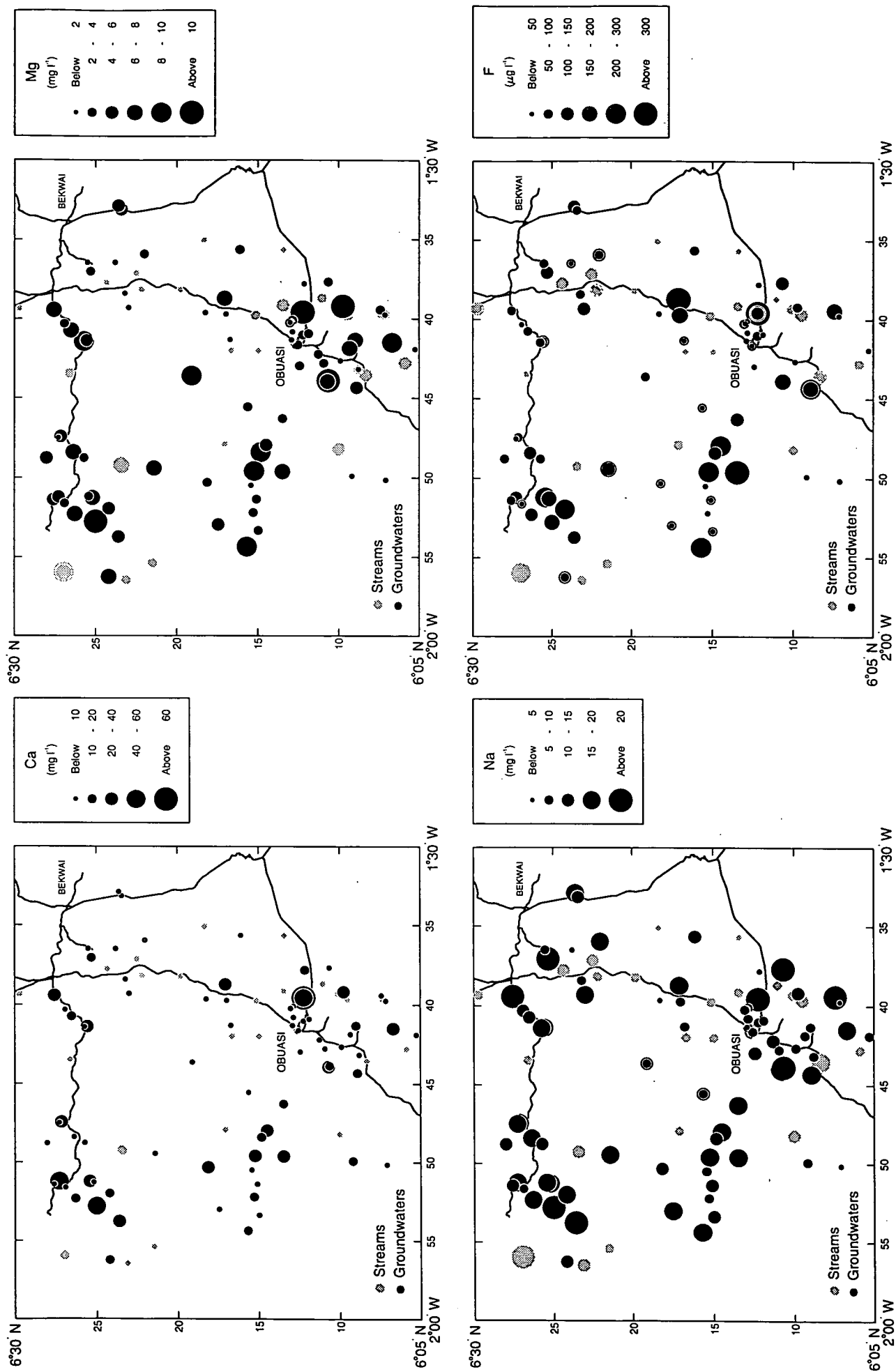


Figure 2.3. Maps of the distribution of Ca, Mg, K and F in surface and groundwaters in the Obuasi area.

260–280 mV. Dissolved oxygen was only measured at one site but gave a low value of 0.1 mg l⁻¹. These groundwaters have high dissolved SO₄ (200–500 mg l⁻¹) and Fe (4–20 mg l⁻¹) concentrations as well as other trace elements such as Mn, Co, Ni, Cu and Zn (Appendices 1A-C). Iron was observed to oxidise and precipitate over the course of several minutes from water abstracted during sampling. These waters are saturated with respect to barite. The high concentrations are most likely the result of oxidation of Fe and related sulphides. One sample of mine drainage being pumped from shafts into a local stream has a particularly high TDS of 1322 mg l⁻¹, high SO₄ of 926 mg l⁻¹ and Fe of 7.6 mg l⁻¹. The sample is saturated with respect to goethite and ferrihydrite. This appears to have undergone extensive sulphide oxidation, probably as a result of introduction of atmospheric oxygen via the open shaft workings.

2.6.3 Distribution of arsenic

Total arsenic concentrations in the Obuasi waters vary between < 2 (detection limit) and 350 µg l⁻¹, although the highest value observed in drinking-water supplies was 175 µg l⁻¹. Twenty per cent of supplies studied exceed the WHO guideline maximum of 10 µg l⁻¹, although only 6% exceed the former WHO and current EC guideline maximum of 50 µg l⁻¹. Concentrations are plotted for streams, wells and boreholes against HCO₃ content as a measure of degree of water-rock (mainly silicate) interaction in Figure 2.4. The streams have the highest values observed. The highest concentration (350 µg l⁻¹) is from the Kwabrafo upstream of the effluent-discharge point and is manifestly affected by mine pollution. Unlike all other samples given in Figure 2.4, this is not a drinking-water supply source.

Shallow wells have universally low As_{total} contents as well as HCO₃ as indicated in Table 2.1. The HCO₃ contents of the groundwaters range up to higher values (258 mg l⁻¹ maximum) as would be expected for groundwaters having infiltrated to deeper levels in the aquifer and having had longer residence times for chemical reaction. The increase in HCO₃ also corresponds with increasing borehole depth (not shown).

Figure 2.4 shows that the total As concentration of the groundwaters notably increases with increasing HCO₃ concentration and suggests that As mobilisation is achieved through greater aquifer residence time. This is corroborated by the observed correlation between As_{total} and borehole depth in at least some of the groundwaters given in Figure 2.5; deeper groundwaters should have had longer periods in contact with aquifer material and hence have undergone greater water-rock reaction with As-bearing mineral phases, particularly sulphides. These deeper, higher-As groundwaters also have lower redox potentials and dissolved-oxygen concentrations (Figure 2.6).

Investigation of the distributions of As_{total} in waters from the Obuasi area (Figure 2.7) shows that the highest values in streams are mainly found to the north of Obuasi town. Groundwaters in this tract of land do not show correspondingly high As concentrations and so it is unlikely that the streamwater As is derived from the bedrock. Since the prevailing wind direction is towards the north, it is suggested that the high-As streamwater values result from airborne pollution derived from the PTP chimney stack in Obuasi. Although an As scrubber has now been fitted to the plant, it is considered that the observed As represents relict pollution which has not yet been flushed from the natural surface-water system because of sorption and precipitation processes involving the soil. Groundwater As_{total} concentrations reach the highest values in the western part (Figure 2.7). This corresponds with deeper (and

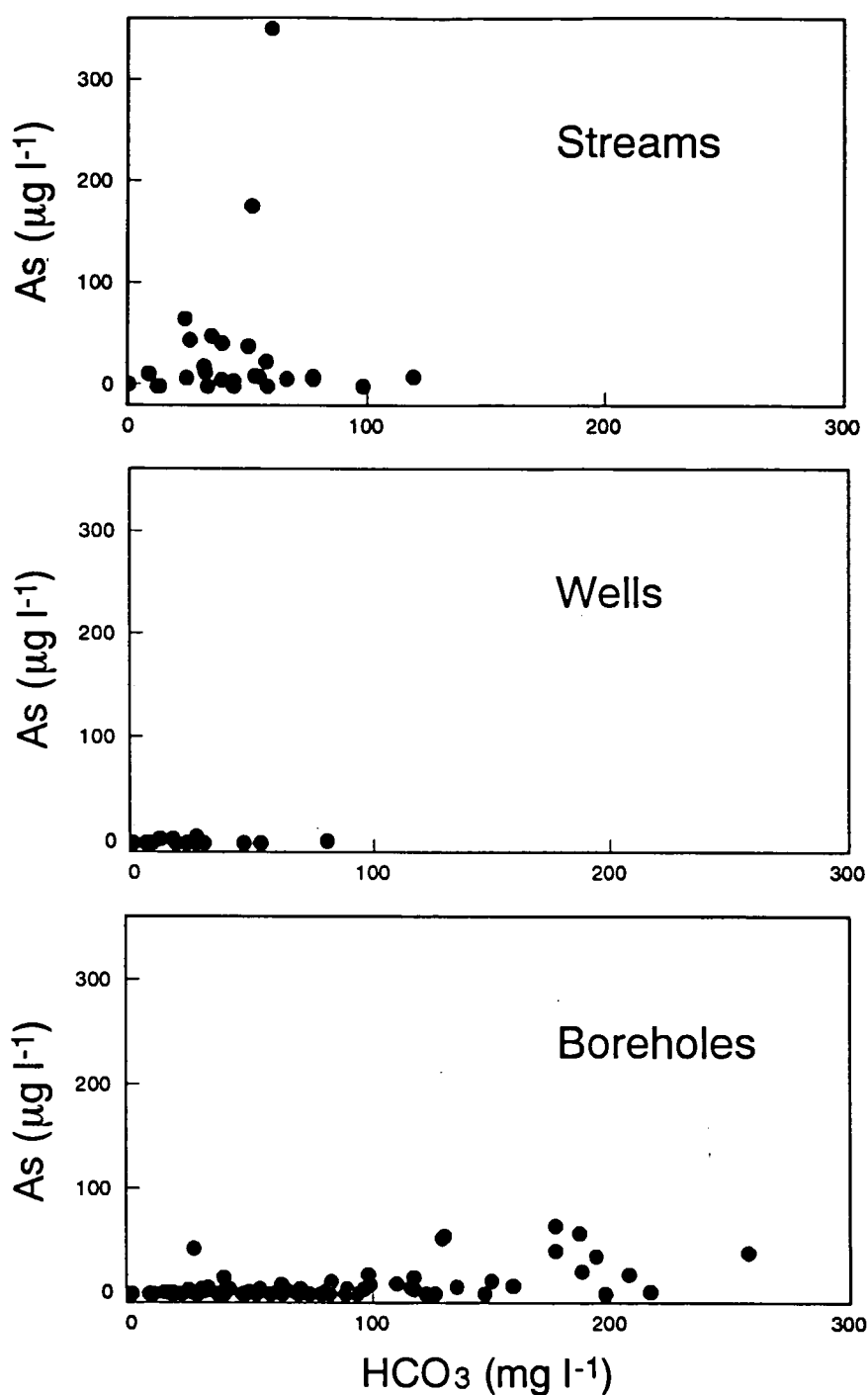


Figure 2.4. Variation of As_{total} with bicarbonate (HCO_3) in water from streams, shallow wells and boreholes in the Obuasi area.

more reducing) groundwaters in this area.

Concentrations of As(III) (strictly As(III) plus DMAA) are presented in Appendix 1B and Table 2.1 and ratios of As(III) to As_{total} are plotted in an Eh-pH diagram in Figure 2.8. The smallest symbols shown in Figure 2.8 represent those samples for which Eh and pH values were determined but either As(III) or As_{total} or both were below detection limits. Figure 2.8

The equations show that the oxidation process may consume all available oxygen and it is likely that this explains why higher As concentrations are observed in low-oxygen, more reducing groundwaters in the Obuasi area (Figure 2.6). The oxidation process also releases Fe and SO_4 (and arsenopyrite releases As) into solution. As noted above, with the exception of the minewaters, SO_4 contents of Obuasi groundwaters are generally quite low. However, the amount of arsenopyrite oxidation required to generate the observed dissolved As concentrations is also small. Assuming a congruent and complete reaction, oxidation of $0.85 \mu\text{mol}$ of arsenopyrite would be required to produce the highest observed As concentration in the drinking-water boreholes ($64 \mu\text{g l}^{-1}$). This would produce a corresponding SO_4 concentration of only $82 \mu\text{g l}^{-1}$ and Fe of $48 \mu\text{g l}^{-1}$. Iron is present in some of the waters in reducing, acidic or organic-rich conditions, but molar Fe/S ratios are usually much lower than the value of 0.5 expected for stoichiometric oxidation of pyrite (and indeed the value of 1.0

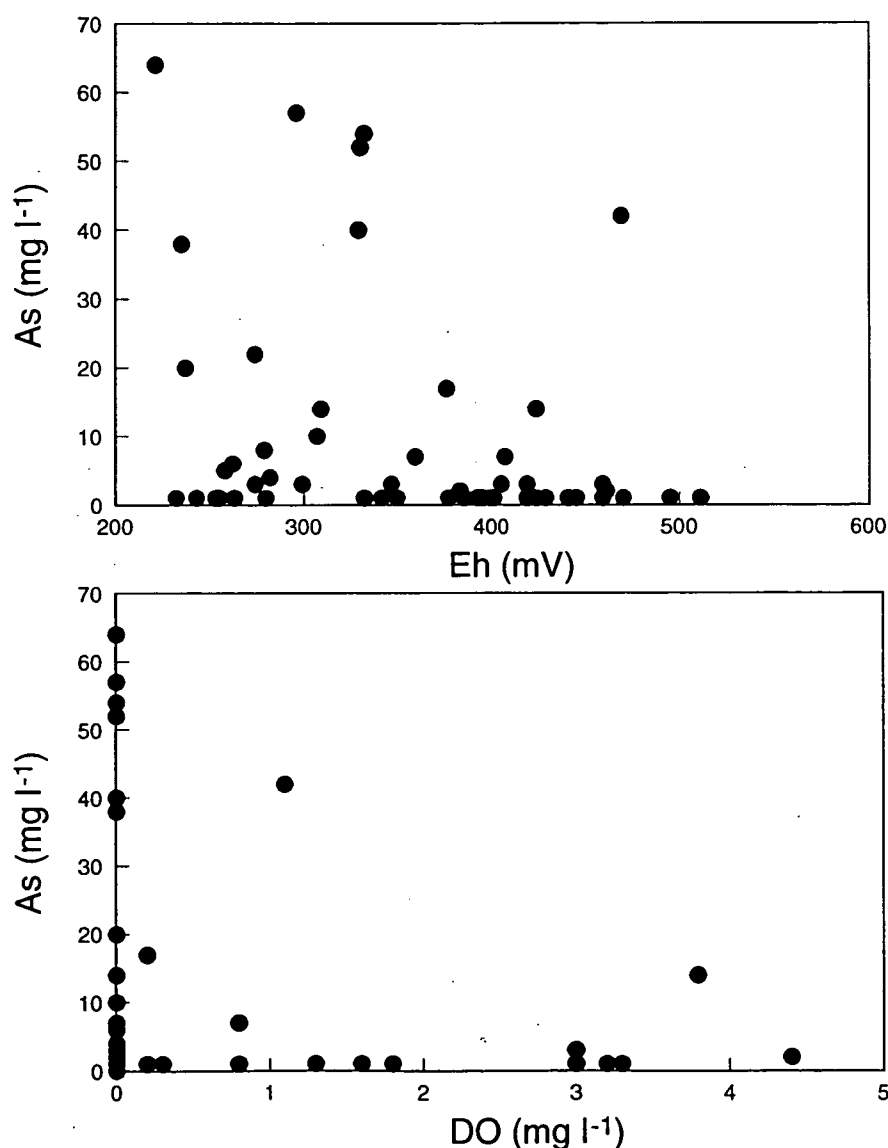


Figure 2.6. Redox potential and dissolved oxygen against As for groundwaters from the Obuasi area.

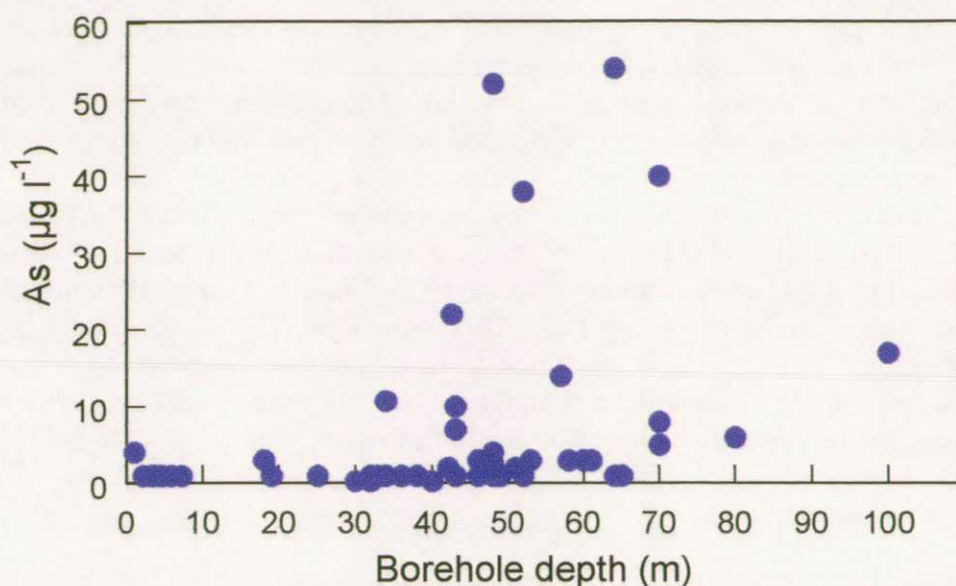


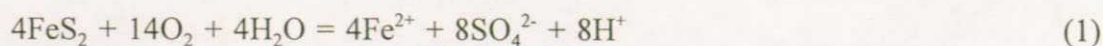
Figure 2.5. Variation of As_{total} with total borehole depth (below ground level) in groundwaters (from wells and boreholes) in the Obuasi area.

shows that the more reducing groundwaters (Eh values ≤ 300 mV) not only have higher As_{total} contents, but also largely have higher $As(III)/As_{total}$ ratios. The higher As_{total} contents of deeper groundwaters may therefore also be due to the lower tendency for sorption of $As(III)$ to Fe species than $As(V)$, together with the lower potential for $Fe(III)$ precipitation under reducing conditions. Since $As(III)$ is much more toxic than $As(V)$, these deeper groundwaters are more a cause for concern with respect to As than the oxidised shallower groundwaters.

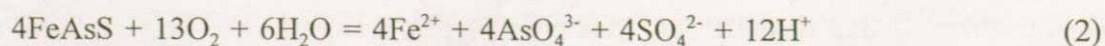
Histograms of the distribution of $As(III)/As_{total}$ in streams and borehole waters are given in Figure 2.9. Whilst most of the groundwaters have ratios lower than 0.5 (the higher values corresponding to the deeper reducing waters), the streams have an apparent bi-modal distribution. Some have values less than 0.3 as would be expected for surface waters in contact with atmospheric oxygen. However, many have $As(III)/As_{total}$ ratios greater than 0.5. Remembering that the streams in the area have high humic and colloidal-Fe contents and high bacterial counts, it is possible that oxidised $As(V)$ has been reduced to $As(III)$ by bacterial activity and that biomethylation reactions have generated DMAA in some of the surface waters.

2.6.4 Arsenic mobilisation

Given the regional distribution of As-bearing minerals in the Obuasi area, the most likely source of the As in the waters is arsenopyrite ($FeAsS$) although minor amounts could also be derived by desorption from clays or secondary minerals (scorodite, arsenolite) formed after arsenopyrite oxidation. Oxidation of pyrite and arsenopyrite by oxygen may be described respectively by the equations:



and



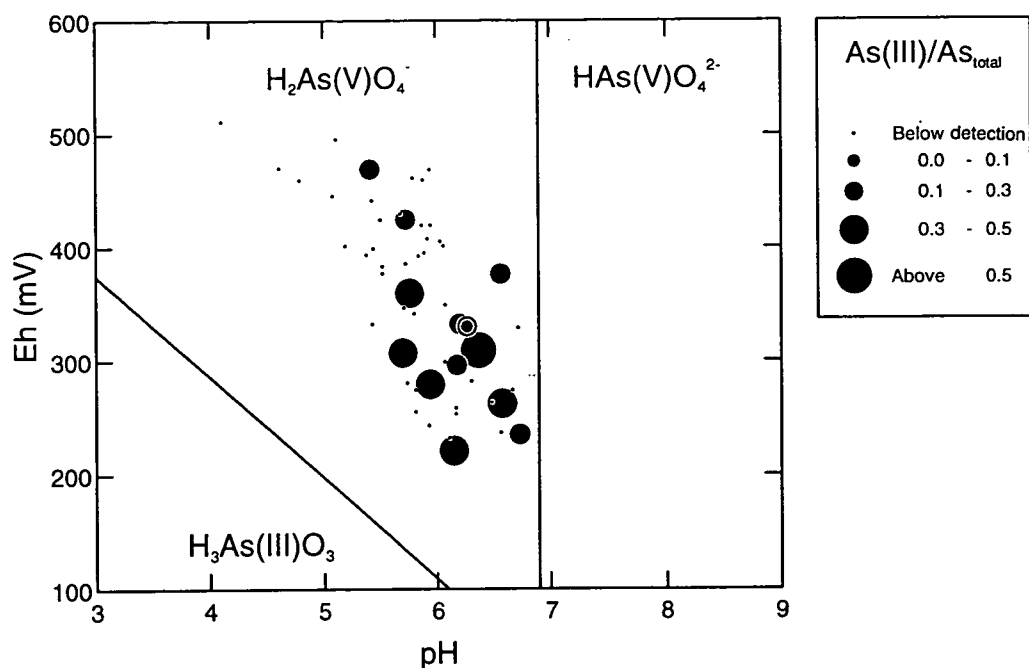


Figure 2.8. Part of the Eh-pH diagram for the As system (25°C, after Brookins, 1988) showing the principal stability fields of arsenate (As(V)) and arsenite (As(III)) species together with measured $\text{As(III)/As}_{\text{total}}$ ratios in water samples from the Obuasi area. The smallest symbols represent those samples for which Eh and pH determinations were made but As(III) or As_{total} values were less than detection limits.

expected for oxidation of arsenopyrite). This is likely due to Fe precipitation as ferric oxyhydroxide in aerobic waters. Even the reducing waters from the mine-exploration boreholes have Fe/S ratios significantly less than 0.5 and suggest that some loss of Fe(III) has occurred by precipitation of minerals such as goethite and ferrihydrite, although the possibility of non-stoichiometric release of As from sulphide minerals under reducing conditions cannot be ruled out.

Arsenic concentrations in the minewaters are relatively low compared to the highest values observed in the study area: the three borehole groundwaters sampled had concentrations of 5, 8 and 17 $\mu\text{g l}^{-1}$ As. This is most likely due to increased sorption of As by ferric oxyhydroxide in waters particularly enriched in dissolved iron, but may also relate to oxidation of larger amounts of As-poor sulphide, particularly pyrite.

Despite the clear potential for As problems in the Obuasi groundwaters, only some of the deeper more reducing waters have concentrations above the WHO recommended limit and are considered potentially hazardous to health. Although streamwaters are also largely below the limit, concentrations are higher than in the shallow groundwaters, probably as a direct result of mining pollution. This concentration of As, together with their poor bacteriological quality renders them undesirable as sources of drinking water and their use should be discouraged.

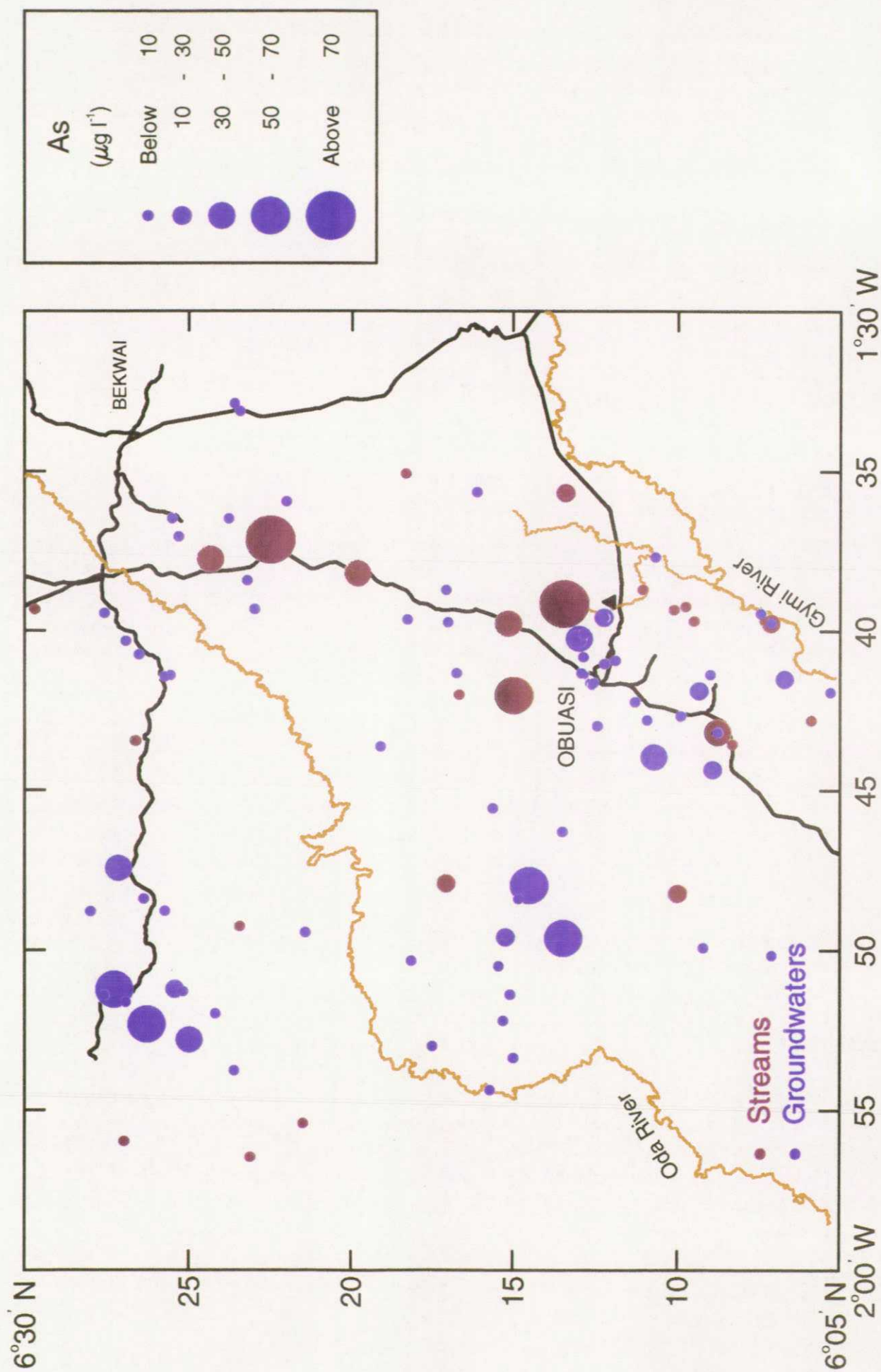


Figure 2.7. Regional distribution of As_{total} in waters from the Obuasi area. Major rivers and roads and the location of the Pompora Treatment Plant (\blacktriangle) are also shown.

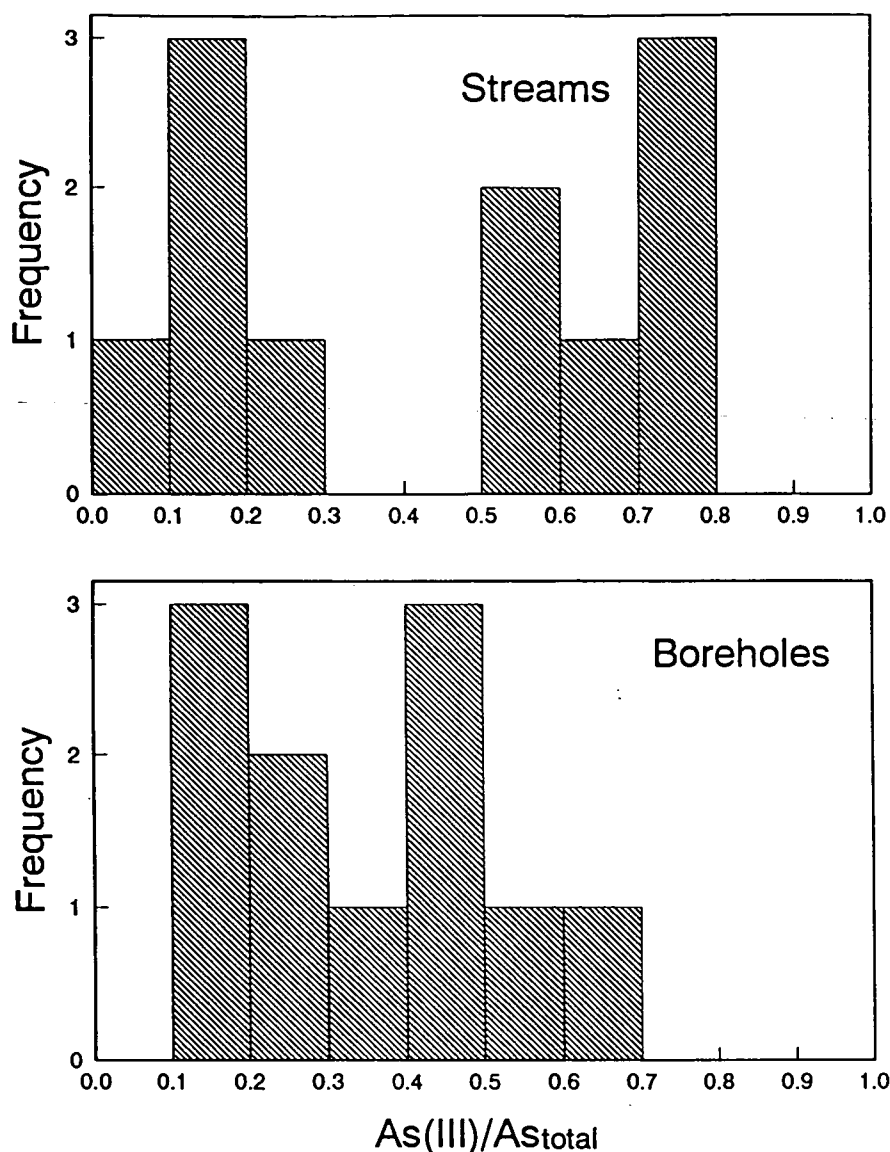


Figure 2.9. Histograms of measured $\text{As(III)/As}_{\text{total}}$ ratio in streams and borehole waters.

2.6.5 Other elements

Although the high concentrations of solutes in the mine-tailings effluent from the Obuasi mine complex are the result of CN complexing rather than natural processes, the composition gives an indication of the range of other elements in local drinking waters which may be present and potentially problematic as a result of both pollution and natural sulphide oxidation. Equations (1) and (2) demonstrate that in the natural system, the oxidation process generates a large amount of acid (H^+), arsenopyrite even more so than pyrite. Consequent reduction of water pH gives greater potential for mineral-dissolution and desorption reactions and under such conditions, Fe, Mn and Al are more stable in solution. Also, other trace elements may be present in the sulphide ores which are released as oxidation proceeds, for example, Ni, Co, Cu, Zn, Mo and Ag.

Other elements of potential health concern have been examined in the Obuasi waters. Most are however not problematic: the waters largely have low TDS concentrations and so major elements are of low concentration. Chloride is mostly $<20 \text{ mg l}^{-1}$, $\text{SO}_4 <4 \text{ mg l}^{-1}$, Na $<30 \text{ mg l}^{-1}$, Ca in the range $0.2\text{--}54 \text{ mg l}^{-1}$ and Mg in the range $0.1\text{--}10 \text{ mg l}^{-1}$. Concentrations

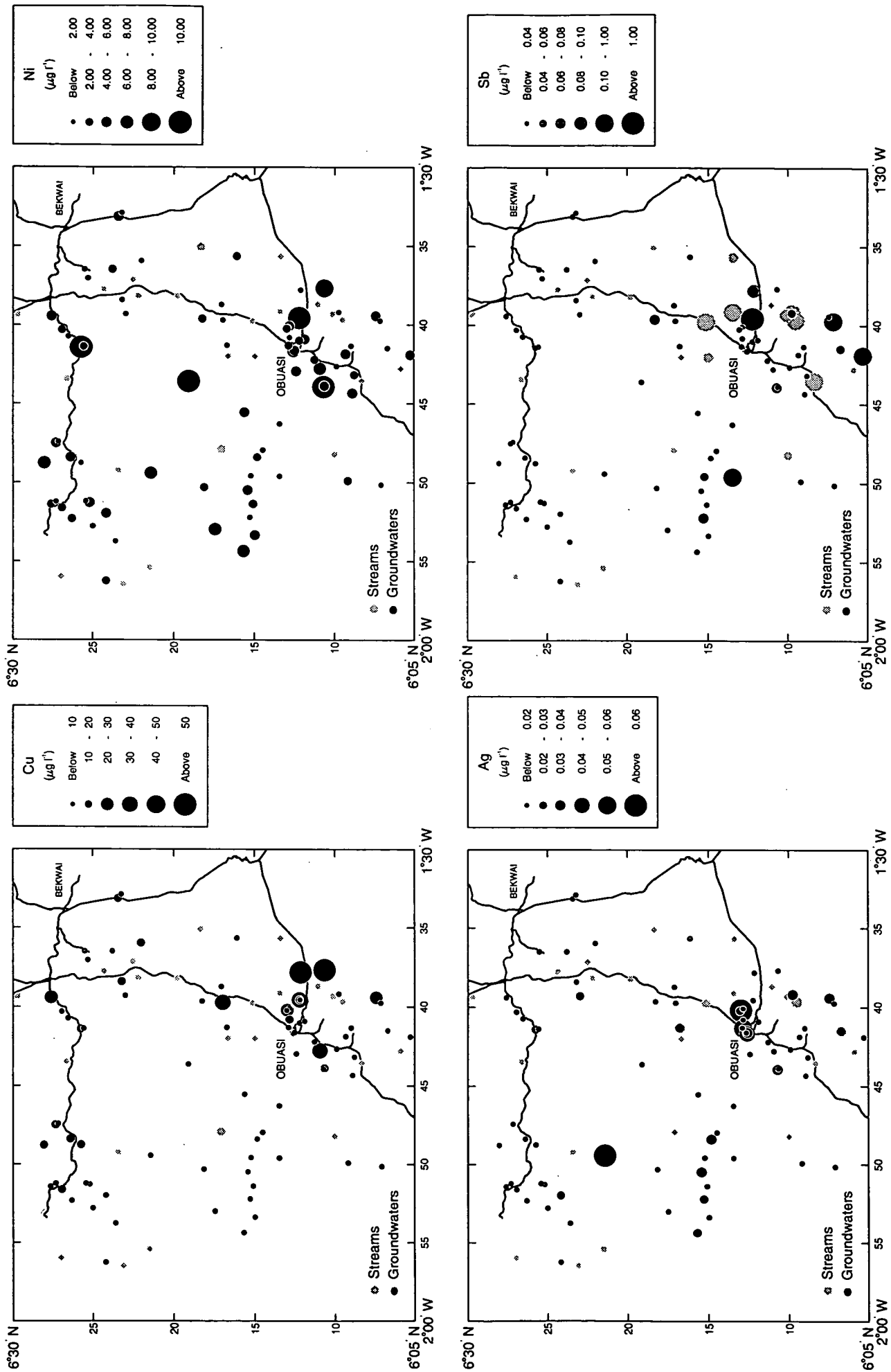


Figure 2.10. Regional distributions of Cu, Ni, Ag and Sb in waters (streams, wells and boreholes) in the Obuasi area.

of constituents commonly attributed to agricultural pollution (NO_3 , K and P) are also usually low: only one sample investigated has a concentration of $\text{NO}_3\text{-N}$ higher than the WHO recommended limit and most are $<5 \text{ mg l}^{-1}$, K values are mostly $<3 \text{ mg l}^{-1}$ and P concentrations are $<0.3 \text{ mg l}^{-1}$.

Aluminium concentrations are quite high in some samples: around 10% of the drinking-water supplies sampled had concentrations above the WHO guideline maximum of $200 \mu\text{g l}^{-1}$, especially some of the streams and shallow wells, the Al largely occurring in colloidal form. The high concentrations reflect the acidic character of the waters (Appendices 1B-C).

Iron, although not detrimental to health, is often mentioned together with Mn in a health context because of aesthetic and acceptability problems. Iron is often quite high in Obuasi waters, notably the more reducing sources and surface sources with heavy particulate matter and humic loads. The WHO guideline maximum value for Fe in drinking water is 0.3 mg l^{-1} but an upper limit of 1 mg l^{-1} should suffice for most purposes (WHO, 1993). About 27% of drinking waters sampled had Fe concentrations greater than 1 mg l^{-1} . Manganese is less problematic, with 3% of sources having concentrations greater than the provisional WHO guideline maximum of 0.5 mg l^{-1} .

Concentrations of halogens in drinking waters, notably I and F, have frequently been linked with health problems, principally goitre (I deficiency) and dental problems respectively. Median I concentrations in Obuasi waters are $7\text{-}10 \mu\text{g l}^{-1}$ (Table 2.1) and are not thought to promote a health problem locally; indeed goitre has not been identified as an endemic problem in the Obuasi area. Fluoride concentrations are generally low (median values $50\text{-}70 \mu\text{g l}^{-1}$, Table 2.1; Figure 2.3) and much lower than the WHO recommended maximum value of 1.5 mg l^{-1} . Dental caries (commonly associated with dietary F deficiency) was identified as a common problem in the study area, although high sugar intake and poor dental hygiene are additional likely causes.

Figure 2.10 shows the regional distributions of Cu, Ni, Ag and Sb in Obuasi waters. Antimony has been included because of its known association with As in mine wastes and high concentrations in mining areas (e.g. Mok and Wai, 1990). Although the elements given in Figure 2.10 are all well below levels considered detrimental to health, their concentrations are higher in the vicinity of Obuasi. This may largely reflect natural water-rock interaction processes in the main sulphide-vein-bearing zone (Figure 2.1). Concentrations of most of these elements are higher in groundwaters than streams but some streamwaters around Obuasi also have high Sb concentrations, probably due to binding with colloidal-Fe and organic materials. It is also possible that the trace-element anomalies around Obuasi are caused by recharge of polluted water from the Pompo and Gyimi river systems to the Birimian aquifer, rather than natural water-rock interaction processes. This would also give rise to elevated concentrations of the elements shown in Figure 2.10 in the groundwaters as a result of mixing. Further investigation of the distributions of elements concentrated in the tailings effluent such as Cl, SO_4 , CN, Sr, B, Rb would help to determine whether this localised area of trace-element anomaly is pollution-derived or natural, although CN should not have long-term stability in oxidising conditions in river systems. Further work on the hydrogeology of the Obuasi area would also help to determine whether the groundwater quality is severely affected by mine-waste recharge.

Table 2.2. Median values for microbiological parameters in Obuasi drinking waters.

	Streams	Wells	Boreholes
Aerobic heterotrophs (CFU ml ⁻¹)	tntc	3750	33
Total microbes (x 10 ³ ml ⁻¹)	30.7	47.5	42.7

CFU: colony-forming unit; tntc: too numerous to count.

2.6.6 Microbiological results

Results of microbiological analyses of water samples from the Obuasi area are given in Appendix 1E and median values for aerobic heterotrophs (plate counts using CPS medium) and total microbes (direct counts) in Table 2.2. The analyses demonstrate the presence of microbes at all sites investigated. Numbers of aerobic heterotrophic bacteria are highest in the streamwaters (median value too numerous to count, tntc) but are also high in the shallow-well waters. The median value for borehole waters is much lower at 33 CFU ml⁻¹. No pathogenic data were collected for the Obuasi sites and so it is not strictly possible to determine the health linkage of these microbial data. However, incidence of diarrhoeal diseases is noted to be locally high in communities drinking water with high counts of aerobic heterotrophic bacteria, notably those using stream and well waters.

Total microbial counts are much higher than aerobic heterotrophic counts at each site. This indicates that most of the microbial population does not comprise aerobic heterotrophs. Concentrations are surprisingly also high in groundwater samples. Their exact composition and growth requirements are undetermined and their relative toxicity uncertain, although they are not necessarily pathogenic.

Many inorganic chemical reactions are known to be catalysed by microbial activity. Indeed, the arsenopyrite and pyrite oxidation reactions may be accelerated microbiologically (Ehrlich, 1990), although As may also act as a toxin to microbial populations. Bacterial catalysis of iron and sulphur oxidation is particularly favoured in acidic conditions by organisms such as *Thiobacillus ferrooxidans* and under near-neutral-pH conditions, Fe oxidation may be accelerated by e.g. *Gallionella ferruginea*. Both these Fe-oxidising bacteria may be present in the Obuasi groundwaters. Most iron and sulphur oxidisers are autotrophs, capable of using CO₂ as the sole carbon source. Thus they would not have been detected using the selective CPS medium. It is possible that the high total counts in boreholes may be accounted for by sulphur and iron oxidisers. However, selective enrichments for these groups would be the only way of confirming their presence. The slightly lower median value for total counts in the streamwaters (Table 2.2) is surprising, although only three streams were assessed using this method, one of which was a mine-waste polluted sample from the Kwabrafo stream (sample 75, Appendix 1E) and is unlikely to be representative of natural microbial populations in Obuasi surface waters. In general, it was recognised that streamwaters should contain very large numbers of microorganisms including protozoa and viruses and hence less effort was focused on these waters for determination of direct microbial counts.

Environmental conditions such as redox, pH and groundwater depth appear to have no effect on total microbial counts. Figure 2.11 shows that As concentration in Obuasi waters also has little effect on microbial populations since there is no correlation between As and

heterotrophic bacterial counts. Indeed, the samples with the highest As concentrations (the tailings effluent and the polluted Kwabrafo stream sample, samples 74 and 75 respectively) had some of the highest bacterial counts and indicate that As is not acting as a major toxin to bacterial populations at these concentrations.

The synthesis of protoplasmic constituents requires carbon (organic or inorganic), nitrogen, sulphur and phosphorus, certain other nutrients and water. In Obuasi waters, no correlations were found between microbial numbers and sulphur, phosphorus or trace elements; the main control appears to be from carbon (dissolved organic carbon, Figure 2.12 and HCO_3^- ; West et al., 1995) which is acting as a nutrient or energy source.

Predictive biomass modelling of selected sites from the Obuasi area has been carried out using the generic microbiology model MGSE (Microbe Growth in Subsurface Environments; West et al., 1994). The model is designed to predict microbial growth rates from available energy and nutrient sources and ambient redox conditions. A total of 22 sites (streams and groundwaters) with relatively well-known water compositions, sample depths, local geology and groundwater-flow rates were selected for investigation. Full details of the modelling are given in West et al. (1995). Since the main microbial populations in the Obuasi waters appear not to be aerobic heterotrophs, the sites chosen were assumed to be anaerobic with dissolved organic carbon as the main reductant and Fe oxide and SO_4 the main oxidants. If oxygen is also present as an oxidant, predicted biomass should be higher than with Fe oxide and SO_4 alone. Many of the waters investigated are aerobic, particularly the surface and shallow-well waters, although microbial growth in these sources is limited by the low concentrations of available nutrients (notably nitrate) rather than the availability of energy sources. Energy appears to be the limiting factor for microbial numbers in borehole waters (West et al., 1995).

The model predicts the growth of microbes at all sites investigated, at concentrations between 10^{10} and 10^{17} microbes $\text{ml}^{-1} \text{yr}^{-1}$. Figure 2.13 shows the relationship between total microbial numbers measured by epifluorescence microscopy and the microbial populations predicted by

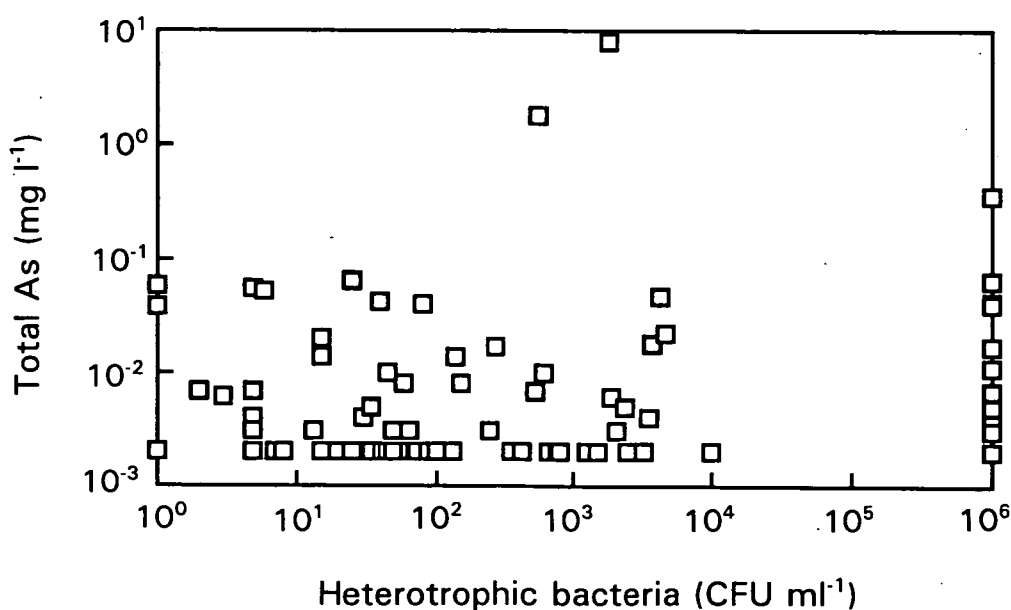


Figure 2.11. Arsenic concentration against numbers of heterotrophic bacteria for Obuasi streams and groundwaters (includes mine-tailings effluent).

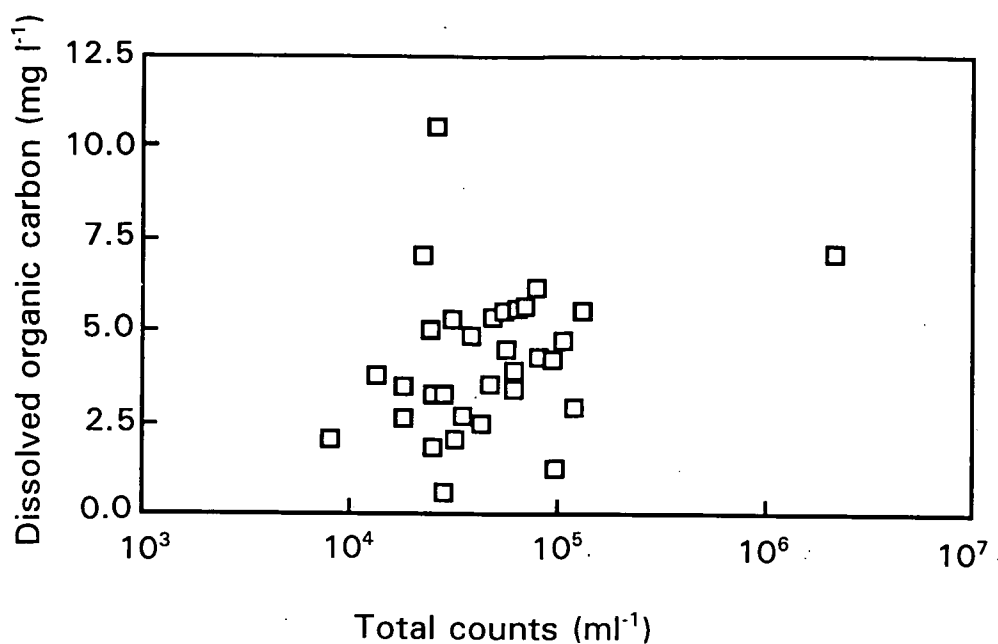


Figure 2.12. Total microbial counts against dissolved organic carbon in Obuasi stream, well and borehole waters.

the MGSE model. Observed and predicted values have a weak positive correlation and suggest that predicted microbiological results can be linked with actual observations. However, there is a large difference between absolute measured and predicted numbers. This may be accounted for in part by the many assumptions made in the MGSE model: all organic carbon was assumed to be the <HCOO> functional group which is associated with a high energy yield and should therefore give maximum microbial growth rates. The model also assumed that all organic carbon present would be available for microbial use. In addition, flow rates chosen assumed homogeneous lithological and hydrogeological conditions. The microbes determined by both plate and direct counts would have only determined those populations in waters: no account was taken of populations attached to surfaces in the rock matrix. Therefore, the numbers obtained from water analysis would be underestimates of those actually present. Nonetheless, the model has been able to predict qualitatively the microbial growth rates in Obuasi waters and suggests that microbial populations are readily available in all the water sources to catalyse chemical redox processes.

2.6.7 Urine samples

Statistical results for urine samples from the two villages studied in the Obuasi area are given in Table 2.3. One village, Kofikuum, situated about 2 km west of the Obuasi mine, is a suburb of Obuasi where the inhabitants have used groundwater from borehole supplies for many years. The chemical analysis for borehole water from this village is given in Table 2.1: As concentration was low at $< 2 \mu\text{g l}^{-1}$. The other village, Wumase, is located 14 km south of Obuasi, where the water supply has traditionally been from a stream source (although a few shallow dug wells are available). Total arsenic concentration from one of the wells was $< 2 \mu\text{g l}^{-1}$ (Appendix 1B) but higher in the local stream (the main source) at $5 \mu\text{g l}^{-1}$. The As_{total} concentration of unfiltered streamwater from this site was found to be $8 \mu\text{g l}^{-1}$, the excess over dissolved concentration probably bound to suspended solids or organic acids. People from both villages eat a diet of rice, cassava, plantain, yam, maize, occasional meat and fish (most volunteers having eaten fish, mostly local freshwater types, within the 24-hour

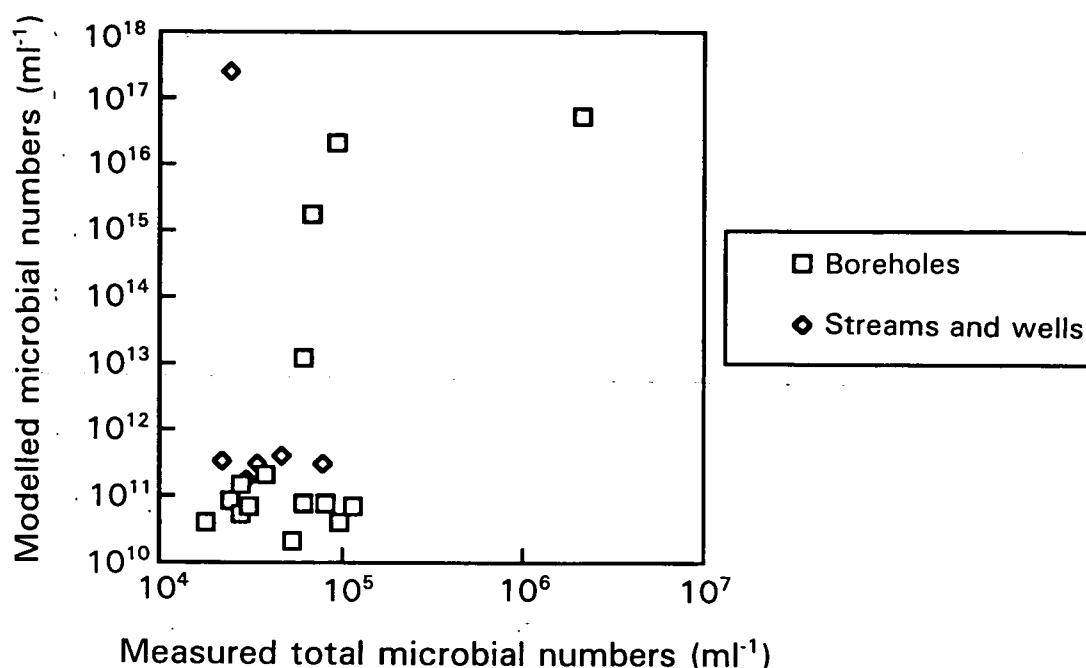


Figure 2.13. Relationship between measured total microbial counts and those predicted from the MGSE microbiological model.

period preceding the sampling). Villagers from Wumase obtain vegetables mainly from local farms, whilst those from Kofikurom obtain vegetables from Obuasi market and a farm at Anyenim (Obuasi). Ages of the volunteers were 10–62 and 15–60 in Wumase and Kofikurom respectively (Table 2.3). Occupations of volunteers in Wumase were mainly farmers, housewives and schoolchildren, whilst those in Kofikurom had a more varied range of occupations and included miners, farmers, traders, security staff and housewives.

Within each community, urinary As concentrations did not vary significantly with age, sex or occupation. Median values of total As concentration were 297 $\mu\text{g l}^{-1}$ for Wumase and 224 $\mu\text{g l}^{-1}$ for Kofikurom. These values are very high compared to concentrations quoted elsewhere in the literature, but reflect the content of organic As (arsenobetaine \pm arsenocholine) derived from recent ingestion of fish in both populations. Inorganic (reducible) As contents were much lower at 42 and 18 $\mu\text{g l}^{-1}$ respectively (Table 3). The median concentration for Kofikurom falls within the range of background urinary As values given by other studies. The value for Wumase is somewhat higher and could be a result of ingestion of drinking water with more As (albeit at a concentration below the WHO recommended maximum) or due to differences in provenance of foodstuffs such as vegetable crops: those purchased at Obuasi market by the Kofikurom inhabitants are likely to be exotic rather than grown locally in potentially As-rich soils. There is also the possibility that Wumase residents use water from the polluted Gympy river since this flows very close to the village. This is however, unconfirmed.

Since Kofikurom is a suburb of Obuasi, situated close to the mine complex and using groundwater abstracted from the vicinity of the auriferous vein systems, the low concentration of inorganic As in Kofikurom urine samples is particularly encouraging and provides further evidence that local shallow groundwater is of good quality with respect to As.

Table 2.3. Concentrations of total and inorganic (reducible) arsenic in urine samples from volunteers in Wumase and Kofikurom. *Strictly includes the methylated metabolite MMAA.

WUMASE: Stream water				KOFIKUROM: Borehole water			
Nº	Age	Total As (µg l ⁻¹)	*Inorganic As (µg l ⁻¹)	Nº	Age	Total As (µg l ⁻¹)	*Inorganic As (µg l ⁻¹)
1	51	199	22	1	25	597	27
2	39	161	15	2	22	184	11
3	48	116	13	3	25	679	32
4	37	524	112	4	15	64	9
5	12	257	74	5	18	234	16
6	60	385	29	6	29	208	6
7	60	55	4	7	55	201	12
8	39	202	25	8	32	244	16
9	60	217	43	9	26	90	11
10	57	130	18	10	45	111	11
11	62	353	37	11	45	139	11
12	28	299	21	12	30	272	24
13	60	274	27	13	45	423	24
14	55	442	44	14	29	119	10
15	40	415	44	15	25	277	22
16	38	532	59	16	16	286	20
17	35	376	68	17	15	377	21
18	33	278	53	18	60	303	60
19	15	286	53	19	17	169	19
20	45	394	56	20		182	20
21	45	177	27	21		318	21
22	55	296	48	22	60	58	5
23	60	298	51	23	60	85	4
24	60	300	25	24	45	152	15
25	25	330	43	25	49	271	26
26	55	264	19	26	35	213	46
27	10	420	56	27	45	351	40
28	35	328	41	28	45	178	12
29	34	229	26	29	21	322	15
30	35	427	93	30	25	339	68
Median		297	42	Median		224	18

2.7 Conclusions

The distribution of As and other trace elements has been investigated in streams, shallow wells and boreholes providing drinking water to rural communities in the Obuasi area. Concentrations of total As range between $< 2 \mu\text{g l}^{-1}$ and $175 \mu\text{g l}^{-1}$, 20% of sources exceeding the WHO guideline maximum value for As of $10 \mu\text{g l}^{-1}$ (although only 6% exceed the current EC and US-EPA maximum of $50 \mu\text{g l}^{-1}$). The high As loads of some local streams and groundwaters result from both mine-derived pollution and natural water-rock interaction processes. Pollution results from the discharging of tailings effluent and mine drainage into streams around Obuasi and historic atmospheric emissions of As trioxide and sulphur dioxide from roasting operations at Obuasi mine. High concentrations of As are also derived from natural oxidation of As-rich sulphide ores, notably arsenopyrite, as well as derivation from secondary As-bearing minerals.

Some of the streamwaters contain the highest concentrations of As, particularly those to the north of Obuasi, in the path of former airborne mine emissions from the treatment plant. Many of the As-rich streamwaters have high colloidal-Fe concentrations and are highly coloured, suggesting a high organic-acid content. The high As concentrations are likely to be facilitated by strong binding to these compounds. Arsenic(III)/As_{total} ratios have a bi-modal distribution, some with values less than 0.5 dominated by As(V) and some dominated by As(III) and possibly DMAA (values greater than 0.5) which are likely to have resulted from biomethylation and reduction reactions involving bacteria and algae.

Arsenic concentrations are universally low in shallow wells (median value $< 2 \mu\text{g l}^{-1}$) but reach higher levels (up to $64 \mu\text{g l}^{-1}$) in groundwater from some of the deeper, more reducing boreholes (40–70 m depth). Deep minewaters (70–100 m) rich in Fe and SO_4 indicative of Fe-sulphide oxidation have As concentrations between 5 and $17 \mu\text{g l}^{-1}$. This range is lower than observed local maxima and probably results from As sorption by precipitating ferric oxyhydroxide, although oxidation of As-poor sulphide minerals such as pyrite may also be responsible for the relatively low concentrations.

Positive correlations between As, borehole depth and bicarbonate content in groundwaters suggest that high As is controlled by depth of circulation and results from greater degrees of water-rock interaction with sulphide minerals, afforded by longer residence times in the aquifer. The higher concentrations in the deeper boreholes are generally accompanied by higher proportions of As(III) which is the stable species under more reducing conditions.

As(III) is known to be more toxic than As(V). The deeper borehole waters and some streams are therefore a greater health concern, both because of higher As_{total} contents and higher proportions of As(III). However, possible risks from As(V) should not be ignored because of the potential for *in vivo* reduction to As(III).

The quality of Obuasi drinking waters with respect to other inorganic constituents is generally good. Concentrations of the major elements are low with Cl mostly $< 20 \text{ mg l}^{-1}$, SO_4 $< 4 \text{ mg l}^{-1}$ and Na $< 30 \text{ mg l}^{-1}$. There is also little evidence of significant agricultural pollution since concentrations of NO_3 , K and P are usually low. Trace metals, particularly those associated with sulphide oxidation and gold-mining activity (e.g. Co, Ni, Cu, Zn, Pb, Ag, Sb) are also all below WHO guideline maxima in drinking waters analysed in this study. However, higher values are observed to the east and south of Obuasi, either as a result of

recharge of polluted river water to the aquifer or from natural sulphide oxidation in the area where the greatest concentration of ore veins occurs.

Microbiological quality of some Obuasi drinking waters is less good, particularly streamwaters and some shallow wells which have high bacterial counts and are often associated with water-borne diseases. Concentrations of aerobic heterotrophs in wells and boreholes have median concentrations of 3750 and 33 CFU ml⁻¹ respectively; the median concentration in streamwaters was above the upper quantification limit (tntc). This, together with potentially high As concentrations, renders the streamwaters largely unsuitable for potable supply. Use of borehole water should therefore be encouraged in the area, with the exception of deeper groundwater sources with potentially high As concentrations.

Microbial populations analysed by direct counts give much higher numbers than analysed by plate counting using CPS medium and demonstrate the need to use several methods to determine numbers of microorganisms in such waters. The discrepancy between counts obtained by plate and direct counting suggests that the majority of microorganisms present in Obuasi waters are not aerobic heterotrophs. The precise forms and growth requirements have not been determined in this study and their pathogenicity is unknown. They are however, not necessarily harmful. Many may be Fe- and S-oxidising bacteria and may effectively catalyse the pyrite and arsenopyrite oxidation reactions. Predictive biomass modelling has demonstrated that large numbers of microbes (up to 10¹⁷ ml⁻¹ yr⁻¹) are theoretically sustainable at all sites investigated given available energy and nutrient sources. Many other inorganic redox reactions may therefore be accelerated by microbial activity.

Urinary total As concentrations in volunteers from two villages, one a rural community 14 km south of Obuasi and the other a suburb of the town, are very high, with median values at 297 and 224 µg l⁻¹ respectively and reflect the high intake of fish in the diet. Median inorganic As contents are much lower at 42 and 18 µg l⁻¹ respectively. Differences between the two probably reflect differences in As concentration of water supplies and provenance of vegetable foods. In particular, the low median value for the village using groundwater, despite its proximity to mining activity and to potential sources of As, attests to the overall good quality of shallow groundwater with respect to As in the Obuasi area.

Concentrations of As in river sediments downstream of the pollutant discharge points were not investigated in this study. This would be an interesting topic for further research since large amounts of aqueous As are known to sorb onto sediments. Since As release from sediments is thought to be achieved more readily under acidic conditions, the river sediments can have a large impact on potential for As dispersion downstream of the pollution injection point and on recharge to the aquifer. This has large implications for groundwater-resource protection in the area to the south and east of Obuasi.

2.8 Recommendations

1. Continued widespread use of surface water is clearly a problem in the Obuasi area and leads to potentially serious gastro-intestinal disorders. Many available boreholes have been abandoned following breakdown due to lack of funds or lack of a sense of responsibility or involvement of the communities themselves. New borehole-drilling programmes should seek to involve communities at the planning, installation

and maintenance stages and education on public health in relation to safe drinking water is also paramount.

2. Arsenic in drinking water is only likely to be a problem in areas where sulphide minerals are common or where pollution locally enhances dissolved concentrations. In such potentially vulnerable areas, waters from newly-drilled boreholes should be analysed for As and related element concentrations (SO_4 , Sb, Fe) prior to borehole completion. Evidence from the Obuasi area suggests that deeper, longer-residence-time groundwaters may be particularly vulnerable to high As concentrations due to protracted sulphide-oxidation processes. In such areas, particular attention should be paid to more reducing waters, having undergone sulphide-mineral oxidation but allowing As to remain in solution under low-oxygen conditions rather than co-precipitating with ferric oxyhydroxide.
3. Despite the fact that some groundwaters in the Obuasi area have As concentrations higher than the revised WHO recommended limit, most investigated have relatively low concentrations. This highlights the fact that even in potentially vulnerable areas such as gold-mining towns, groundwater can provide a much healthier source of potable water than local surface waters which may have high concentrations of toxic trace metals derived from both mining activity and natural sulphide-mineral oxidation, as well as being of poor bacteriological quality. In sulphide-bearing aquifers therefore, groundwater As concentrations should be investigated as a potential health risk, but the groundwaters should not necessarily be dismissed as unsuitable for rural-water supply.

3 IODINE, FLUORIDE AND ELEMENTS OF HEALTH SIGNIFICANCE IN GROUNDWATERS FROM THE BOLGATANGA AREA, UPPER EAST REGION

3.1 Introduction

Potentially the most important inorganic water-quality problems to affect large parts of the developing world are I deficiency and F excess. Many millions of people in the poorest countries suffer from endemic goitre and fluorosis (dental and/or skeletal) as a result. Drinking water constitutes an important source of both elements and can therefore have a major impact on the health of affected populations.

Communities living in the Upper Regions of Ghana have long been known to suffer from endemic goitre (e.g. Kelly and Sneddon, 1960). More recently, dental fluorosis has been recognised in localised areas of the Upper East Region (J. Asedem, pers. commun., 1993). Dietary I deficiency and F excess respectively are assumed to be the causes, but concentrations of I and F in drinking water and their variation have not been investigated in the region in detail. Since lithological variations have often been cited as the cause of both iodine-deficiency disorders (IDDs) and fluorosis in endemic areas, the Bolgatanga area in the Upper East Region, with a variation in lithological types from which groundwater is abstracted for drinking, has been chosen for investigation. This report presents a comprehensive set of major- and trace-element data (including I and F) for groundwaters from the area and investigates the relationships between groundwater quality, geochemistry and health of the Bolgatanga communities. Microbiological quality (including pathogenic organisms) of the groundwaters is also assessed.

The Upper East Region is also the locus of sulphide mineralisation (partly auriferous), although it is economically less significant than in the Ashanti Region further south. Gold mining activities ceased in the Bolgatanga area in the 1930s. Since sulphide minerals including pyrite, chalcopyrite and arsenopyrite are known to be present in vein complexes in the Bolgatanga area, regional distribution of As has also been investigated in this study area and comparisons are made with the Obuasi area.

3.2 Dietary iodine requirements

Iodine has long been identified as an essential element in human and animal metabolism. It is instrumental to the manufacture of thyroid hormones which are essential for development and function of the nervous system and for maintenance of body heat and energy (Dunn and Van der Haar, 1990). Dietary I deficiency inhibits production of thyroid hormone in the thyroid gland and can result in a number of characteristic IDD. The most common IDD manifestation is goitre, an enlargement of the thyroid gland, effected by overproduction of thyroid-stimulating hormones to compensate for the I deficiency. Chronic I deficiency can induce growth of goitres several inches across which may cause pain and discomfort due to restriction of blood supply and compression of the trachea and oesophagus and may also induce choking. Women of child-bearing age and children are particularly at risk. Other IDD symptoms include hypothyroidism (low blood-levels of thyroid hormone) which leads to lethargy, dry skin, intolerance to cold, growth- and mental-retardation and cretinism (severe mental retardation due to neo-natal hypothyroidism, which may also produce stunted growth

and deaf-mutism). Inhibition of physical growth and mental development of children is a particular problem. IDD's have also been linked with high incidence of infant mortality and reproductive failure (Dunn and Van der Haar, 1990). They have also been held responsible for the impairment of economic development, quality of life and educability of millions of children and adults (Phillips et al., 1988). It is estimated that up to a billion people globally (around 19% of the world's population) are at risk from IDD. Around 200-300 million have visible goitre or similar manifestations and around 6 million are cretins (Dunn and Van der Haar, 1990).

The daily I requirement of humans is about 100-200 μg (Fuge, 1987). It has been estimated that the bulk of this (around 80%) is derived from food, the remainder from drinking water. Historically, IDD's have been identified in parts of most continents throughout the world. Today the problem tends to be mainly restricted to the poorer developing countries where diet is of limited nutritional quality and health education is less well disseminated. In populations taking an I-rich diet (notably dairy products, fish and meat), I concentration of drinking water is relatively unimportant but takes on an increased significance where diet does not provide the daily requirement. The distribution of I in the local environment (water, soils, rocks) is also important as it determines the ranges of I concentrations in locally-produced foodstuffs.

3.3 Iodine in food and drinking water

The principal source of I for human and animal metabolism is food. Dairy products, fish and meat tend to have the highest concentrations. Roche and Lissitzky (1960) quoted a range of 0.08-0.12 mg l^{-1} I in human milk and Wenlock et al. (1982) gave a range of 0.05-0.58 mg kg^{-1} in British milk and milk products. Fuge and Johnson (1986) quoted a range of 1-6 mg kg^{-1} in marine fish. The high concentrations reflect the enrichment of I in seawater but also the extreme enrichments found in some marine plants which may act as food sources: I concentrations in the range 20-8800 mg kg^{-1} have been determined in brown and red algae for example (Shacklette and Cuthbert, 1967). Concentrations in fruit and vegetables are generally lower. Shacklette and Cuthbert (1967) claimed that I concentrations in vegetables were largely between 2 and 10 mg kg^{-1} , although much lower ranges (0.05 to 0.5 mg kg^{-1} and 0.01 to 0.08 mg kg^{-1}) have been quoted by Whitehead and Truesdale (1982) and Wenlock et al. (1982) respectively. McGrath and Fleming (1988) also quoted an I range in Irish herbage (species not specified) of 0.08-0.42 mg kg^{-1} . Food-I concentrations are dependent on those found in the local environment. Mahadeva et al. (1968) found that I in food in IDD-prone areas in Sri Lanka was significantly lower than in unaffected areas. Various foodstuffs in the goitrous and non-goitrous areas were respectively: rice: 0.004-0.2 mg kg^{-1} and 0.9 mg kg^{-1} , pulses: 0.002-0.3 mg kg^{-1} and 0.9 mg kg^{-1} , plantain: 0.001-0.16 mg kg^{-1} and 0.63 mg kg^{-1} , coconut: 1.0-1.3 mg kg^{-1} and 1.7 mg kg^{-1} (wet weights). The I concentration in vegetation presumably reflects soil-I concentration (allowing for species-specific concentration factors) although there is evidence that a significant amount may be derived by direct uptake from the atmosphere (e.g. Brauer and Ballou, 1975; Whitehead, 1979). Vegetative uptake is also dependent on the retentive capacity of the soil for I: uptake has been found to be less from organic-rich soil due to the great binding capacity of organic matter for I.

In areas prone to IDD, drinking waters with low I concentrations are commonly held responsible. McClendon and Williams (1923) suggested that concentrations of less than 3-5 $\mu\text{g l}^{-1}$ I in drinking water were goitrogenic. Coble et al. (1968) found that in populations inhabiting Egyptian oases, drinking water with concentrations of 7-18 $\mu\text{g l}^{-1}$ gave rise to

goitre whilst concentrations of 44–100 $\mu\text{g l}^{-1}$ did not. Wilson (1954) associated goitre incidence in Sri Lanka with drinking water I ranging between 1.4 and 2.7 $\mu\text{g l}^{-1}$. Mahedeva and Senthe Shanmuanathan (1967) found that goitrous areas in Sri Lanka had drinking-water I concentrations of 2.2 to 10.1 $\mu\text{g l}^{-1}$ whilst non-goitrous areas had 19.4 to 183 $\mu\text{g l}^{-1}$. They defined the local critical I concentration as 10 $\mu\text{g l}^{-1}$. Again however, it should be emphasised that prevalence of IDD relates to additional factors such as quality of nutrition: Fuge (1989) noted a mean I concentration in UK domestic drinking waters of only 1.9 $\mu\text{g l}^{-1}$, despite the fact that the UK is no longer a country vulnerable to IDD.

Although IDDs are most commonly attributed to I deficiency, goitrogens have often also been cited as possible contributory causes. The most commonly invoked food goitrogens are thiocyanate and thiouracil which are concentrated in foodstuffs such as cassava, millet, maize and cabbage (e.g. Ekpechi et al., 1966; Ekpechi, 1967; Fernando et al., 1986; Stewart, 1990). It is established that the ratio of I to thiocyanate in urine is an important factor in development of IDD (Delange et al., 1980; Hennart et al., 1982). Other constituents in water which have been claimed to be goitrogenic include Ca, Mg, Mo, As, Co, Zn and F as well as the pathogenic organism *E. coli*. (e.g. Fuge, 1987; Stewart, 1990) although evidence is frequently contradictory (for example, Wilson, 1954 described goitre in Sri Lanka among people drinking soft water (low Ca, Mg) from metamorphic and igneous aquifers). It is perhaps significant that in areas where dietary I intake is adequate, there is no evidence that goitrogenic substances have been responsible for generating goitre (Taylor, 1956). Only in areas where I intake is low may the goitrogens tip the balance in favour of goitre development.

There is also the question of genetic predisposition to IDDs since prevalence is often found to be familial (Fernando et al., 1986). However, it is also likely that this relationship is a response to sharing the same family environment and dietary habits. The question is still in doubt.

3.4 Recognition and treatment of goitre

Goitre is the most common manifestation and one of the earliest signs of IDD. It is also the easiest to identify by means of visual inspection and palpation. A classification of goitre, endorsed by WHO and the International Council for Control of Iodine-Deficiency Disorders (ICCIDD), is given in Table 3.1.

Urinary I concentration also gives an indication of susceptibility to, and prevalence of, IDD in an endemic area. Excretion of I at a concentration of 50 $\mu\text{g day}^{-1}$ or less is considered goitrous (Dunn and Van der Haar, 1990). This roughly equates with a concentration of 40–50 $\mu\text{g g}^{-1}$ creatinine. Coble et al. (1968) found a mean urinary I concentration of 53 $\mu\text{g g}^{-1}$ creatinine in IDD-endemic males in Egypt. Phillips et al. (1988) found a mean urinary I concentration in goitrous women from eastern Zaire of only 10.9 $\mu\text{g g}^{-1}$ creatinine. Daily urinary concentrations of 25 μg or less have been linked with cretinism (Dunn and Van der Haar, 1990).

Dietary I supplements are an effective means of treatment of the goitre problem, provided that treatment begins early. Small goitres (type 1) regress effectively after supplementary I is administered but treatment becomes less effective and more difficult at more advanced stages of the disease as the enlarged gland may become hard and nodular and underlying fibrous

Table 3.1. Classification of goitre size (from Dunn and Van der Haar, 1990).

Grade	Description
0	No goitre
1A	Thyroid lobes larger than ends of thumbs
1B	Thyroid enlarged, visible with head tilted back
2	Thyroid enlarged, visible with neck in normal position
3	Thyroid enlarged, visible from a distance of 10 m

changes may have taken place (Phillips et al., 1988). Such nodular goitres require surgery. Recommended I supplements include use of iodised salt, a policy which needs to be instigated at governmental level, or the use of slow-release oral or intramuscular iodine supplements (e.g. iodised oil, Lipiodol®). Administration of iodised salt can often prove difficult in developing countries due to difficulties of manufacture and distribution, particularly in remote areas. Iodised oil is often a more appropriate solution if administration by means of salt proves difficult as it ensures that the people most in need receive treatment and, once administered, it can be effective for several years (Phillips et al., 1988).

3.5 Geochemistry (and biogeochemistry) of iodine

Natural I minerals are very rare, being restricted to a few insoluble iodides of copper and silver. Iodine is also not found in high concentrations in most rocks as it does not easily enter the crystal lattice of rock-forming silicates (the I⁻ ion has a large ionic radius, 0.215 nm). Concentrations in most silicate rocks are therefore generally low at less than 2 mg kg⁻¹ (Table 3.2). However, they may be elevated in late-stage residual melts or hydrothermal solutions. Fuge et al. (1986) for example gave a range of 30–3760 µg l⁻¹ in hydrothermal waters.

Iodine is known to be chalcophile. Fuge and Johnson (1984) noted that I concentrations are higher in rocks containing sulphide-mineral phases (e.g. 0.2–6 mg kg⁻¹ in pyrite, chalcopyrite, galena) than equivalent gangue minerals. Sedimentary rocks, particularly organic- and sulphide-rich shales, have higher concentrations than igneous or metamorphic rocks, recent sediments containing up to 200 mg kg⁻¹ (Table 3.2). Weathered rocks have often been found to contain higher I concentrations than their pristine equivalents, presumably due to interaction with meteoric water (growth of lichen may be an additional factor; Fuge and Johnson, 1986).

Goitre prevalence has often been noted in limestone areas (e.g. Becker et al., 1972; Mollet et al., 1987; Fuge, 1989). Until the turn of the century, goitre was endemic in north Derbyshire in the UK, being worst in areas where Carboniferous Limestone cropped out (Fuge and Long, 1989). The observed correlation has been linked with the occurrence of hard waters in such aquifers (cf. the assumed goitrogenic nature of Ca and Mg, Section 3.3). The presence of such goitrogens in groundwater may help to explain why goitre has been observed in some areas without notable I deficiency in local waters, rocks and soils. Fuge and Long (1989) also considered that goitre prevalence in north Derbyshire, despite relatively high soil I

Table 3.2. Concentrations of I in some rocks (mean values, taken from Fuge and Johnson, 1986). *Soil I concentration varies according to type (especially organic content) and to distance from the coast.

Rock type	I (mg kg ⁻¹)
Granite	0.25
Gabbro	0.32
Basalt	0.27
Rhyolite	0.20
Schist	0.36
Gneiss	2.3
Metaquartzite	0.6
Carbonate	2.7
Shale	2.3
Sandstone	0.8
Recent sediments	5-200
Soil*	4-8

concentrations (mean 8.2 mg kg⁻¹), was due to fixation of I by Ca in the soil and resultant decreased efficacy of uptake by plants.

The principal natural source of I is seawater (mean value 58 µg l⁻¹; Fuge and Johnson, 1986). Iodine readily volatilises to gaseous I (I₂ or as methyl iodide, CH₃I) and ocean-to-atmosphere transfer followed by subsequent loss to the biosphere and lithosphere as wet and dry deposition are important processes in the geochemical cycling of the element (e.g. Whitehead, 1984; Fuge and Johnson, 1986; Fuge, 1989). Iodine in rainfall in coastal areas is therefore generally higher (0.8-16 µg l⁻¹; Whitehead, 1984; Fuge and Johnson, 1986) than over continental areas (1 µg l⁻¹ or less, Fuge, 1989). This correlates with the fact that goitre and related endemic disorders are often concentrated in inland areas remote from the sea, although IDD's have also been reported in some coastal areas with relatively high local water, soil and food I concentrations (e.g. Dissanayake and Chandrajith, 1993).

Soil-I concentrations are variable, depending on a number of factors including parent rock type and geographical location (including proximity to the coast; Yuita, 1983). Many however, especially shallow soils, tend to have higher concentrations than their parent rocks, presumably due to addition of I from the atmosphere (Fuge and Johnson, 1986). Concentration of organic matter and Fe and Al oxides in soils is also important since these readily bind I. Peaty and Fe-rich soils typically have I concentrations of 6-15 mg kg⁻¹, although Whitehead (1979) found up to 98 mg kg⁻¹ in a fen peat from the UK. Soil pH also influences the sorption behaviour of I: sorption of the I⁻ ion being generally greater at low pH



Plate 3.1. Early development of goitre in a young woman from the Bolgatanga area. Goitres are readily treatable with iodine supplements if treated sufficiently early.



Plate 3.2. Large (grade 3) goitre in a young woman from the Bolgatanga area.

(less than around 5; Whitehead, 1973a). Clay minerals have also been associated with higher I concentrations, although this relationship does not always hold: Whitehead (1973a) found only a poor correlation between I and clay content in British soils. Fuge and Johnson (1986) defined a tentative mean soil-I concentration of 4–8 mg kg⁻¹ (Table 3.2) and McGrath and Fleming (1988) noted that I ranges between 0.1 and 10 mg kg⁻¹ in most soils. Goitre prevalence has been reported frequently in areas where soils are thin and organic-poor, the best examples being young mountainous areas, such as the Himalaya (Day and Powell-Jackson, 1972; Stewart, 1990), Andes (Meyer et al., 1978) and the Alpine regions.

Iodine concentrations in surface water and groundwaters range between 0.01 and 70 µg l⁻¹, depending on geographical position and local geology and soils (mean river water content 5 µg l⁻¹; Fuge and Johnson, 1986; Fuge, 1989). The species present in water depend upon redox conditions but in groundwaters tend to be present as iodide, I⁻, and in surface waters as iodide or iodate, IO₃⁻. Some I may also be organically bound.

Iodine concentrations in drinking waters and soils are increased by man's activities. The element is used in herbicides, fungicides, dairy sterilants, detergents, table salt, pharmaceuticals and bread-making. It is also enhanced in the atmosphere from fossil-fuel combustion, car exhausts and sewage. Whitehead (1979) suggested that surface waters draining industrialised and urban areas contain considerably more I than those draining rural areas.

3.6 Geochemistry of fluorine and the fluorosis problem

Fluoride in drinking water may have a beneficial effect in the prevention of dental caries at concentrations of around 1 mg l⁻¹, but chronic exposure to concentrations much above this can lead to serious health problems from the development of fluorosis. The WHO recommended maximum concentration for F in drinking water is 1.5 mg l⁻¹. At concentrations greater than this, chronic exposure from drinking water can promote dental fluorosis ('mottled enamel') involving discoloration, weakening and possible eventual loss of teeth. In severe cases, skeletal fluorosis, a potentially crippling disease, can develop. Dental fluorosis is the most common manifestation of the disorder and since exposure to F is most detrimental during early tooth development, young children (< 7 years) are especially vulnerable. The effects of fluorosis are permanent and incurable.

Dissanayake (1991) suggested that dental fluorosis can develop where drinking water has F concentrations greater than 1.5 mg l⁻¹ and skeletal fluorosis at concentrations greater than 10 mg l⁻¹, although the precise concentrations at which populations are vulnerable are likely to vary as nutrition plays an important additional role in prevention of the disease. In particular, dietary deficiency in Ca and vitamin C is considered a contributory factor (A. K. Susheela, pers. commun., 1995) and helps to explain why poor rural communities in developing countries without access to good nutrition are particularly vulnerable. Many millions of people in developing countries throughout the world are at risk from fluorosis but parts of India, Sri Lanka, China and East Africa are worst affected (e.g. Handa, 1975; Teotia et al., 1981; Zhaoli et al., 1989; Dissanayake, 1991; Gaciri and Davies, 1993).

The average crustal abundance of F is 300 mg kg⁻¹ (Tebbutt, 1983). Fluorite (CaF₂) is the most common F-bearing mineral but it is also present in apatite (Ca₅(Cl,F,OH)(PO₄)₃) and topaz (Al₂[SiO₄](OH,F)₂), and in trace quantities in amphibole, mica, pyroxene and sphene.

These minerals are particularly abundant in acid-igneous (granite, pegmatite) and metasomatic assemblages, as well as the products of hydrothermal activity. Thermal, high-pH waters can have especially high concentrations.

Since water-rock interaction is the mechanism by which F is built up in drinking water, groundwater tends to be most vulnerable to high F concentrations. Surface waters typically have less contact time with primary minerals and unweathered bedrock and so concentrations rarely exceed about 0.5 mg l⁻¹.

The principal form of F in water is as free dissolved F⁻ but at low pH, the species HF⁰ may be stabilised (at pH 3.5, this may be the dominant species; Hem, 1985). Fluorine readily forms complexes with Al, Be, Fe³⁺, B and Si. Concentrations of F in water are limited by fluorite solubility, such that in the presence of 10⁻³ M Ca, F should be limited to 3.1 mg l⁻¹ (Hem, 1985). It is therefore likely to be the absence of Ca in solution which allows higher concentrations of F to be stable. High F concentrations may therefore be expected in groundwater in Ca-poor aquifers and in areas where F minerals are common. Fluoride concentrations will also increase in groundwaters where cation exchange of Ca for Na takes place, resulting in a decrease in the Ca activity (e.g. Handa, 1975).

3.7 Bolgatanga: local environment and geology

Rainfall in the Upper Regions of Ghana is much lower than in the tropical rainforest belt which covers the southern part of the country (including Obuasi). Average annual rainfall in the Bolgatanga area is 1000 mm and, unlike further south, there is a single rainy season extending from May to October with most rain falling between July and September. Maximum temperatures range between 20 and 40°C (Murray, 1960).

The area investigated is bordered to the north-east by the Red Volta which forms the boundary between Ghana and Burkina Faso and thereafter flows southwards. Just to the south of the area, the White Volta flows largely west to east and joins the Red Volta approximately 45 km south-east of Bolgatanga (Figure 1.1). Drainage of minor rivers in the area is towards the south and south-west, largely controlled by the geological strike. The Red Volta, together with most of the minor streams, frequently dry up during the dry season (Murray, 1960).

The main hill range runs south-westerly from Nangodi (Figure 3.1) to the White Volta south of Shiega and reaches a height of up to about 370 m. Much of the remaining area comprises flat low-lying plains. The topography is closely related to the underlying geology. Outcrops of granite typically form rounded outcrops rising some 100 m above the surrounding plains (Plate 3.3), particularly in the Bongo and Tongo areas.

Geology comprises Upper Birimian (Precambrian) basement rocks divided into metavolcanic (greenstone, lava, amphibolite, tuff) and metasedimentary (sheared conglomerate, greywacke, quartzite, grit, arkose, phyllite and quartz-sericite-schist; Figure 3.1) rocks as well as meta-igneous lithologies (hornblende- and biotite-granodiorite, tonalite, adamellite, biotite-gneiss and migmatite). The Birimian forms a folded, steeply-dipping, complex group of formations, metamorphosed to greenschist grade, which have not been dated clearly. Cleavage is usually steep or vertical.

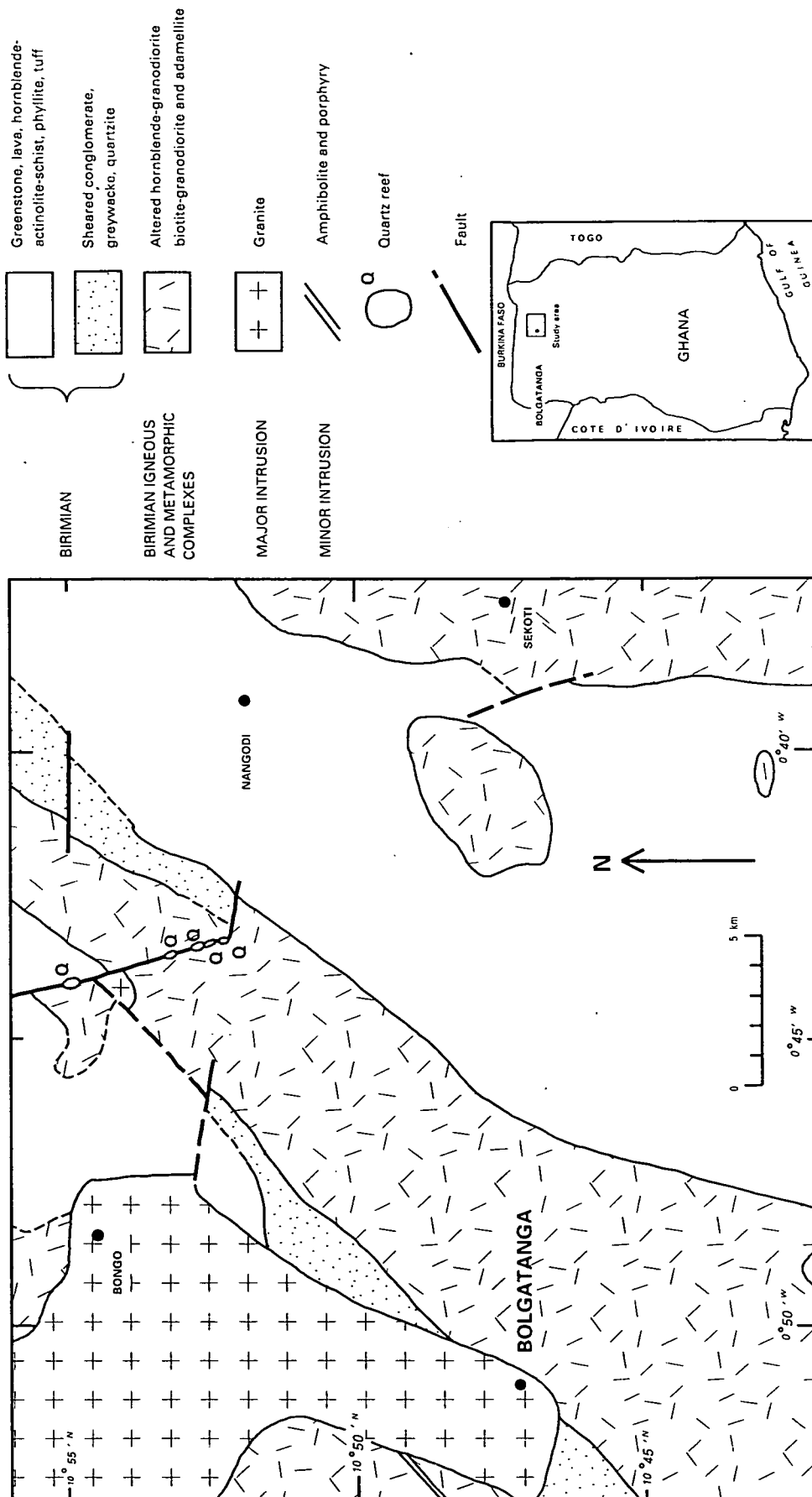


Figure 3.1. Geological map of the Bolgatanga study area (after Murray, 1960).



Plate 3.3. Outcrop of the Bongo Granite approximately 15 km north of Bolgatanga. The granite is responsible for the occurrence of dental fluorosis in the area.



Plate 3.4. Young boy from the Bongo area with early signs of dental fluorosis.

Later magmatic activity produced a suite of coarse-grained granites, the Bongo Granite suite, and associated minor intrusions (now amphibolite and porphyry; Figure 3.1). The age of these intrusions is largely unknown, but they are of Precambrian origin. The Bongo Granite is variable in composition but comprises typically a pink microcline-hornblende-granite (euhedral microcline and amphibole phenocrysts, the former up to 1 cm long) with interstitial quartz, plagioclase (Ab90) and biotite. The granite is in many places quite fresh, but everywhere plagioclase shows evidence of sericitisation. The granite is thought to be slightly alkaline: the amphibole appears to be in the hornblende-arfvedsonite range (Murray, 1960). The central portion of the outcrop comprises coarse biotite-granite. Proportions of biotite and amphibole vary laterally across the pluton. Accessory phases include abundant sphene as well as magnetite, apatite, zircon, rutile, clinozoisite, allanite and chlorite. The Tongo Granite just to the south of the study area is similar in composition to the Bongo suite but is more quartzose and contains a higher proportion of biotite (Murray, 1960).

Lithologies marked in Figure 3.1 are usually quite variable laterally and the classification is a simplification of a range of compositions. Although the large north-south-trending mass of granodiorite surrounding Sekoti to the east of the study area has been grouped with other hornblende- and biotite-granodiorites in Figure 3.1 (and in Murray, 1960), in outcrop, it forms rounded knolls resembling those of the Bongo Granite and Coe (1953) grouped the Sekoti Granodiorite with the Bongo compositional suite, although Murray (1960) subsequently disputed this association. The Sekoti Granodiorite is distinct from other granodiorites in the area and from the Bongo Granite in being more sodic (Murray, 1960). The Bongo suite is notably potassic (Table 3.4). The Sekoti Granodiorite comprises mainly plagioclase and quartz. Biotite is the dominant mafic mineral and often replaces amphibole. Accessory minerals include apatite and sphene.

Quartz reefs are well-developed in the north-central part of the study area, striking 340° and associated with a large fault zone (Figure 3.1). A small (2 km wide) porphyritic microgranite has exploited this same zone of structural weakness. Quartz reefs are also present in other small patchy outcrops in the study area and are occasionally auriferous, the most notable being in a north-east to south-west line from Nangodi [0° 40.3'W, 10° 51.3'N] to Dusi [0° 41.8'W, 10° 46.5'N]. Gold mining was carried out in the area during the 1930s, principally at Nangodi mine (Murray, 1960), but there has been no active prospecting more recently. Sulphide minerals are widely dispersed, principally comprising pyrite and chalcopyrite (and minor arsenopyrite) associated with the auriferous reefs.

Due to the torrential nature of rainfall in the wet season and a paucity of vegetation in many areas, soil erosion is high. Depth of weathering is variable, but generally thin due to torrential runoff. Soil compositions vary according to underlying geology and topography. Those produced on greenstone and schist are commonly dark, loamy soils of relatively good quality but since many are on hillslopes, erosion rates of these are high. Soils developed on granitic rocks are sandy, acidic and generally of poor quality, although millet appears to be a successful crop on the Bongo Granite, perhaps due to the high K content of the bedrock (Murray, 1960). Soils are lateritic in places.

Groundwater storage in all the Birimian rocks is generally poor but is locally increased at shallow depths by weathering. Groundwater flow is principally via fissures and joints in the bedrock. Static water levels are variable but generally shallow, at 1–15 m below ground level. Borehole yields are typically between 0.5 and 3 l s⁻¹ (Gill, 1969).

Apart from a concentrated population in the city of Bolgatanga, communities are widely disseminated in the rural areas, often consisting of small collections of houses rather than as larger, discrete villages that occur in the Obuasi area. Bolgatanga is supplied with piped, treated water from a reservoir at Gowrie, 10 km to the north of the town. Rural communities use groundwater, mainly from hand-pumped boreholes installed within the last 20 years, although a few communities also use groundwater from shallow dug wells. Unlike the Obuasi area, streamwater is generally not used due to its much more limited availability, particularly towards the end of the dry season. Some of the dug wells are also vulnerable to drying up during the dry season.

3.8 Health of Bolgatanga communities

The diet of the communities living in and around Bolgatanga is generally of limited range and nutritional quality. It consists mainly of locally-grown produce, most notably millet and rice with a little meat (chicken, mutton, very little fish), along with cassava and plantain. Fruits are difficult to obtain and are seasonal (e.g. mango, oranges).

Despite the fact that communities living in and around Bolgatanga drink mainly groundwater, water-borne diseases such as bilharzia and diarrhoea still exist, largely due to bathing and paddling in surface waters (notably the Red Volta) and the poor quality of some shallow dug wells (Appendix 2E). Guinea worm and river blindness are also occasionally reported despite the belief that the latter had been eradicated several years ago (Bolgatanga Ministry of Health, pers. commun., 1993).

Goitre has been observed in the Bolgatanga area (Plates 3.1, 3.2), particularly in the villages of Sekoti, Bongo and Builsa (Bolgatanga Ministry of Health, pers. commun., 1993; Builsa is in the Upper East Region, a few kilometres to the south-west of the present study area). Women are particularly affected and the goitre is often familial. A survey of the prevalence of goitre and cretinism in the Sekoti and Builsa districts was carried out by the Department of Nutrition and Food Science, University of Ghana (supported by UNICEF) in January 1991. Five communities were surveyed in Builsa district and 7 in Sekoti district. In each district, about 250 women of child-bearing age and about 250 school children were selected at random for interview and physical examination. Results of the physical examination are given in Table 3.3. Although the prevalence of visible goitre (grades 2 and 3) is less than 10% in all groups surveyed apart from women in Builsa district, the total prevalence of goitre is shown to be 59% or higher and indicates that IDD is indeed endemic in the area. There was however, no evidence of endemic cretinism.

Casual urine samples were collected from 12% of the population surveyed (125 samples). Concentrations of urinary I (carried out at Department of Medicine, University of Virginia, USA) were all found to be low at $<50 \mu\text{g l}^{-1}$, 83% of samples having $<20 \mu\text{g l}^{-1}$ I, and consistent with observations of goitrous patients elsewhere (Section 3.4).

Following the pilot survey by the University of Ghana, a regional council for the control of IDD was constituted and an iodine supplementation and health-education programme implemented in the Bolgatanga area. The supplement comprises capsules of iodised oil, administered by the district health authority. Vitamin A supplements are administered simultaneously. Although the I supplementation programme has shown very positive results where it has been carried out, it is apparent that the main barrier to remediation of the

Table 3.3. Prevalence of goitre in the Bolgatanga District. Data are from the Department of Nutrition and Food Science, University of Ghana.

Sekoti District									
Age group	N° examined	Grade 0		Grade 1		Grades 2, 3		Total goitre	
		N°	%	N°	%	N°	%	N°	%
10-14	286	117	40.9	165	59.7	4	1.4	169	59.1
15-45	261	61	23.8	177	67.8	23	8.8	200	76.6
Bulsaa District									
Age group	N° examined	Grade 0		Grade 1		Grades 2, 3		Total goitre	
		N°	%	N°	%	N°	%	N°	%
8-16	254	58	22.8	175	68.9	21	8.3	196	77.2
15-45	260	95	36.5	108	41.6	57	21.9	165	63.5

problem remains the lack of dissemination of health education to the rural communities: many people are still unaware of the link between goitre and dietary I deficiency and many more are unaware that iodised oil is available from the district health authority. Increased health education would improve the situation greatly and remains an important priority.

Villagers in some parts of the study area also suffer from dental fluorosis. The problem is particularly prevalent in Bongo and Sekoti districts, although the numbers of people affected and the regional extent is not known in detail. The fluorosis is particularly prevalent among children (Plate 3.4). There is to date no evidence of skeletal fluorosis.

3.9 Sampling and analysis

A total of 118 water samples were collected from boreholes and wells (7 samples) in a 30 x 30 km area around Bolgatanga. Sample localities along with sample numbers (referred to in Appendix 2) are given in Figure 3.2. Sampling and analytical methods for inorganic constituents and microbial populations in Bolgatanga groundwaters were as outlined in Section 2 for the Obuasi area. During the sampling, additional analysis of faecal- and total- coliform bacteria was also carried out using a Delagua (University of Surrey, UK) dual-incubator kit. At each site, duplicate water samples were filtered through sterile filters and the latter placed onto paper pads impregnated with sterilised membrane lauryl-sulphate broth. Samples were incubated for 24-36 hours at 44°C and 37°C for thermo-tolerant (faecal) and total coliforms respectively. Positive colonies (indicated by a colour change of the culture medium from red

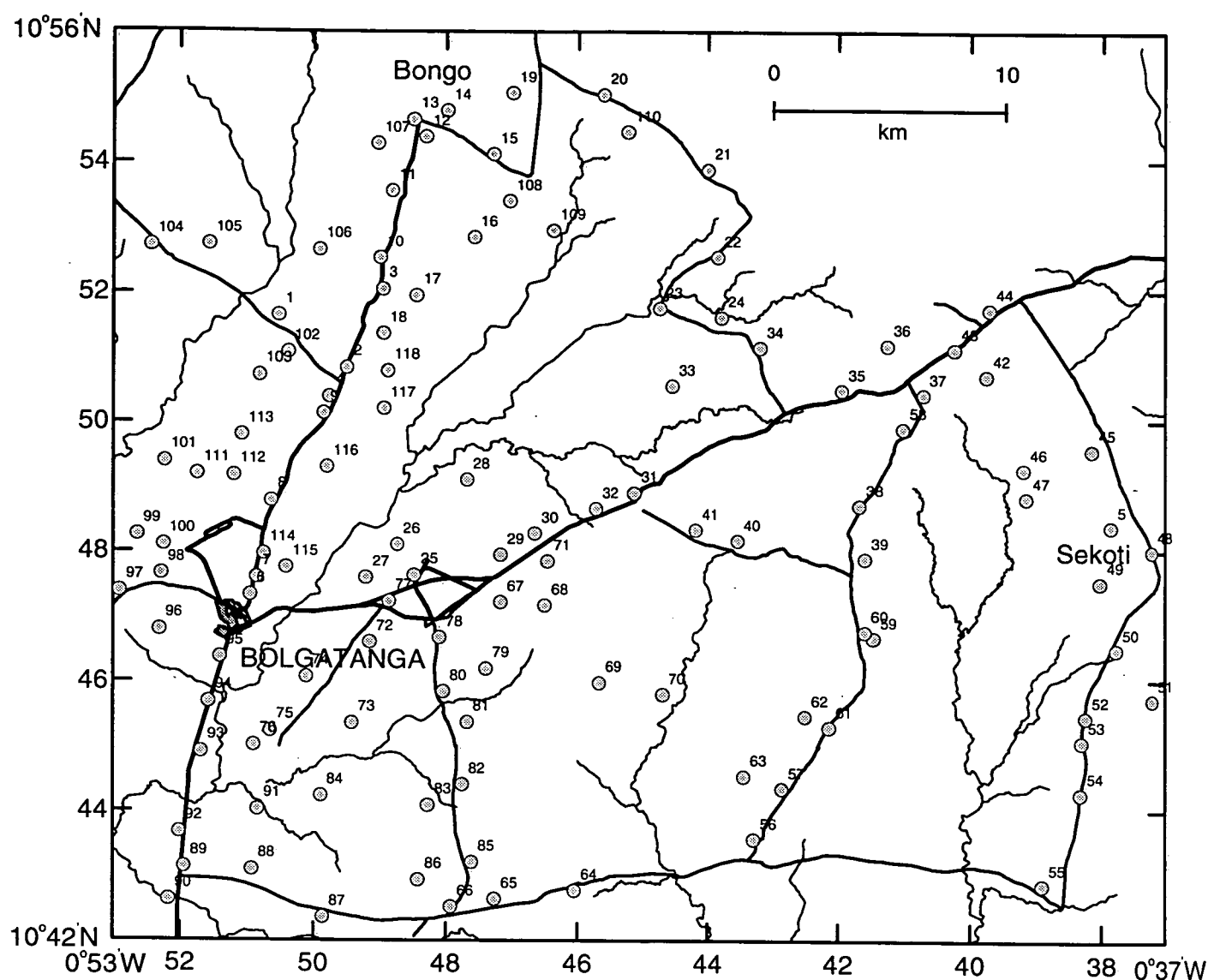


Figure 3.2. Sample localities of groundwaters from the Bolgatanga area showing sample numbers referred to in Appendix 2. Major roads and streams are also shown.

to yellow) were then counted and expressed in colony-forming units (CFU) 100 ml⁻¹.

Selected soil samples were also collected for analysis of I concentration as well as Fe, Al and organic carbon. Samples were collected from fields adjacent to 7 of the water-sampling sites and sample numbers correspond to the water-sample localities. In each case, samples were taken from the plough layer (top 15 cm) of cultivated soils from which the main crops were millet, rice and tomatoes.

Soils were air-dried at 25°C and passed through a 2.36 mm sieve prior to analysis. Soil-solution pHs were measured on 5 g aliquots using deionised water (pH_w) and 0.01M CaCl₂ (pH_{CaCl2}), following the methods of McLean (1982). Loss on ignition (LOI) was calculated by the weight loss of 5 g of soil (dried at 110°C) after heating in a furnace for 2 hours at 540°C.

Soil organic carbon was determined using a Carlo Erba CNS analyser at the BGS laboratories in Keyworth. Samples were washed with 10% HCl to remove any inorganic carbon before analysis. Aliquots were then combusted with oxygen at 1070°C. Interfering gases (halogens and sulphur compounds) were retained using chromium-oxide and cobaltous-oxide catalysts. The carbon present (as CO₂) was then re-reduced (using Cu), separated on a chromatographic column and detected by a thermal-conductivity detector. Calibration was performed using standard organic materials.

Amorphous iron oxides in soil samples were analysed by ICP-AES following extraction in ammonium oxalate-oxalic acid solution (after McKeague and Day, 1966; McKeague, 1978). Duplicate aliquots of 0.5 g were crushed using a pestle and mortar and 20 ml 0.113 M (NH₄)₂C₂O₄·H₂O - 0.087 M H₂C₂O₄·2H₂O were added. Sample solutions were then shaken for 4 hours, the shaking carried out in the dark to prevent photochemical reaction and hence enhanced amorphous-iron-oxide dissolution. Solutions were then centrifuged and filtered through 0.45 µm filters before analysis. Concentrations of Al, Si and Mn were also determined in these solutions and all analyses were carried out using matrix-matched standards. Analytical accuracy was within 10%. Three procedural blanks extracted at the same time as the soil samples gave maximum concentrations of 6, 3.2, 2.4 and 0.4 µg g⁻¹ for Fe, Al, Si and Mn respectively. Sample concentrations have not been blank-subtracted.

Crystalline iron oxide was determined in soil samples using a dithionite-citrate-bicarbonate extraction following the method of Jackson (1956) and Mehra and Jackson (1960). Duplicate 3 g aliquots of air-dried, crushed soil were placed in acid-washed centrifuge tubes and 2.5 g 1 M NaHCO₃ and 20 ml 0.3 M trisodium citrate (Na₃C₆H₅O₇·2H₂O) added. Samples were heated on a hotplate at 75-80°C (temperature maintained at not more than this to prevent precipitation of FeS) for 10-15 minutes. Na dithionite (1.5 g) was then added to each and samples were again heated to 75-80°C. Solutions were then centrifuged, 10 ml solution aliquots taken and diluted to 100 ml with deionised water. Any soil samples that were still brown after this extraction were put through the same procedure a second time to remove any remaining Fe-oxide material. Solutions were analysed for Fe, Al, Si and Mn by ICP-AES using matrix-matched standards. Analytical accuracy was within 12%. Three procedural blanks gave maximum concentrations of 7, 1.9, 0.7 and 0.3 µg g⁻¹ for Fe, Al, Si and Mn respectively. Sample concentrations have not been blank-subtracted.

Iodine in soils was determined by a sodium-hydroxide extraction method similar to that of Whitehead (1973b). Extraction was achieved by refluxing 3 g of air-dried, sieved soil in 30 ml 2 M NaOH for 45 minutes, centrifuging and dilution of the solution to 2000 ml using deionised water. Iodine analysis was then carried out by ICP-MS using internal and matrix-matched standards. A 20 µg g⁻¹ standard extracted at the same time as the samples was accurate to within 20% and a procedural blank gave an I concentration of 0.5 µg g⁻¹; no blank-subtraction of sample concentrations was carried out.

Analysis of major elements and F was carried out for selected minerals in two samples of granite from the Bongo Granite suite (Gowrie and Vea Asoranabisi). Determinations were made by wavelength-dispersive electron-probe microanalysis using a Cameca SX50 instrument at BGS, Keyworth. Counting times were 30 seconds for biotite and 50 seconds for apatite and amphibole, with an accelerating voltage of 15 kV and a beam current of 20 nA. Fluorine concentrations of unknowns were checked against the international mineral standard MC APAT2 (accepted value 3.75 wt% F, O=F correction of -1.88) and the mean value

obtained was 3.64% with an O=F correction of -1.53. This is considered acceptable given the potential natural inhomogeneities within the reference material.

3.10 Results and Discussion

3.10.1 Regional groundwater quality

Inorganic chemical data for the Bolgatanga groundwaters are given in Appendices 2A-D and median concentrations for water from wells and boreholes in Table 3.4. The groundwaters are mostly neutral to slightly acid (pH 6.0–7.4) with a range of conductivities from 100 to 1000 $\mu\text{S cm}^{-1}$. The major ions are Ca (Na and Mg) and HCO_3 . Most are relatively oxidising with Eh values in the range 200–360 mV, although a few have values less than 200 mV and correspondingly low dissolved-oxygen concentrations (0.1 mg l^{-1} or less; Appendix 2A). Nitrate is detectable although concentrations are relatively low in most waters, only 3% of samples investigated having a concentration greater than the WHO recommended maximum of 10 mg l^{-1} (as N). Some of the higher nitrate concentrations occur in waters from shallow dug wells and have correspondingly high concentrations of faecal and total coliforms (Section 3.10.5). These appear to have been polluted by surface inputs of domestic or agricultural contaminants. However, some of the well waters have relatively low nitrate concentrations (<5 mg l^{-1}) and a few of borehole waters have >10 mg l^{-1} such that the correlation between nitrate and coliform counts for most samples is rather poor. Some *in-situ* denitrification may have taken place in the reducing groundwaters (dissolved organic carbon is available in most at a concentration of about 1–4 mg l^{-1} to act as a terminal electron acceptor for the process, Appendix 2A) although this is likely to be limited given that most of the groundwaters are insufficiently reducing for the process to have been important. Nitrate and ammonium are low in almost all samples.

Regional distributions of Ca, Mg, Na and K in the groundwaters are given in Figure 3.3. Calcium is variable across the region but the lowest concentrations occur in the Bongo Granite, between Bongo and Bolgatanga. Calcium concentrations in the granite are low at around 2–3% (Table 3.8). Dissolution of feldspars is thought to be the main process by which major cations are built up in the groundwaters flowing through the granite. These are dominantly sodic plagioclase and microcline (Murray, 1960) and so Ca release from feldspar should be relatively minor. This may explain the lower Ca concentrations in the Bongo area. Calcium concentrations in the other rock types in the study area are not notably different from those in the granite (Table 3.7) but the Ca concentrations of feldspars in the other lithologies are likely to be more calcic, especially in the more mafic greenstone and granodiorite assemblages.

Magnesium and Na in groundwaters show no distinctive variation with lithology (Figure 3.3). Magnesium may be from hornblende, biotite, chlorite and other clay minerals which are present in most of the lithologies in the study area. Dissolved Na is likely to be derived mainly from sodic feldspar, amphibole and clay minerals. There do not appear to be anomalously high concentrations of Na in groundwaters from the Sekoti Granodiorite to the east of the study area, despite the observation of the pluton's sodic composition.

Potassium concentrations are notably higher in groundwaters from the granodioritic and granitic host rocks than from the greenstone-metasediment lithologies outcropping between Nangodi and Shiega (Figure 3.3, compare with Figure 3.1). The main K source is likely to

Table 3.4. Median concentrations of selected inorganic constituents in groundwaters from wells and boreholes in the Bolgatanga area.

	Units	Wells	Boreholes	*WHO maximum
Depth	m	6.78	25.4	
Temperature	°C	29.5	30.9	
pH		6.79	6.70	
Eh	mV		266	
DO	mg l ⁻¹		1.10	
SEC	µS cm ⁻¹	306	482	
Ca	mg l ⁻¹	20.62	31.74	
Mg	mg l ⁻¹	3.41	10.97	
Na	mg l ⁻¹	12.4	22.0	(200)
K	mg l ⁻¹	3.3	1.7	
Cl	mg l ⁻¹	6.5	3.6	(250)
SO ₄	mg l ⁻¹	3.1	2.5	500
HCO ₃	mg l ⁻¹	71	179	
NO ₃ -N	mg l ⁻¹	3.55	2.91	10
NO ₂ -N	mg l ⁻¹	<0.03	<0.03	0.91
NH ₄ -N	mg l ⁻¹	<0.02	<0.02	(1)
DOC	mg l ⁻¹		1.61	
Si	mg l ⁻¹	19.5	29.1	
Al	mg l ⁻¹	0.10	<0.01	0.2
P	mg l ⁻¹	0.09	0.07	
Sr	µg l ⁻¹	333	499	
Ba	µg l ⁻¹	136	58.2	700
Fe _{total}	µg l ⁻¹	36	158	300
Mn	µg l ⁻¹	11.3	4.4	500
As _{total}	µg l ⁻¹	<4	<4	10
I	µg l ⁻¹	1.7	3.2	
F	µg l ⁻¹	340	500	1500
Br	µg l ⁻¹	20	20	
B	µg l ⁻¹	8.6	9.0	
Li	µg l ⁻¹	3.1	10.5	
Cr	µg l ⁻¹	0.78	0.36	
Ni	µg l ⁻¹	1.48	1.37	
Cu	µg l ⁻¹	1.14	1.81	
Zn	µg l ⁻¹	8.9	38	
Mo	µg l ⁻¹	0.21	1.51	
U	µg l ⁻¹	0.17	0.26	
Pb	µg l ⁻¹	0.27	0.08	10

*WHO (1993) recommended maxima for drinking water. Values in parentheses are for elements for which no recommended maximum has been given but the value represents the limit above which taste problems might occur.

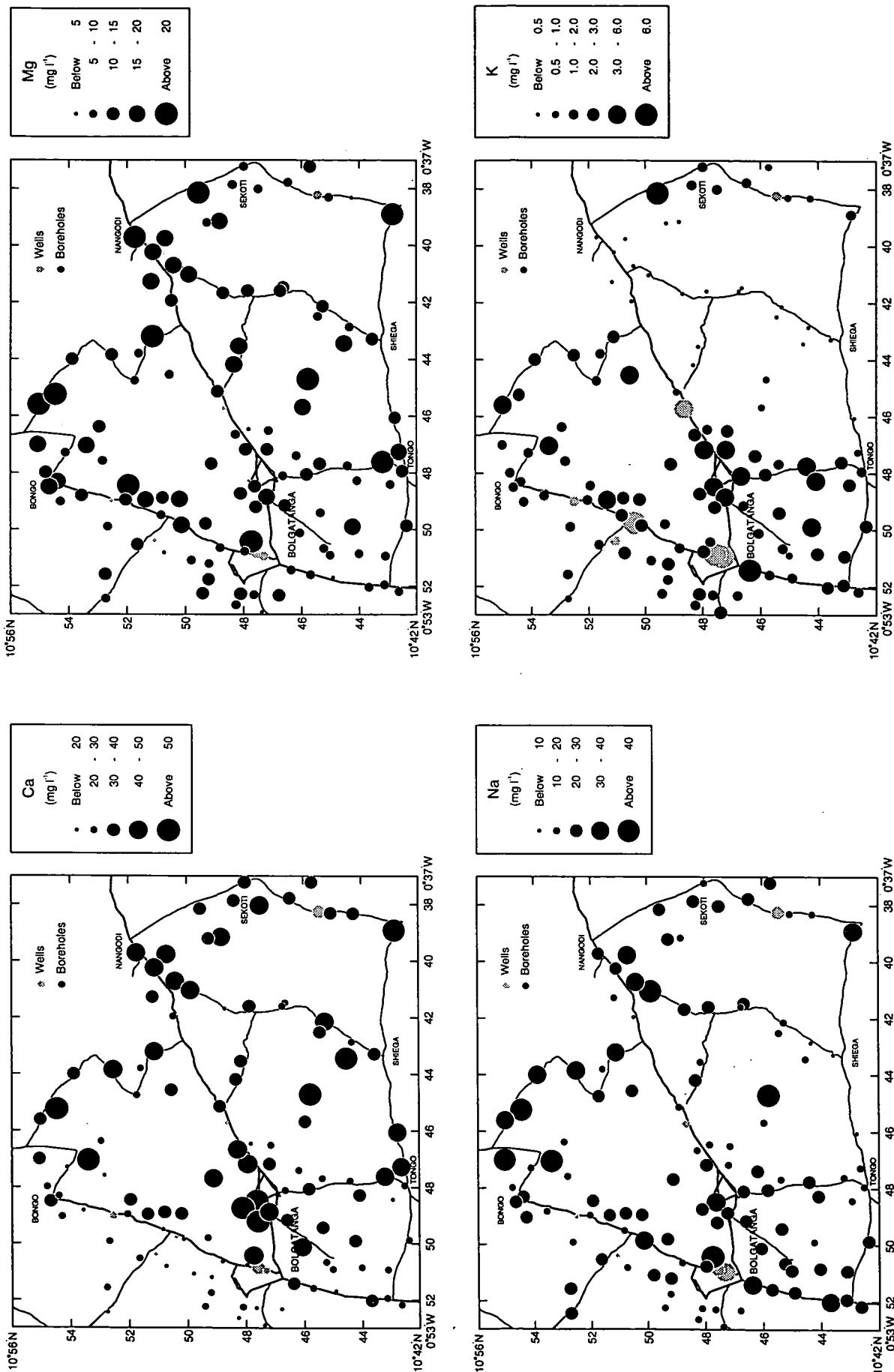


Figure 3.3. Concentrations of Ca, Mg, Na and K in groundwaters from the Bolgatanga area. Major roads are also shown.

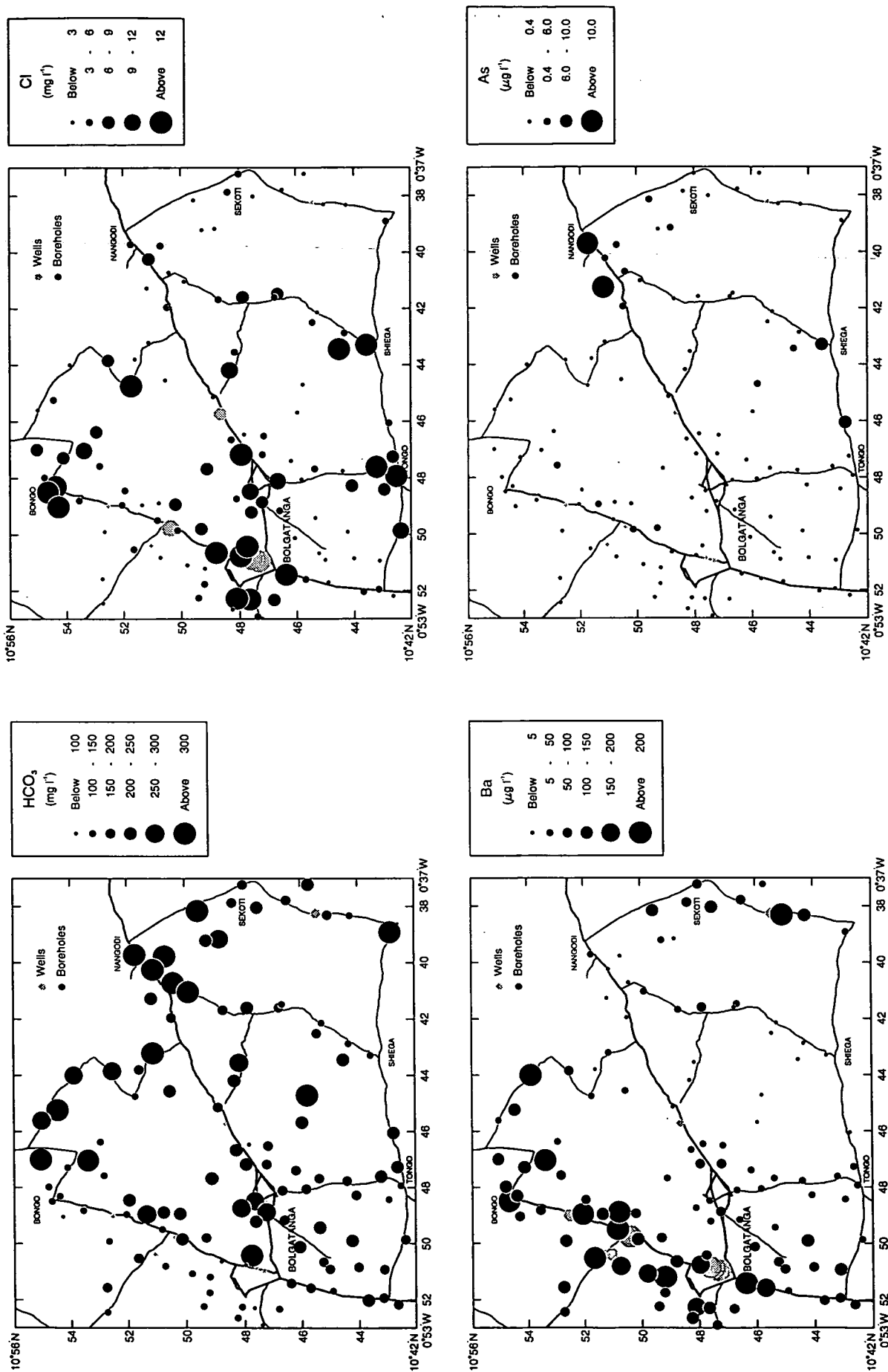


Figure 3.4. Concentrations of HCO_3^- , Cl, Ba and As in groundwaters from the Bolgatanga area. Major roads are also shown.

be biotite which is more concentrated in the granitic-granodioritic assemblages. The Bongo Granite has already been noted as a potassic granite (Section 3.7, Murray, 1960). Potassium concentrations of biotite in the Bongo Granite have been observed at between 8 and 10 weight % (Tables 3.9, 3.10). It is possible that some additional dissolved K may be derived from surface pollution, although this is considered a relatively minor source. Less than 2% of the groundwater samples analysed have K concentrations greater than the EC maximum for drinking water of 12 mg l⁻¹ (WHO does not give a recommended maximum value for K).

Groundwater-HCO₃ concentrations range between 58 and 451 mg l⁻¹. Concentrations appear to be slightly lower in samples from the Bongo Granite and the Sekoti Granodiorite (Figure 3.4) and probably relate to a paucity of carbonate minerals in these rocks.

Chloride distribution in the groundwaters tends to be higher in the Bongo, Bolgatanga and Tongo areas (Figure 3.4), a feature which may relate to derivation from biotite as micas are known to have potentially high concentrations of halogens. However, the regional distribution of nitrate (not shown) correlates reasonably well with that of Cl and it is therefore more likely that Cl is pollution-derived (domestic and agricultural). This is consistent with the Cl anomaly observed in the Bolgatanga area, corresponding with the greatest population density.

Many trace elements in the groundwaters show a dominant lithological control, many being higher in groundwaters from the Bongo Granite and Sekoti Granodiorite (e.g. Li, Ba, Sr, Mo, B). Concentrations of Ba highlight these outcrops particularly well (Figure 3.4). Barium is likely to be mainly derived from dissolution of alkali feldspar in the rock matrix.

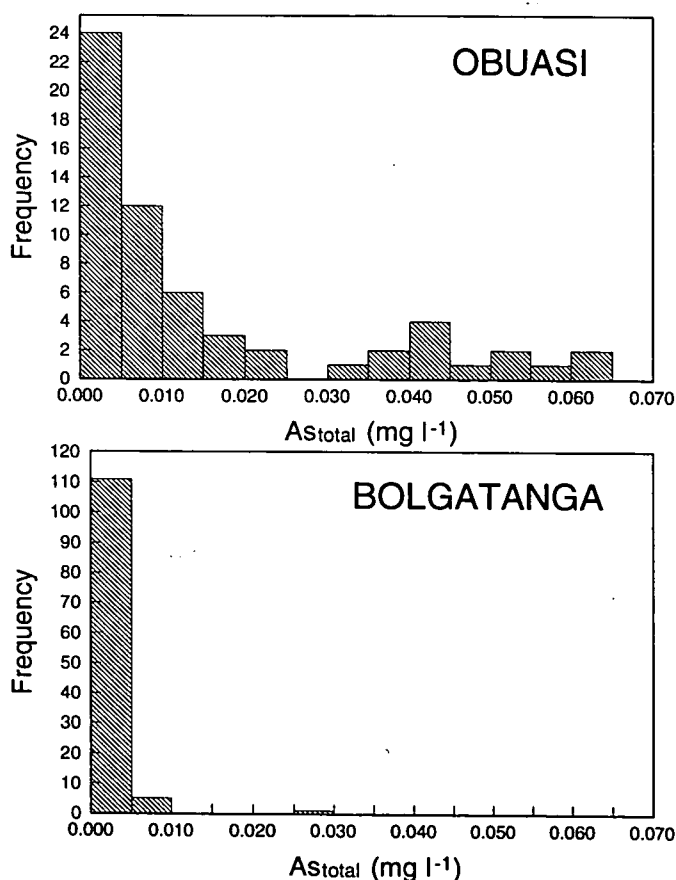


Figure 3.5. Total As concentration in drinking waters from the Bolgatanga area (Nangodi sample 44 not included) compared with those investigated from the Obuasi area.

Concentrations of As are notably lower than in the Obuasi area, the median concentrations in waters from wells and boreholes both being $<4 \mu\text{g l}^{-1}$ (Table 3.4). Less than 2% of samples analysed exceed the revised WHO maximum recommended value of $10 \mu\text{g l}^{-1}$, in contrast to the Obuasi area, where 20% of samples exceed this value. Arsenic(III) was analysed for in the Bolgatanga groundwaters but not detected (concentrations were less than $4 \mu\text{g l}^{-1}$). Histograms of total As concentration in waters from the Bolgatanga area are compared with those from Obuasi in Figure 3.5, although one high-As sample from Nangodi (sample 44, $141 \mu\text{g l}^{-1}$ total As) has been excluded for clarity.

Figure 3.4 reveals a small anomaly in As concentration around the Nangodi area, close to the formerly active gold mine. The source is therefore most likely to be sulphide minerals (pyrite, arsenopyrite, chalcopyrite) associated with vein gold within the Birimian metasediment. The highest observed As concentration ($141 \mu\text{g l}^{-1}$) is in a relatively oxidising water with 1 mg l^{-1} dissolved oxygen (sample 44, Nangodi Clinic). Sulphide oxidation is therefore likely to be the dominant mechanism of As release into solution. Given that the concentration in this localised area is considerably higher than the WHO maximum recommended concentration, further monitoring of groundwater quality should be carried out and if As is a persistently high constituent, use of the affected boreholes should cease. Evidence from the Obuasi area suggests that shallower boreholes in the area may yield water with lower As concentrations.

Aluminium concentrations are mostly low in the Bolgatanga groundwaters, at $<0.02 \text{ mg l}^{-1}$. Only two samples analysed (less than 2%) have concentrations higher than the WHO recommended maximum of 0.2 mg l^{-1} . The highest values, including these two samples, are from shallow wells (Table 3.4). The fact that high concentrations occur in groundwaters with near-neutral pH (>6 , Appendices 2A, 2B) suggests that the Al is present in colloidal rather than dissolved form. Some of the well waters are also cloudy, a feature which supports the suggestion of the presence of colloidal Al.

3.10.2 Iodine in Bolgatanga groundwater

Following the discussion in Section 3.5, the major sources of I in Bolgatanga groundwater are expected to be from rainfall and water-rock interaction. The I concentration of local rainfall is not known in detail but is expected to be low due to the remoteness of the study area from the sea (ca. 600 km). Only one analysis of rainfall I is available from the present study. This, from a sample collected in Bolgatanga during July 1993, gave a low concentration of $<0.6 \mu\text{g l}^{-1}$. Concentrations in rainfall may be expected to vary throughout the course of the wet season (July-September), being higher in the early part due to removal of the bulk of atmospheric I present in the earlier torrential falls. The available analysis suggests however, that even early-season rainfall has a low I concentration.

The ranges of I concentrations in the igneous and metamorphic rocks which comprise the major lithologies of the Bolgatanga area are also expected to be low at less than 5 mg kg^{-1} (Table 3.2), although no I analyses of rocks were carried out in this study. Iodine build-up in groundwater due to mineral dissolution is therefore expected to be minor. Indeed, median values for I in groundwaters from greenstone/metasediment, hornblende- and biotite-granodiorite, Sekoti Granodiorite and Bongo Granite are low at 2.6, 3.6, 2.7 and $3.3 \mu\text{g l}^{-1}$ respectively (Table 3.5) and show little inter-lithological variation, although a few samples from the hornblende- and biotite-granodiorite and greenstone/metasediment lithologies have

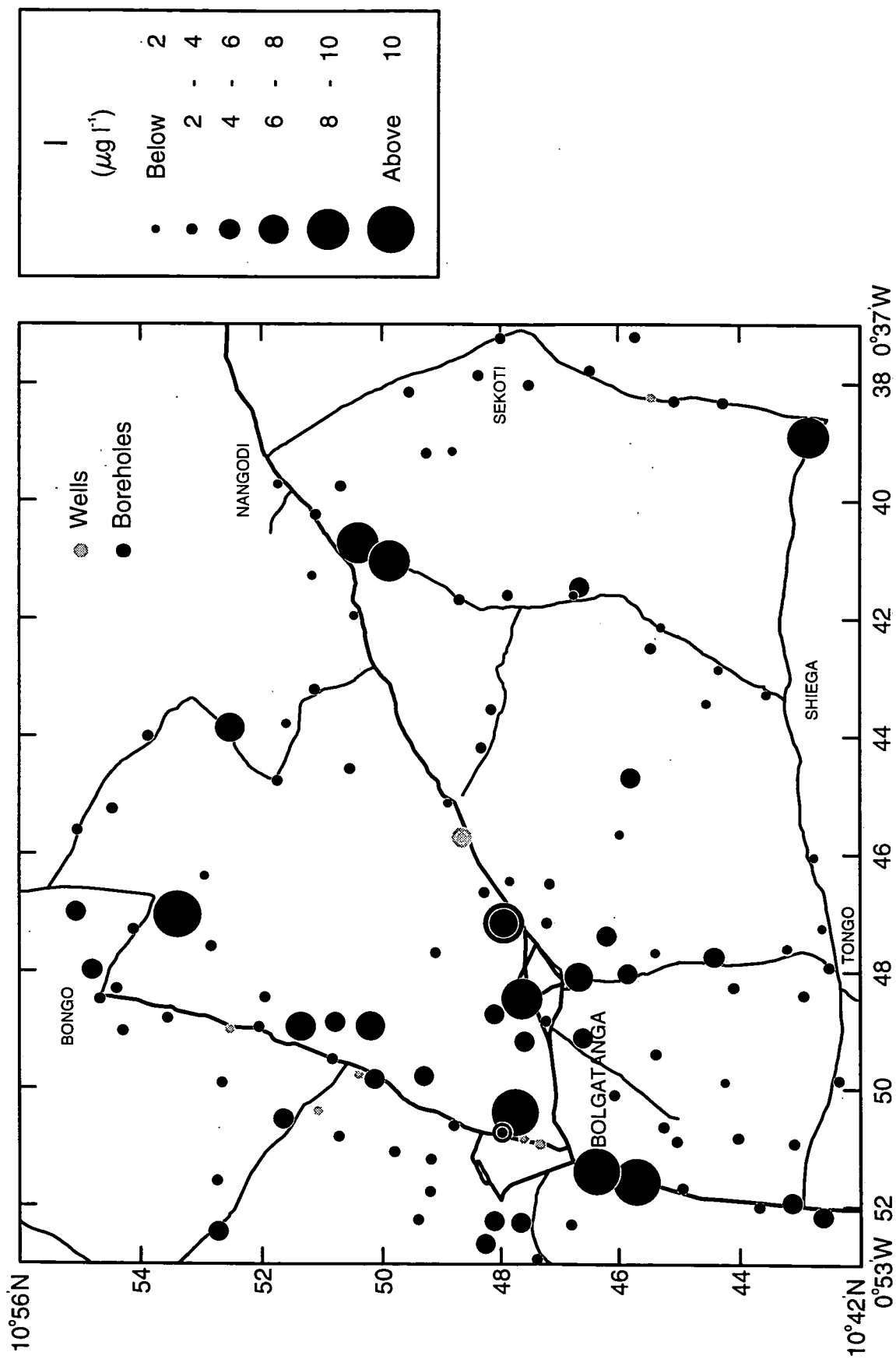


Figure 3.6. Regional concentrations of I in groundwaters from the Bolgatanga area. Major roads are also shown.

concentrations greater than $5 \mu\text{g l}^{-1}$, which is rare in the other lithologies. Median concentrations for the groundwaters divided into well or borehole sources show a slight difference at 1.7 and $3.2 \mu\text{g l}^{-1}$ respectively (Table 3.4). The slightly higher concentration in the borehole waters may be due to increased release from bedrocks due to their assumed longer residence times in the aquifer than the shallow well waters, although it is evident that the Bolgatanga groundwaters have generally low I concentrations.

A map of I concentrations in Bolgatanga well and borehole waters is given in Figure 3.6 and indicates little distinctive regional variation apart from slightly higher concentrations south and east of Bolgatanga and south-west of Nangodi. These correspond with the greenstone/metasediment and hornblende-granodiorite lithologies. Domestic pollution cannot be ruled out as an additional source in waters close to the urban area of Bolgatanga since sewage effluent is known to have elevated I concentrations (Fuge, 1989), although there is no correlation between I and other indicators of pollution such as Cl or NO_3 .

Comparison of groundwater-I concentrations in the Bolgatanga study area with those in drinking water from elsewhere (Section 3.3) indicates that the low concentrations observed are goitrogenic. Figure 3.7 shows a comparison of the distribution of I concentrations from Bolgatanga groundwaters with those from the Obuasi area. The overall median value for Bolgatanga waters ($3.2 \mu\text{g l}^{-1}$) contrasts with the median value of $8.3 \mu\text{g l}^{-1}$ in drinking waters from the Obuasi area where goitre is not endemic.

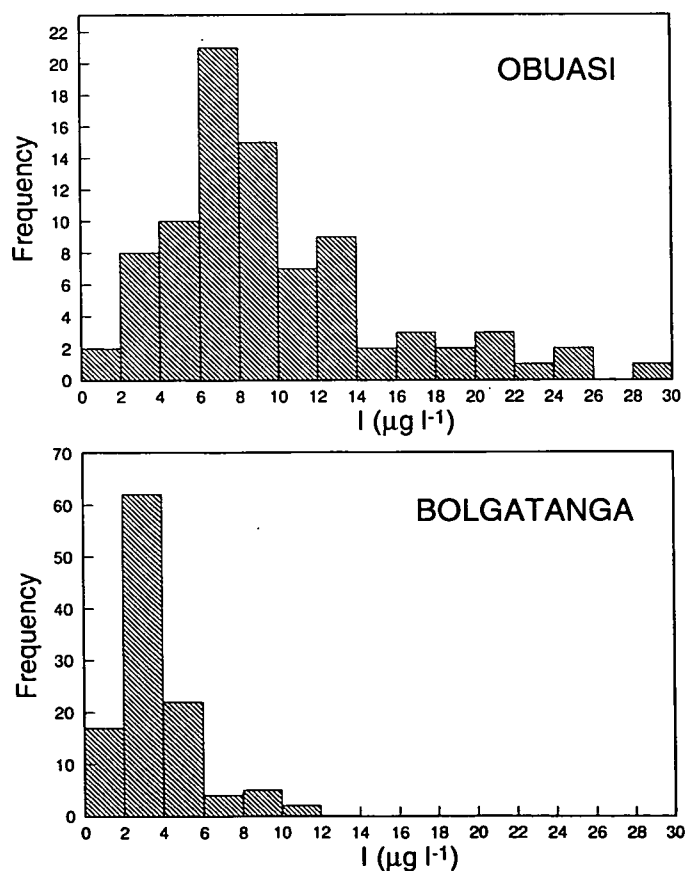


Figure 3.7. Histograms of I concentrations in drinking water from the Bolgatanga area compared with those in the Obuasi area.

Table 3.5. Median concentrations of suspected goitrogens in Bolgatanga groundwaters divided into lithological units.

Lithology	Median value							
	I $\mu\text{g l}^{-1}$	I/Ca _{mol} $\times 10^3$	I/Mg _{mol} $\times 10^3$	Mo $\mu\text{g l}^{-1}$	As $\mu\text{g l}^{-1}$	Co $\mu\text{g l}^{-1}$	Zn $\mu\text{g l}^{-1}$	F mg l^{-1}
Greenstone/metasediment	2.60	3.92	0.032	1.68	<0.4	0.152	25	0.22
Hornblende-granodiorite	3.60	2.56	0.075	1.84	<0.4	0.138	61	0.41
Sekoti Granodiorite	2.70	3.97	0.063	0.35	<0.4	0.071	41	1.19
Bongo Granite	3.25	1.83	0.053	1.31	<0.4	0.076	20	2.80

As indicated in Section 3.5, I tends to be found in higher concentrations in organic-rich sediments and in association with carbonate minerals. No organic-rich sediments occur in the Bolgatanga area, but carbonate minerals occur as occasional vein fillings and as secondary replacements in some rock matrices. The possibility of release of I from carbonate minerals has been investigated in Figure 3.8 which shows the variation of groundwater-I concentrations with calcite saturation index ($\text{SI}_{\text{calcite}}$) for Obuasi and Bolgatanga waters. In the Obuasi area, there is a slight positive correlation between $\text{SI}_{\text{calcite}}$ and I which suggests that I may have been released from calcite during its dissolution in calcite-undersaturated conditions. In contrast, groundwaters from the Bolgatanga area are all low in I apart from two samples from close to Bolgatanga with $>60 \mu\text{g l}^{-1}$ (Figure 3.6). These samples may have derived their I from dissolution of calcite, although as noted above, they occur close to the Bolgatanga urban area and may relate to pollution.

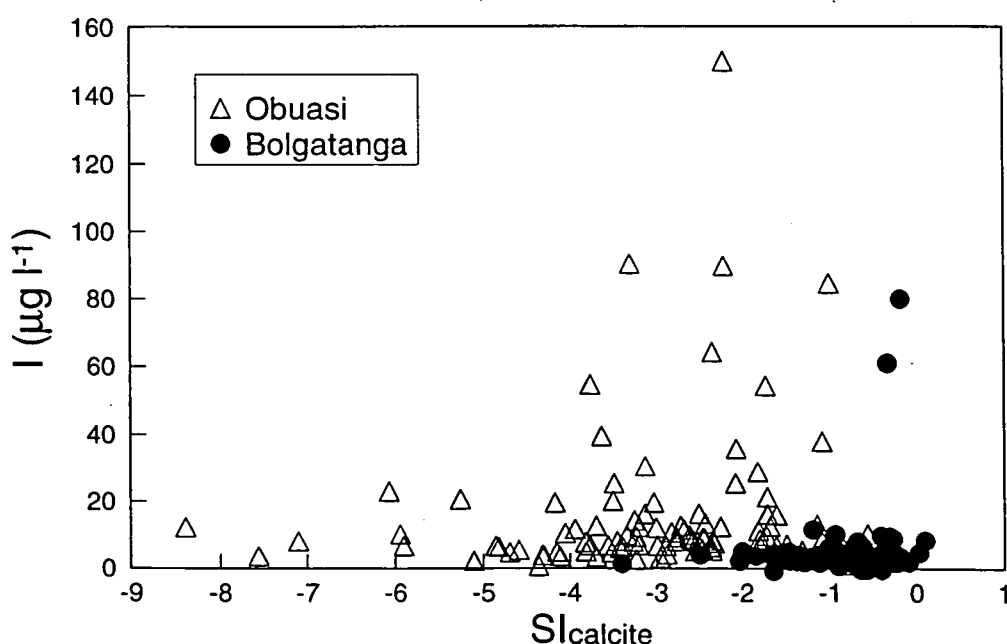


Figure 3.8. I concentration against calcite saturation index in groundwaters from the Bolgatanga area compared with those from Obuasi.

The main districts in the present study area known to be affected by goitre are Bongo and Sekoti, although other districts have not to date been investigated in detail and the prevalence of the disorder may be greater than presently recognised. Indeed, the widespread occurrence of low-I drinking waters suggests that this may be the case. It was noted in Section 3.3 that other dissolved inorganic constituents in water such as Ca, Mg, As, Mo and F can have goitrogenic effects. Variation in these elements regionally should be controlled by aquifer lithology. Table 3.5 shows a range of median values for these proposed goitrogens in different lithological units from the Bolgatanga area. Median values for most parameters do not vary significantly with aquifer lithology. Arsenic is unimportant as it is mostly very low in the groundwaters (below detection limit). Molybdenum and Co are also unlikely to have had an effect since the median concentrations are slightly lower in the proven endemic areas than in the other districts (as expected for granitic lithologies). Magnesium, Ca and Zn show little regional variation. Only F concentrations appear to be significantly higher in groundwaters from the Bongo and Sekoti districts than in other lithological terrains. It is possible that F is acting as a goitrogen in the Bolgatanga groundwaters although this is uncertain. The fact that IDD's are endemic throughout other parts of the Upper Regions of Ghana (Kelly and Sneddon, 1960) away from F-rich granitic rocks suggests that the link with F is coincident rather than causal, although the relationship deserves further consideration. If populations in the Bongo and Sekoti areas are more vulnerable to goitre than other districts locally, the fact that drinking waters abstracted from these rock types rarely exceed $5 \mu\text{g l}^{-1}$ I (slightly lower than the maxima for the other lithologies) may be a simpler explanation.

Despite the claimed link between goitre occurrence and presence of *E. coli* (Fuge, 1987), there is no evidence for a link in the Bolgatanga waters: there is no correlation between I and faecal-coliform concentration (West et al., 1995). Since faecal coliforms are an indicator of domestic pollution, the link with goitre may be due to the presence of high concentrations of organic carbon in water, derived from the same pollution source. Iodine mobility is known to be restricted in the presence of organic carbon (Whitehead, 1979). However, there is no significant correlation between dissolved organic carbon and I in the Bolgatanga groundwaters and the presence of organic pollutants therefore does not appear to be an important factor in the development of goitre locally.

It is suggested that the prevalence of endemic goitre in the Bolgatanga area can be explained best by deficiency of I in the drinking water regionally and the paucity of I-rich food sources. High F concentrations in the drinking water may be an additional exacerbating factor but this is unlikely to be the dominant cause.

3.10.3 Bolgatanga soil compositions

Chemical data for the seven soil samples collected from selected groundwater-sampling sites are presented in Table 3.6. The soils analysed are moderately acidic (pH in CaCl_2 3.9 - 6.9). Organic-carbon concentrations are mostly very low (0.2–1.9%) with total concentrations of organic matter likely to be in the range 0.4–3.6% (typically around 1.9 times the organic-carbon content; Allison, 1965; Avery, 1990). LOI values are correspondingly low.

Concentrations of ammonium-oxalate- and dithionite-extractable Fe and Al are also extremely low (Table 3.6). Dithionite-extractable Fe concentrations of British brown earths and podzols are typically 1% or greater and amorphous Fe and Al concentrations (from oxalate or pyrophosphate extraction) typically in the range 0.1–0.5% (Avery, 1990). In most of the

Table 3.6. Chemical data for selected soil samples collected from the plough layer (top 15 cm) in the Bolgatanga area. Sample localities correspond to water-sampling sites (see Appendix 2).

Sample no	pH _w	pH _{CaCl2}	LOI	Ammonium-oxalate-extractable				Citrate-dithionite-extractable				I
				C _{organic}	Fe	Al	Si	Fe	Al	Si	Mn	
			%	%	%	%	%	%	%	%	%	mg kg ⁻¹
5	5.33	4.68	0.22	0.43	0.034	0.022	0.004	0.025	0.013	0.012	0.007	1.1
7	5.88	5.54	0.39	1.18	0.069	0.028	0.009	0.012	0.016	0.020	0.013	2.3
10	4.77	3.88	0.29	0.64	0.34	0.039	0.017	0.009	0.017	0.020	0.001	0.9
17	6.12	5.35	0.17	0.21	0.096	0.015	0.007	0.013	0.009	0.012	0.010	2.0
31	7.39	6.88	0.52	0.72	0.18	0.077	0.027	0.197	0.022	0.019	0.106	3.6
63	6.98	6.37	1.31	1.91	0.22	0.120	0.042	0.146	0.039	0.027	0.126	3.7
118	6.10	5.31	0.32	0.67	0.15	0.022	0.011	0.019	0.007	0.017	0.009	1.3

Percentage values are all given on weight basis.

pH_w: pH of soil solution comprising deionised water; pH_{CaCl2}: pH of a soil solution comprising 0.01M CaCl₂.

Element concentrations in ammonium-oxalate and citrate-dithionite extracts are means of duplicate analyses.

LOI: loss on ignition.

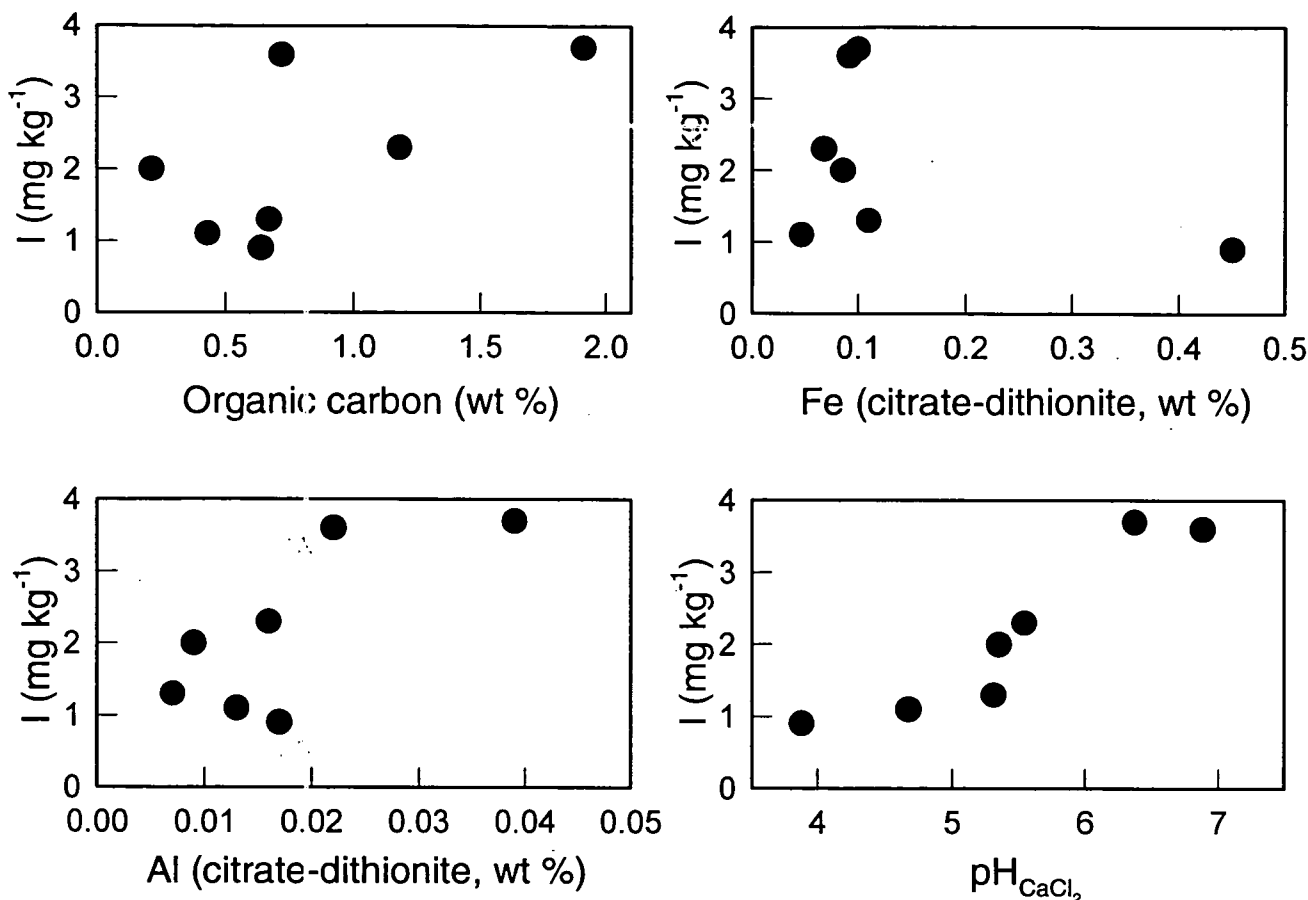


Figure 3.10. Concentration of soil I against organic carbon, Fe- and Al-oxide (citrate-dithionite-extractable) and pH (CaCl_2).

Relationships between I in Bolgatanga soils and concentration of organic carbon, 'crystalline' Fe and Al oxides (citrate-dithionite-extractable, Table 3.6) and pH are illustrated in Figure 3.10. The plots show clear positive correlations between I and both organic carbon and Al oxide, as described for other soils by Whitehead (1973a, 1979), although the correlation is less good for Fe oxide. There is a particularly good correlation with soil pH (CaCl_2). Although anions such as iodide and iodate in soils are expected to be more readily sorbed in acidic conditions (Dzombak and Morel, 1990), the noted increase in soil I at higher (near-neutral) pH appears to be related to the higher concentrations of organic carbon and Al in these soils. The lower concentrations of Al oxide in the more acidic soils probably relate to its increased solubility at low pH. Although concentrations of organic carbon and Al oxide are low in the Bolgatanga soils compared to soils elsewhere, these constituents appear to be the main controls on I retention.

3.10.4 Fluoride in Bolgatanga groundwater

As noted in Section 3.8, dental fluorosis has been observed in some populations from parts of the current study area, particularly in Bongo and Sekoti districts. Fluorine in drinking water plays a crucial role in the development of fluorosis, although nutrition is also important (Section 3.6). The regional distribution of F has been examined in the Bolgatanga groundwaters and a map of F concentrations is given in Figure 3.11, along with the major lithological units. Fluoride concentrations are clearly highest in the Bongo area, reaching up to 4 mg l^{-1} , but values also reach up to 3.2 mg l^{-1} in Sekoti district. The concentrations

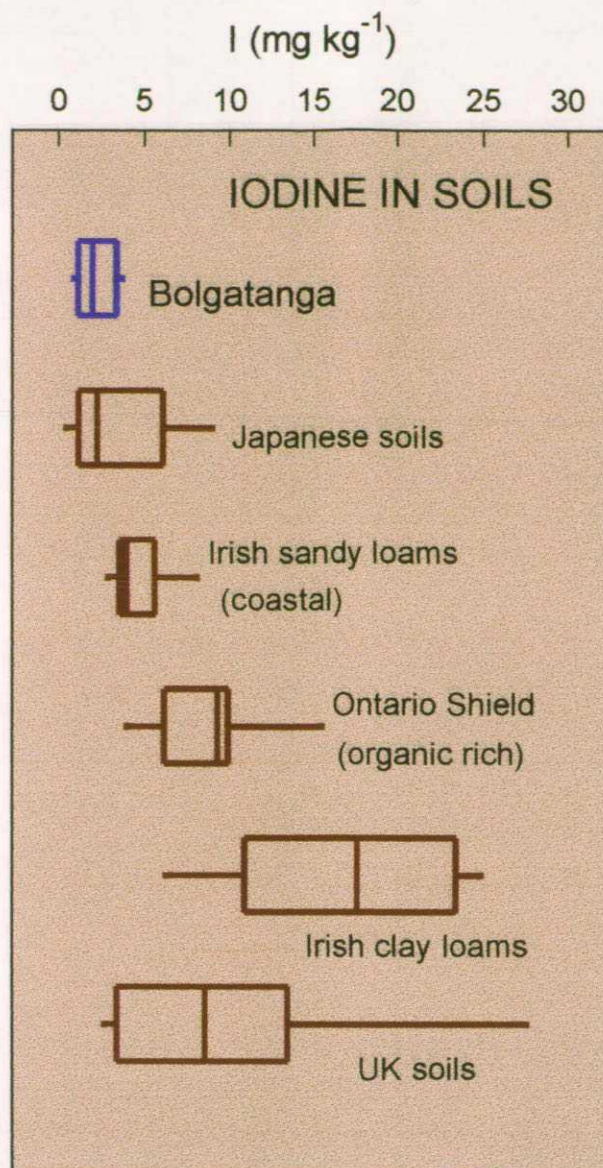


Figure 3.9. Concentrations of I in soils from Bolgatanga compared to those elsewhere (data from other regions from Whitehead, 1973a; Yuita, 1983; Koch and Kay, 1987; McGrath and Fleming, 1988).

Bolgatanga soil samples analysed, oxalate-extractable Fe and Al concentrations are as high as or slightly greater than those determined in dithionite extractions. This suggests that most or all of the Fe and Al present in the soils is as labile amorphous sesquioxides (metal-organic complexes, poorly crystallised oxyhydroxides and allophanic material) rather than from more well-crystallised material such as goethite, haematite and gibbsite. Some of the slightly higher concentrations of oxalate-extractable Fe and Al may be due to analytical uncertainty.

Iodine concentrations in the Bolgatanga soils are also very low, ranging from 0.9 to 3.7 mg kg^{-1} (Table 3.6). Comparisons of the I concentrations with those determined in some other studies are given in Figure 3.9 and demonstrate the overall deficiency of soil I in the Bolgatanga area. It is conceivable therefore that crops grown in these soils (e.g. millet, rice, cassava, tomatoes) will also be deficient in I and will add little of this essential element to the diet of local communities.

clearly relate to underlying geology, the principal F source being the Bongo Granite and Sekoti Granodiorite (see also Table 3.4). Concentrations of F in the main underlying rock types are given in Tables 3.7 and 3.8 (data taken from Murray, 1960). Although concentrations are highly variable, the highest occur in the Bongo Granite with up to 0.2 wt % F. Dominant F-bearing minerals in these two rock types are hornblende, biotite, apatite and sphene, although fluorite is present as a rarer accessory mineral in some parts of the Bongo Granite (Table 3.8).

Fluorine analyses of selected minerals in two samples from the Bongo Granite are given in Tables 3.9 and 3.10. Both are samples of coarse, altered, two-feldspar, amphibole-rich granite with minor biotite and accessory apatite and sphene. Fluorite is a minor accessory mineral in sample B10. Feldspars are cloudy throughout. Concentrations of F in amphibole are mostly around 1% (range 0.62–1.15% in both samples) and biotites have 2–3% F (range 2.1–3.1%). Apatite in sample B2 has 4.7–7.0% F. No microprobe data have been collected for F-bearing minerals from other rock types in the area. Although amphibole and biotite are also present in other lithologies outlined in Figure 3.11, it is likely that these minerals have higher F concentrations in the Bongo and Sekoti granitic suites than in other lithologies since the rocks represent late-stage residual melts, which commonly have high concentrations of incompatible elements such as halogens and large-ion lithophile elements.

As suggested in the Obuasi study for As, there is some indication that F concentration increases in groundwater with increasing residence time in the aquifer. Figure 3.12 shows the relationship between F concentration and groundwater depth in different aquifer lithologies. As no data were available for total depth of boreholes, depth is here taken as basal screen depth (metres below ground level), a value less than the total depth. Total depth values have been used for shallow wells. Borehole depth is taken to be a measure of groundwater residence time as in the Obuasi investigation. Many samples have low F concentrations, at less than 1 mg l⁻¹ and these appear to have little or no depth dependence. However, for samples with concentrations greater than the WHO recommended maximum for drinking water of 1.5 mg l⁻¹, F concentration increases notably with borehole/well depth, particularly in the samples from the Bongo Granite (Figure 3.12). Although the maximum F concentration observed in groundwaters from the Bongo Granite was 3.8 mg l⁻¹, the maximum from shallow wells on the Granite was 0.37 mg l⁻¹. It is therefore apparent that shallower groundwaters in such F-vulnerable zones may be generally safer sources of drinking water with respect to F than deeper sources, although the possibility of bacteriological contamination in such open, shallow wells must always be borne in mind. Wells and boreholes also need to be sufficiently deep to obtain requisite groundwater yields.

As mentioned in Section 3.6, groundwaters deficient in Ca tend to be those most susceptible to high F concentrations because of the solubility limit of fluorite (CaF₂). The relationship between Ca and F in Bolgatanga groundwaters is displayed in Figure 3.13. The solubility limit of fluorite (at 25°C) is also given. Most of the groundwaters are undersaturated with respect to fluorite, but many of the samples from the Bongo Granite and some from the Sekoti Granodiorite are saturated or approaching saturation. Fluorite appears to be the main control on F concentration in these groundwaters.

Some workers have indicated a link between high F and high HCO₃ concentrations in groundwaters as a result of coupled equilibrium with fluorite and calcite (Handa, 1975). However, this is not the case in Bolgatanga groundwaters. These instead show a weak negative correlation between the two parameters in waters close to fluorite saturation. This

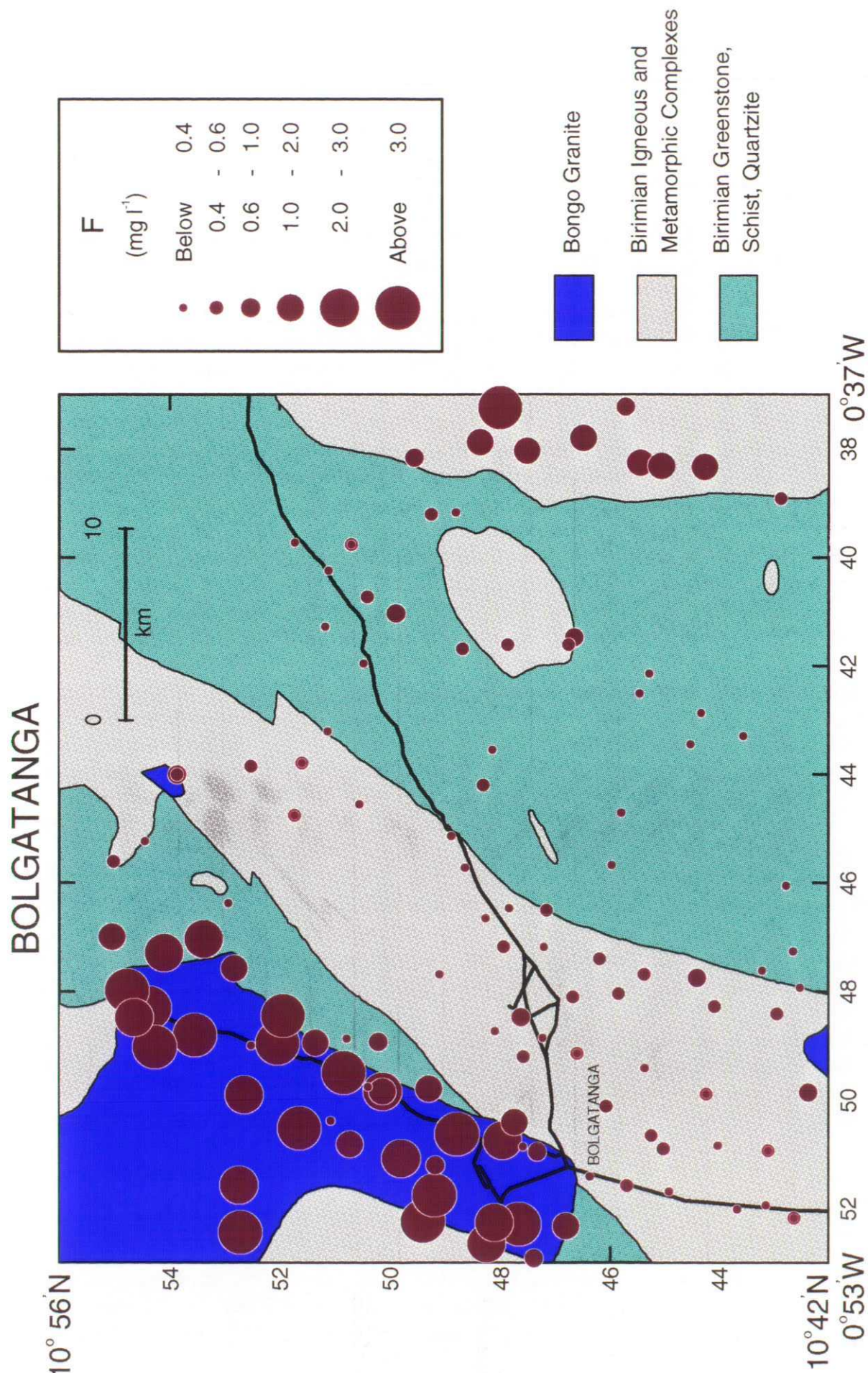


Figure 3.11. Simplified geological map of the Bolgatanga study area showing the regional variation in F concentration in groundwaters. Highest concentrations are restricted to groundwaters abstracted from the Bongo Granite and Sekoti Granodiorite (the latter in the eastern part of the map area).

Table 3.7. Chemical analyses (weight %) and mineral modes (volume %) of rocks from the Bolgatanga area, taken from Murray (1960).

	Metasediment/greenstone				Biotite-hornblende-gr'diorite				Altered hornblende-granodiorite									
	1	2	3	4	1	2	3	4	1	2	3	4	5	6	7	8	9	10
SiO ₂	58.73	73.63	72.23	66.01	58.28	63.24	63.29	65.64	63.31	65.61	68.32	68.76	68.00	69.79	69.04	68.63	71.23	71.02
Al ₂ O ₃	14.66	14.42	14.83	14.44	18.23	17.18	16.00	16.08	16.29	15.23	14.96	14.79	14.87	15.31	15.32	15.46	14.77	14.76
Fe ₂ O ₃	1.12	1.36	1.59	2.36	1.75	1.45	2.25	1.09	2.88	2.13	1.77	1.61	1.90	1.60	1.44	1.68	1.66	1.27
FeO	6.03	0.36	0.29	2.40	4.31	2.90	2.87	3.12	2.13	2.30	1.10	1.35	1.09	1.00	1.15	0.86	0.66	0.94
MgO	4.97	0.35	0.53	2.10	3.45	2.51	2.74	2.00	2.27	2.32	1.11	1.16	1.06	0.86	0.87	0.76	0.75	0.66
CaO	5.88	1.57	1.77	3.74	5.93	4.92	4.64	4.06	4.10	3.91	3.62	3.34	3.11	2.75	2.71	1.99	1.83	2.58
Na ₂ O	2.98	4.29	4.17	3.21	4.68	4.96	4.30	4.84	3.25	3.71	4.79	4.72	5.23	5.08	4.66	4.17	4.25	4.94
K ₂ O	1.67	2.93	3.48	3.70	1.50	1.11	2.00	1.50	3.84	2.62	1.59	1.60	2.01	2.25	2.46	3.06	2.97	2.17
H ₂ O+	1.75	0.90	0.96	1.00	0.94	0.37	0.79	0.42	1.03	1.07	0.61	0.72	0.80	0.68	1.14	1.47	1.05	0.78
H ₂ O-	0.05	0.03	0.06	0.03	0.06	0.03	0.16	0.11	0.12	0.15	0.07	0.03	0.02	0.09	0.07	0.10	0.13	0.08
TiO ₂	0.74	0.19	0.19	0.61	0.81	0.55	0.62	0.38	0.48	0.38	0.33	0.32	0.33	0.32	0.29	0.30	0.26	0.27
P ₂ O ₅	0.20	0.14	0.13	0.22	0.33	0.29	0.31	0.20	0.01	0.15	0.15	0.22	0.11	0.15	0.10	0.20	0.10	0.10
MnO	0.33	0.05	0.05	0.10	0.12	0.08	0.07	0.09	0.08	0.09	0.05	0.05	0.04	0.07	0.11	0.07	0.03	0.04
F	tr	0.02	0.05	tr	0.02	0.02	0.05	tr	0.05	tr	tr	tr	tr	0.02	tr	0.03	tr	nil
Total	100.05	100.73	100.55	100.22	100.74	99.88	100.33	99.87	100.08	100.31	99.68	99.50	99.50	100.20	100.21	99.90	100.21	100.13
Qz					21.3	15.3	21.8	33.3	33.3	30.9	31.5	32.8	33.2	28.2	33.3			
Mel					-	-	1.1	0.3	0.3	3.4	-	-	-	3.0	11.5			
Plag					58.6	65.5	60.2	52.9	52.9	58.4	60.4	56.6	59.3	65.5	53.1			
Hbl					7.9	3.5	7.5	3.0	3.0	-	-	-	-	-	-			
Bio					11.7	14.2	7.4	8.4	8.4	3.8	1.1	1.7	5.4	1.0	-			
Chl					-	-	0.1	-	-	3.1	3.5	1.5	0.4	0.7	1.4			
Epi					0.1	1.5	1.0	1.9	1.9	-	2.7	6.1	0.8	0.4	-			
Sph					-	-	0.2	0.1	0.1	-	0.3	0.7	0.1	1.0	0.7			
Ap					0.1	-	0.2	0.05	0.04	-	-	0.1	-	0.1	-			
Mt					0.3	-	0.5	0.05	0.05	-	-	-	-	-	-			

Table 3.8. Chemical analyses (weight %) and mineral modes (volume %) of rocks from the Bolgatanga area, taken from Murray (1960).

	Sekoti Granodiorite					Bongo Granite									
	1	2	3	4	5	1	2	3	4	5	6	7	8	9	10
SiO ₂	67.04	70.48	71.06	71.35	72.83	59.97	60.91	63.06	65.14	67.14	67.36	68.66	69.85	71.60	70.22
Al ₂ O ₃	16.52	14.98	16.02	14.93	14.99	13.54	17.64	16.98	15.11	15.07	15.84	15.12	15.64	14.73	15.03
Fe ₂ O ₃	1.28	0.92	1.27	1.51	0.53	1.80	1.95	1.82	1.36	1.41	0.18	0.94	0.94	0.93	0.92
FeO	2.08	1.39	1.33	0.79	0.88	1.97	1.38	1.57	2.46	1.73	1.81	1.76	1.31	1.01	1.33
MgO	1.30	0.88	0.40	0.90	0.65	3.26	1.64	1.29	2.02	1.37	1.23	1.11	0.77	0.53	0.76
CaO	2.94	2.74	2.40	2.06	2.02	7.62	4.41	2.92	3.04	2.59	2.75	2.11	2.32	2.16	2.08
Na ₂ O	4.91	4.64	4.95	5.06	5.07	2.15	4.30	5.14	3.90	5.39	4.01	4.10	4.76	4.85	4.22
K ₂ O	2.48	1.72	1.31	2.75	2.67	7.74	6.34	5.69	5.44	3.99	5.14	5.45	3.60	3.21	4.36
H ₂ O+	0.56	0.63	0.39	0.45	0.24	0.42	0.34	0.31	0.34	0.20	0.22	0.20	0.24	0.26	0.16
H ₂ O-	0.17	0.16	0.11	0.14	0.10	0.02	0.11	0.17	0.10	0.11	0.08	0.12	0.12	0.12	0.13
TiO ₂	0.41	0.27	0.38	0.26	0.20	0.82	0.60	0.55	0.55	0.55	0.92	0.48	0.46	0.37	0.36
P ₂ O ₅	0.14	0.16	0.05	0.07	0.10	0.12	0.30	0.22	0.41	0.22	0.15	0.10	0.14	0.15	0.21
MnO	0.06	0.06	0.05	0.04	0.03	0.09	0.07	0.05	0.06	0.05	0.05	0.05	0.03	0.04	0.04
F	tr	0.10	0.06	0.05	0.02	0.10	0.02	0.05	0.20	0.06	0.13	0.04	0.05	0.05	0.05
Total	100.27	100.15	99.97	100.62	100.52	100.30	100.43	100.44	100.71	100.47	100.34	100.64	100.53	100.46	100.30
Qz	31.9		33.7	24.2	31.3	7.2	4.1	5.5	15.8	16.5	11.6	19.5	30.2	32.3	27.3
Mcl	0.3		0.1	10.3	6.9	65.3	54.8	56.7	47.3	50.4	49.3	50.6	28.9	22.4	26.9
Plag	61.7		59.7	62.7	57.4	7.3	23.7	25.7	21.9	23.1	29.0	24.4	34.3	40.4	37.2
Hbl	-		-	-	-	-	9.2	5.3	12.9	6.7	2.5	5.1	-	-	-
Bio	1.6		-	1.6	2.6	-	-	-	-	0.9	0.2	-	6.3	3.1	4.9
Pyx	-		-	-	-	18.3	-	-	-	-	-	-	-	-	-
Chl	1.2		3.5	-	-	-	-	-	-	-	-	-	-	-	-
Epi	3.1		1.9	0.9	1.5	0.4	7.3	-	-	0.3	0.5	-	-	-	3.0
Sph	0.2		1.0	0.2	0.1	0.5	0.9	6.8*	2.1*	1.3	0.5	0.4	0.3*	1.8*	0.7*
Ap	-		0.1		0.1	1.0	-	-	-	0.3	-	-	-	-	-
Mt	-		-	0.1	0.1	-	-	-	-	0.5	0.2	-	-	-	-
Fluor	-		-	-	-	-	-	-	-	-	0.2	-	-	-	-

* Total accessory minerals.

Table 3.9. Electron microprobe analyses (wt %) of amphibole, biotite and apatite from Bongo Granite, sample B10, Ve-a-Asoranabisi [0°51.85'W,10°52.35'N].

Amphibole

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO ₂	46.24	47.24	46.58	46.72	45.89	47.71	46.66	44.24	47.03	46.84	48.45	47.32	46.09	46.23	45.35	46.26	47.15
Al ₂ O ₃	6.81	5.84	7.32	6.63	6.82	5.61	6.54	6.70	6.57	6.12	5.84	6.25	6.19	6.85	7.08	6.68	6.40
FeO	17.73	16.77	19.53	17.27	15.23	16.16	17.04	17.97	17.97	16.95	15.82	17.44	17.17	17.53	18.48	16.93	17.58
MgO	10.96	12.22	10.21	11.24	12.92	11.83	11.48	11.14	11.40	11.85	12.32	11.83	12.05	11.28	10.80	11.57	11.41
CaO	11.22	11.11	11.44	11.15	11.25	11.04	11.25	11.04	10.97	11.20	11.41	11.26	11.37	11.27	11.16	10.91	11.28
Na ₂ O	1.72	1.91	1.56	1.83	2.06	1.59	1.77	1.89	1.72	1.81	1.67	1.90	1.54	1.93	1.72	1.91	1.78
K ₂ O	1.08	0.89	1.13	0.96	0.94	0.90	1.00	0.97	0.96	0.82	0.90	0.90	0.92	1.06	1.08	0.91	0.90
TiO ₂	1.05	0.96	0.30	1.18	1.52	1.16	1.46	1.06	1.30	1.19	1.11	1.02	0.85	1.15	0.68	1.53	1.01
MnO	0.53	0.49	0.46	0.42	0.38	0.40	0.49	0.49	0.48	0.31	0.44	0.38	0.51	0.41	0.49	0.28	0.50
H ₂ O	1.54	1.53	1.65	1.66	1.45	1.61	1.67	1.44	1.65	1.65	1.55	1.65	1.68	1.58	1.54	1.50	1.60
F	0.93	0.98	0.73	0.70	1.15	0.80	0.70	1.04	0.76	0.73	1.01	0.76	0.62	0.86	0.89	1.03	0.86
Total	99.82	99.93	100.98	99.82	99.61	98.85	100.06	98.04	100.82	99.46	100.51	100.70	98.99	100.15	99.26	99.55	100.50

Biotite

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	39.53	39.77	39.84	37.70	40.11	39.40	38.91	40.45	39.31	40.33	38.04	38.77	40.18	39.14	41.14
Al ₂ O ₃	12.97	13.00	12.93	12.06	12.75	12.29	12.11	12.48	12.57	12.80	12.27	12.49	12.32	12.68	12.76
FeO	15.70	16.40	16.10	14.80	15.68	15.95	16.17	14.42	14.76	15.54	14.38	14.42	14.26	15.92	14.19
MgO	15.66	15.53	15.52	15.25	16.22	15.55	14.51	16.48	16.49	15.99	15.75	15.45	16.33	16.40	17.33
CaO	0.05	0.05	0.04	0.12	<0.02	0.05	0.09	0.07	0.03	0.06	0.11	0.10	0.16	0.12	0.07
Na ₂ O	0.04	<0.03	0.05	0.06	0.05	0.07	0.03	0.07	0.04	0.04	0.05	0.05	0.05	0.05	0.04
K ₂ O	9.04	8.70	9.03	8.86	7.94	9.58	9.16	10.30	8.73	8.83	9.68	8.91	9.38	9.38	8.65
TiO ₂	0.74	0.79	0.92	0.64	0.76	1.05	1.43	0.56	0.77	0.81	0.75	0.74	0.41	0.78	0.51
MnO	0.42	0.34	0.31	0.32	0.31	0.36	0.39	0.32	0.28	0.38	0.39	0.41	0.36	0.34	0.28
H ₂ O	2.84	2.92	2.84	2.76	2.77	2.90	2.89	2.78	2.78	2.82	2.78	2.78	2.49	2.92	2.74
F	2.40	2.27	2.44	2.17	2.59	2.24	2.12	2.62	2.47	2.52	2.26	2.29	3.11	2.24	2.81
Total	99.44	99.77	100.01	94.74	99.17	99.44	97.82	100.54	98.24	100.12	96.44	96.42	99.05	99.98	100.60

Apatite

	1	2	3	4	5	6	7
SiO ₂	0.23	0.53	0.38	0.32	0.37	0.24	0.51
CaO	55.86	55.48	56.17	56.06	56.55	56.13	55.74
Na ₂ O	0.14	0.12	0.12	0.11	0.13	0.16	0.16
K ₂ O	<0.01	0.04	<0.02	0.02	<0.01	0.02	<0.01
P ₂ O ₅	39.73	35.05	37.39	39.98	37.28	39.63	39.71
MnO	<0.04	0.12	<0.04	0.11	<0.04	<0.04	0.10
SrO	0.23	0.14	0.17	0.28	0.26	0.20	0.21
F	5.93	6.95	6.32	4.77	6.11	5.84	5.19
Total	102.33	99.26	100.89	101.86	100.69	102.39	102.17

Table 3.10. Electron microprobe analyses (wt %) of amphibole and biotite from the Bongo Granite, sample B2, Gowrie [0°49.65'W,10°50.70'N].

Amphibole

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	46.64	46.00	45.23	45.71	45.56	46.38	46.27	45.25	46.53	45.87	45.55
Al ₂ O ₃	6.48	6.09	7.19	7.09	6.00	6.12	6.21	6.44	6.27	6.53	6.22
FeO	17.11	17.12	16.03	17.77	17.00	16.84	16.18	17.52	17.87	16.71	16.81
MgO	11.56	11.61	11.72	10.99	11.64	11.67	11.83	11.54	11.15	11.35	11.40
CaO	11.11	11.32	11.10	11.13	10.74	10.84	10.92	11.06	10.87	10.36	10.94
Na ₂ O	1.47	1.40	1.98	1.66	1.90	1.90	1.86	1.84	1.77	1.66	1.89
K ₂ O	1.00	0.98	1.05	1.13	0.88	0.95	0.92	0.96	0.96	0.86	0.90
TiO ₂	0.55	0.40	1.14	0.88	1.02	0.66	1.00	0.72	0.83	0.92	0.93
MnO	0.51	0.48	0.41	0.46	0.49	0.43	0.40	0.48	0.38	0.47	0.55
H ₂ O	1.67	1.53	1.53	1.49	1.53	1.52	1.51	1.45	1.61	1.57	1.48
F	0.65	0.90	0.91	1.01	0.87	0.93	0.96	1.05	0.75	0.80	0.98
Total	98.74	97.88	98.35	99.31	97.65	98.24	98.10	98.32	98.98	97.10	97.65

Biotite

	1	2	3	4	5	6
SiO ₂	40.13	39.06	39.42	39.15	39.54	41.30
Al ₂ O ₃	13.03	13.07	12.84	12.84	12.63	13.15
FeO	15.73	15.84	15.85	15.58	13.23	14.81
MgO	15.52	14.88	15.03	15.45	17.16	16.08
CaO	0.10	0.04	0.11	0.05	0.10	0.09
Na ₂ O	0.06	0.06	0.06	0.05	0.04	0.05
K ₂ O	7.51	6.95	7.43	8.30	8.02	6.13
TiO ₂	0.66	0.80	0.73	0.68	0.41	0.75
MnO	0.44	0.37	0.37	0.29	0.39	0.46
H ₂ O	2.78	2.94	2.85	2.82	2.54	2.81
F	2.53	2.01	2.25	2.32	2.93	2.57
Total	98.48	96.00	96.93	97.53	96.99	98.19

follows from the strong positive correlation between HCO₃ and Ca (Figure 3.14), suggesting that the Ca is derived principally by dissolution of calcite, and the negative correlation between Ca and F in the fluorite-saturated groundwaters. Equilibrium with calcite has not been achieved in the Bolgatanga groundwaters as most are undersaturated.

The dominant species present in the high-F groundwaters is F⁻, usually accounting for more than 90% of the dissolved F present (using the WATEQ4F speciation model, Ball and Nordstrom, 1991). However, in samples where Al is present, the model predicts that complexes such as AlF₂⁺, AlF₃aq and AlF₄⁻ may also be present in small concentrations. These complexes may have enhanced fluorite solubility in some waters although Al is not present in high concentrations in most. It is thought to be coincidence that some of the shallow-well waters in the Bongo Granite have high Al and also low F concentrations since the Al is considered to be principally colloidal at the given pH range. Low F is instead taken to be due to slow fluorite reaction kinetics in groundwaters of short residence time.

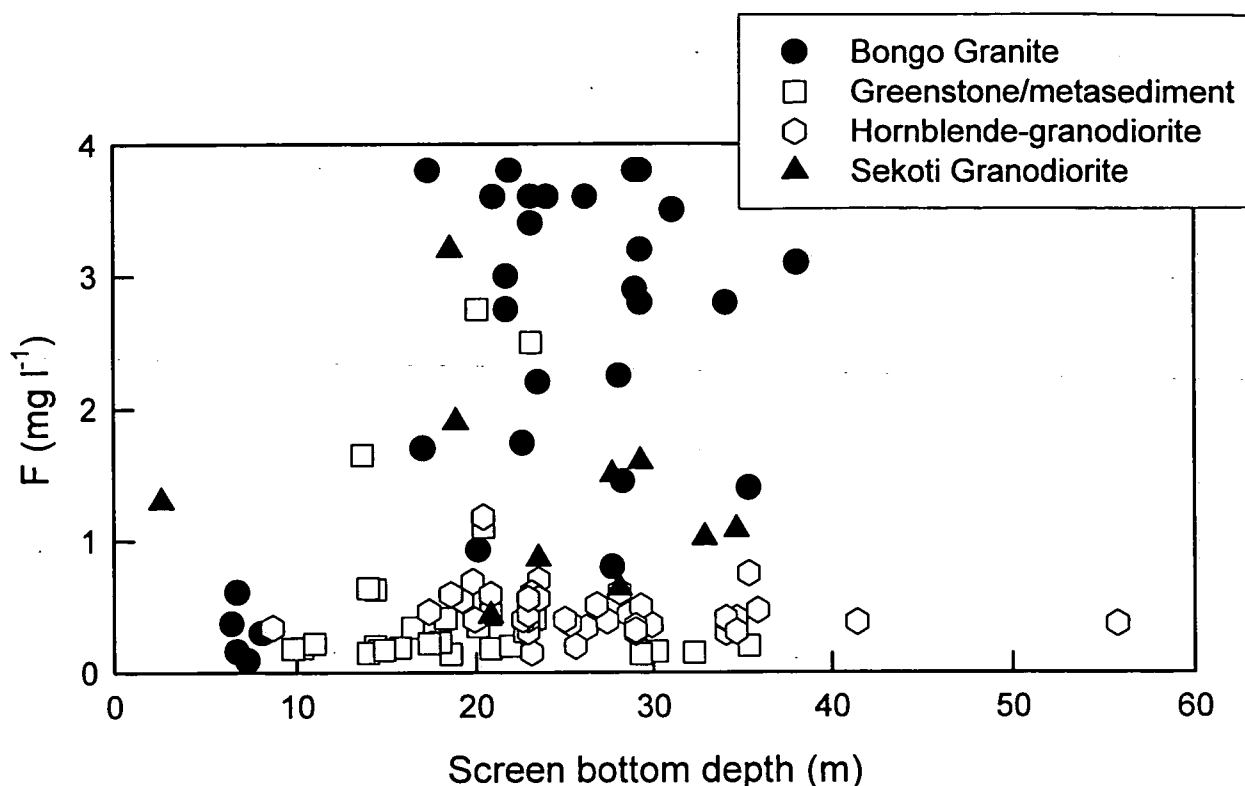


Figure 3.12. Fluoride concentration against groundwater depth (basal-screen depth in boreholes, total depth in wells, metres below ground level) in Bolgatanga waters.

Other species considered to complex readily with F and hence to have potential for increasing the dissolved concentration include B, Be and Fe. No correlation is observed between either B or Fe and F but a relatively good correlation is found with Be (not shown). Both Be and F are highest in the groundwaters from the Bongo Granite (Be up to $0.83 \mu\text{g l}^{-1}$; Appendix 2C) as would be predicted from the trace-element geochemistry of granitic rocks (Taylor and McLennan, 1985). Speciation models did not include Be as a potential complexing ligand as thermodynamic data are rather poor for this element.

Despite the potential for complexation with other ligands, the main control on F concentrations in the Bolgatanga groundwaters is believed to be solubility of fluorite and the associated concentration of dissolved Ca. High-F waters are common in the Bongo Granite and Sekoti Granodiorite but rare in other local lithologies. This is due to a combination of the presence of high-F minerals in the rock matrices, including biotite, amphibole, apatite, sphene and occasional fluorite and also a paucity of Ca in granitic rock types: feldspars are typically sodic rather than calcic and the granitic rocks of the Bolgatanga area typically have low whole-rock Ca concentrations (Table 3.8). Calcium is likely to be concentrated mainly in amphibole.

3.10.5 Microbiological results

As discussed in Section 2.6.6, microbial populations in groundwaters may be indicators of surface pollution, some of which may be pathogenic (e.g. coliform bacteria). Others may

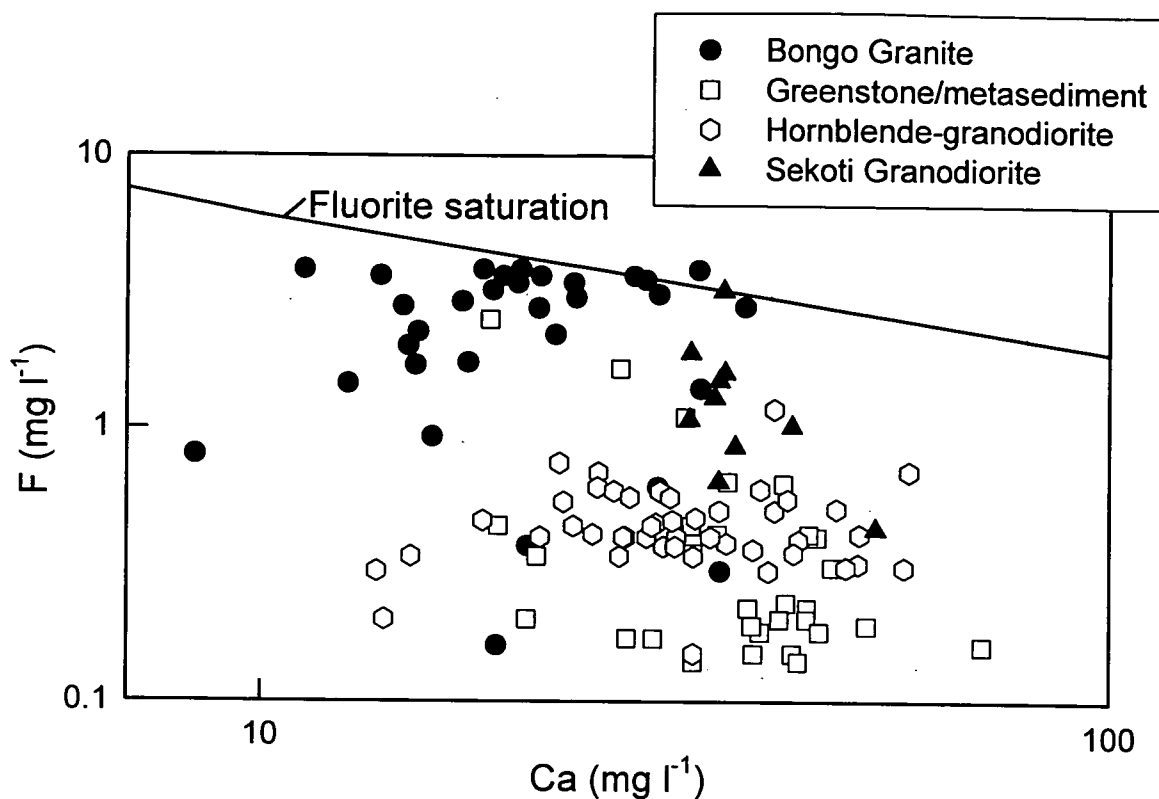


Figure 3.13. Calcium against F in Bolgatanga groundwaters. The solubility of fluorite is also given, calculated at 25°C using a value of 10^{-6} for the solubility product.

simply represent natural indigenous populations that may contribute towards biogeochemical reactions in the sub-surface, but which have no detrimental health effects. The WHO

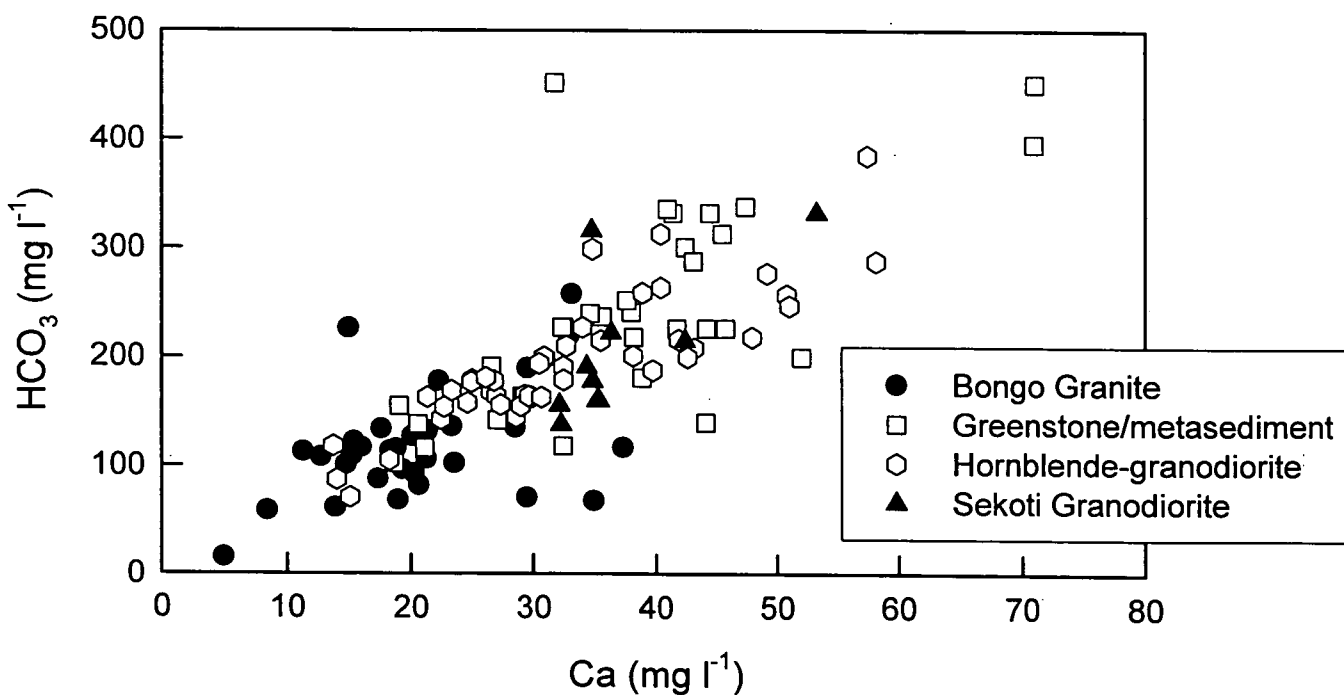


Figure 3.14. Calcium against HCO_3 in Bolgatanga groundwaters from different geological terrains.

recommends that drinking waters should contain no faecal or total coliforms but gives no recommendations for limits of non-pathogenic microorganisms such as heterotrophic plate-count bacteria.

Numbers of coliforms, heterotrophic bacteria and total bacteria (epifluorescence microscopy) in samples from the Bolgatanga area are given in Appendix 2E and median values for wells and boreholes in Table 3.3. As in the Obuasi study, microbiological analysis indicates the presence of microorganisms at all sites investigated, although counts are much higher in dug-well waters than in borehole waters: faecal and total coliforms for example have a median value too numerous to count in shallow wells but of zero in the boreholes (Table 3.3). This is largely indicative of poor sanitary conditions around shallow wells which allow contamination of water close to the water table from domestic pollution. Many of the shallow wells investigated were open and unprotected, some close to latrines. Lower bacterial counts in borehole waters are indicative of less faecal pollution. However, around 40% of the boreholes also contained detectable coliform counts, albeit in low concentrations of a few CFU ml⁻¹ in most (Appendix 2E). This suggests that many of the boreholes in the area have not been properly completed and allow leakage of small quantities of surface contaminants down to the borehole screens. The microbial results indicate the need for maintaining high standards of hygiene close to drinking-water abstraction points, particularly though not only, around shallow wells.

The main control on microbial numbers in the Bolgatanga waters is carbon (DOC and HCO₃) which acts as an energy or nutrient source. No correlations were found with environmental conditions such as pH or redox (West et al., 1995).

As in the Obuasi study, total counts in the Bolgatanga waters are higher than plate counts on the selective CPS medium (heterotrophic bacteria). Again this indicates that the observed aerobic heterotrophs are only a subset (capable of growing on the given medium) of the total microbial population present. The total microbial population in borehole waters from the Bolgatanga area is significantly lower than that in Obuasi borehole waters (2500 and 42700

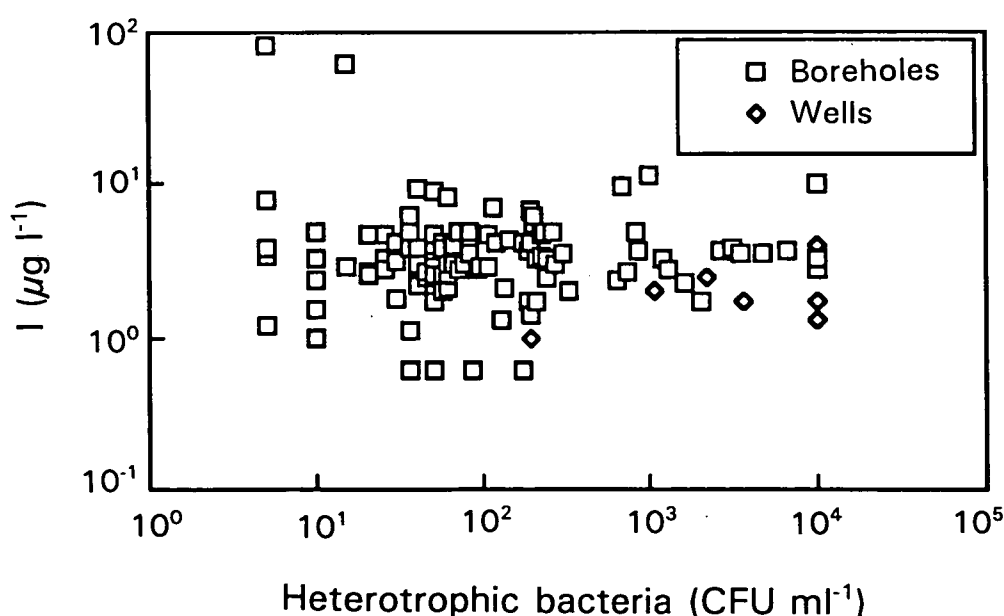


Figure 3.15. Iodine concentration against heterotrophic bacteria (CFU ml⁻¹) for Bolgatanga drinking waters (boreholes and wells).

Table 3.11. Microbial counts in groundwater from shallow wells and boreholes in the Bolgatanga area. CFU: colony-forming unit, tntc: too numerous to count.

	Units	Wells	Boreholes
Faecal coliforms	CFU 100 ml ⁻¹	tntc	0
Total coliforms	CFU 100 ml ⁻¹	tntc	0
Total heterotrophs	CFU ml ⁻¹	3600	65
Total microbes	CFU ml ⁻¹	20000	2500

bacteria ml⁻¹ respectively). This indicates that nutrients or energy sources are more freely available in the Obuasi groundwater environment. This may be related to differences in geology and overlying soil types in the two areas: the Bolgatanga area is dominated by granitic bedrocks with thin organic-poor overlying soils and contrasts with the predominantly metasedimentary lithology and organic-rich ferralsols of the Obuasi study area. Organic-carbon concentrations are also slightly lower in the Bolgatanga groundwaters (median DOC 1.1 and 3.9 mg l⁻¹ in Bolgatanga and Obuasi borehole waters respectively). The low-nutrient (oligotrophic) environment of Bolgatanga appears to be less capable of supporting a large *in-situ* microbial population.

Since I may be toxic to certain microorganisms (Greenberg et al., 1992), the relationship between microbial counts and I concentration in the groundwaters was investigated. Most of the groundwaters have low I concentrations which appear to have little influence on microbial numbers. However, the two samples with the highest I concentrations (samples 108, 115; Appendix 2E) have relatively low aerobic-heterotroph counts (Figure 3.15). Unfortunately, total microbial counts were not measured in these two samples and coliform measurements are incomplete (due to equipment failure). However, available coliform data for the two samples indicate zero counts. The data suggest that growth of microorganisms may be inhibited in high-I groundwaters (>60 µg l⁻¹) although insufficient numbers of high-I groundwater samples were found in the area to test this hypothesis adequately.

3.11 Conclusions

Groundwater is the main supply source for drinking and domestic purposes for rural communities in the Upper East Region of Ghana. Although the inorganic quality of groundwaters from the Bolgatanga area is generally good, their compositions are believed to be an important contributory factor in the regional development of endemic goitre and dental fluorosis. The geology of the Bolgatanga area is dominated by granitic, granodioritic, metasedimentary (mainly arenaceous) rocks and greenstone. Soils are thin and organic-poor and the area is some 600 km from the coast. These features are all concomitant with the development of low-I groundwater and the granitic rocks are prime areas for the development of high-F groundwater. Coupled with the fact that rural settlements are in many cases remote and food sources usually of local provenance and limited range, development of endemic goitre and fluorosis should be of little surprise.

The 39th World Health Assembly (1986) called for the eradication of I deficiency within a period of 5-10 years. This interval has now almost elapsed and goitre and IDD's still remain an endemic problem throughout large parts of the developing world. Details of the causes of

IDD are still in dispute but deficiency in dietary I (from both food and drinking water) is recognised as the single most important underlying factor and correction of the deficiency by administration of I supplements the best means of treatment. Goitre is clearly most prevalent among the poor where good nutrition is lacking. This, together with the lack of education on the nature and causes of health problems associated with IDD, promotes the biggest obstacle to the eradication of the disease today. Poor education is certainly a major factor in the perpetuation of goitre in the Bolgatanga area and needs to be addressed if goitre prevalence is to be reduced in the area.

Although only two areas (Bongo and Sekoti) have been surveyed in detail for goitre prevalence and are proved to be endemic, it is thought likely that other districts in the study area are affected because goitrous patients were observed in all districts during the water-sampling campaign and because goitre is known to be present in other parts of the Upper Regions. The median I concentration of Bolgatanga groundwaters is $3.2 \mu\text{g l}^{-1}$, much lower than the median of $8.3 \mu\text{g l}^{-1}$ for Obuasi, and comparable to I ranges observed in goitrous areas in other parts of the world. Potential goitrogens in the drinking water such as Ca, Mg, As, Mo, Cu and Zn are not thought to be contributory to the development of the disease locally, but the influence of other goitrogenous substances (thiocyanate, thiouracil, F) cannot be discounted. Nonetheless, low I in groundwater and poor nutrition are considered the most important factors. Little variation was observed in I concentration with borehole depth (groundwater residence time) or with geology such that in determining solutions to the problem, little can be gained from resiting of boreholes or exploitation of other aquifers locally. The goitre problem can therefore only be tackled by continued I supplementation and community education.

Unlike the distribution of goitre, dental fluorosis is a localised problem related strictly to underlying geology: only populations drinking groundwater abstracted from the Bongo Granite and Sekoti Granodiorite are vulnerable to development of the disease. Concentrations of F in waters from these areas reach up to 3.8 mg l^{-1} . There is some indication, especially in the waters from the Bongo Granite, that F concentrations increase with groundwater residence time: the shallow-well waters in this vulnerable area have acceptably low F concentrations. It is apparent that F builds up in the groundwater with time due to dissolution of high-F minerals such as amphibole, biotite, apatite, sphene and fluorite. Fluoride concentrations are limited by fluorite solubility and the highest F concentrations in the Bongo and Sekoti waters are associated with low Ca concentrations. The groundwaters in these areas are particularly vulnerable to F problems due to the combination of high-F and low-Ca mineral assemblages which typify late-stage granitic melts.

The inorganic quality of the groundwaters is otherwise good, major elements are usually below WHO recommended limits and nitrate and other nitrogen species are almost universally low. Arsenic is lower than in the Obuasi area and is mostly not detectable in the Bolgatanga groundwaters, apart from a few sources close to the former Nangodi gold mine which contain unacceptably high concentrations (up to $141 \mu\text{g l}^{-1}$). Aluminium is also mostly low, but is present in high concentrations (up to 7 mg l^{-1}), probably in colloidal form, in some of the shallow-well waters. It is not known whether such sources show persistently high Al concentrations as no monitoring of the sources has been carried out. Despite the fact that health risks associated with Al in drinking water are largely tenuous and unproven, care should be taken where possible to find alternative drinking-water sources.

An additional potential health problem arises from the presence of pathogenic microorganisms in the drinking waters. The primary source of pathogenic contamination is animal and human domestic waste. Results from the Bolgatanga area demonstrated the presence of coliforms (indicating faecal contamination), mostly in wells but also in some boreholes as a result of poor hygiene in the immediate vicinity of water sources. The enclosed construction of boreholes provides a degree of protection from potential sources of contamination but the wells are mainly open structures, often located in densely populated areas and frequented by animals.

The total microbial population (2500 bacteria ml⁻¹) in borehole waters from the Bolgatanga area is considerably smaller than that observed in the Obuasi area (42700 bacteria ml⁻¹). This suggests that fewer nutrients or energy sources (e.g. organic carbon) are available to support microbial growth. The granitic basement rocks of the Bolgatanga area form a low-nutrient (oligotrophic) environment which is only capable of supporting a small *in-situ* microbial population. In both study areas, carbon appears to be the controlling factor for microbial growth.

3.12 Recommendations

1. Iodine deficiency is seen as the single most important factor in development of endemic goitre in the Upper East Region. Provision of a source of increased dietary I is therefore important. Very few of the groundwaters in the area are believed to provide sufficient I and dietary supplements are therefore necessary. Iodised oil, together with vitamin A supplements, are already being supplied by the district health authority but better community education would improve the success of the programme considerably. The lack of public awareness in India of the goitre problem has recently been tackled by UNICEF in supplying I-testing kits to school teachers for the measurement of I concentrations in salt (Imam, 1994). Such targeting of school children would be one effective way of disseminating important health information.
2. It was noted above that both organic matter and seaweed (often used as a fertiliser) contain high concentrations of I. Use of such materials as soil amendments would therefore increase the concentrations of I in soils, improve nutrient quality and may consequently increase plant-I uptake. However, this may not necessarily follow, as organic matter is known to *retain* I: Whitehead (1975) for example, found that increasing the concentration of farmyard manure in a British sandy-loam soil by 5% decreased the resultant uptake of I in ryegrass tenfold. Soil-I amendment may therefore be worth investigation but may not necessarily provide increased dietary I from local crops.
3. Excess groundwater-F is a problem restricted to specific geological formations (in this case, the Bongo Granite and Sekoti Granodiorite). The geological map should be consulted to highlight potentially vulnerable areas before new borehole-drilling programmes are instigated and preferably, samples taken for F analysis before boreholes are completed with hand pumps for community use. Since evidence suggests that groundwater-F increases with residence time in high-F rocks, abstraction from shallower levels may help to alleviate the F problem. Open dug wells are sources for potential contamination from surface pollutants but generally

have lower F concentrations. Care should be taken that these are maintained in good hygienic condition, with raised walls, covers and preferably with one dedicated, attached receptacle for drawing water. In basement terrain where groundwater yields are low, yield from shallow boreholes may be increased by installation of boreholes of larger diameter.

4. Water abstracted from existing high-F boreholes should ideally be treated before use. Appropriate-technology treatments have been investigated using sorption onto media such as bone char and clay or methods using dissolution of minerals such as calcite and gypsum to increase the Ca concentration of treated waters. However, such methods usually have only limited success as they require regular maintenance and beneficiary involvement as well as comprehension. Provision of low-F groundwater without the need for treatment is seen as a preferable solution.
5. Populations in the Bolgatanga area generally use chewing sticks for cleaning teeth. However, in other parts of the world where fluorosis and high-F groundwaters occur, F toothpastes are still readily available and actively marketed. Fluoride toothpastes should not be used, especially by children, in high-F areas.
6. Whilst complete elimination of pathogens from shallow-well waters in areas such as those seen around Bolgatanga is almost impossible, a significant reduction in numbers could result through basic education particularly in sanitation and public health.
7. Other inorganic-quality problems in the Bolgatanga area include the rare occurrence of high-As and high-Al waters. Arsenic is a known toxin and carcinogen. High-As waters should be monitored more regularly and if As concentrations persistently occur at $>10 \mu\text{g l}^{-1}$ (the WHO maximum recommended concentration), alternative water supplies should be sought. Areas close to zones of sulphide-mineral oxidation such as mined areas are particularly vulnerable to the development of high-As water. High-Al waters should also be monitored to assess potential chronic health risks and if Al is a persistent element, alternative sources should be sought. Colloidal Al concentrations in shallow dug wells may be reduced by construction of proper well linings to act as filters.
8. Despite the noted occurrence of health problems due to the inorganic quality of some groundwater supplies, it is emphasised that groundwater in tropical terrains is of much better microbiological quality than surface waters. The latter are all too often faecally contaminated and are sources of gastro-intestinal problems which remain the most important threat to human health in rural communities. Once groundwater of good potable quality has been supplied to a community, efforts should be made to increase awareness of its health benefits and to discourage use of more traditional water supplies.

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APPENDIX 1A. Site details and major-element data for water samples from the Obuasi area.

Locality	Field Samp	Long	Lat	Water level	Temp	Well	pH	Eh	DO	SEC	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃ N	NO ₂ N	NH ₄ N	Si	DOC
	no	s' r'ce	(1°W)	(6°N)	level	°C	depth	mV	mg l ⁻¹	µS cm ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	µg l ⁻¹	µg l ⁻¹	mg l ⁻¹	mg l ⁻¹
		mins	mins	mins	m	m	m															
Nyamso north	1a	7	41.63	12.65	29.3	48		5.86	0.8	107	4.42	3.83	10.3	0.28	53.0	0.84	4.78	<0.2	nd	nd	nd	16.66
	2a	7	41.67	12.59	27.1	32		5.66	<0.1	79.9	1.42	2.87	5.1	0.16	24.4	0.29	3.51	0.2	nd	nd	nd	7.94
	3a	7	41.34	12.86	27.5	30		5.31		92.7	0.91	1.61	8.6	0.17	13.4	0.27	7.4	2.3	nd	nd	nd	7.078
	4a	7	42.22	11.29	28.2			5.84		94.5	2.59	2.1	11.0	0.29	67.4	0.79	3.84	0.9	nd	nd	nd	11.59
Apitikokoo	5a	7	42.78	10.93	26.6	40		5.21		115	1.4	3.94	8.8	3.11	16.0	0.17	7.95	4.8	nd	nd	nd	9.82
	6a	7	43.94	10.71	26.6			6.37		346	37.79	7.14	24.9	0.71	194	2.13	22.0	<0.2	nd	nd	nd	29.31
	7a	7	41.50	6.71	26.8	34		6.38		262	23.2	8.1	16.1	1.98	150	1.95	2.13	<0.2	nd	nd	nd	32.56
	8a	7	43.18	8.78	25.8			5.48		65.7	1.48	1.16	8.8	0.18	29.9	0.43	6.02	1	nd	nd	nd	9.33
Nyameke stream	9a	3	43.18	8.78	25.2			6.08		96.3	4.73	2.53	6.1	3.74	50.0	1.84	7.61	<0.2	nd	nd	nd	7.30
	10a	7	41.35	8.99	24.1			6.79		132	10.66	6.59	5.7	0.43	80.5	2.16	7.06	<0.2	nd	nd	nd	10.62
	11a	7	41.86	9.33	26.4			5.95		160	9.86	6.52	9.7	0.44	98.1	1.16	4.57	<0.2	nd	nd	nd	3.55
	1	7	39.20	9.75	3.57	26.3	42.5	6.67	274	399	39.04	12.32	13.8	0.51	217	0.63	5.5	<0.2	<5	<5	<10	23.06
Odumase stream	2	3	39.23	9.76		24.2		6.53		168.8	6.9	4.18	8.4	0.54	54.3	1.87	6.2	<0.2	<5	<5	10	8.58
	3	3	39.65	7.36		23.4		6.4		141.5	7.61	3.79	7.3	0.49	52.7	1.16	6.0	<0.2	<5	<5	<10	7.70
	4	8	39.43	7.45	3.19	27.7		3.85		649	7.51	3.68	71.3	19.18	<1.0	1.08	37.2	21.9	<5	<5	<10	4.88
	5	8	39.75	7.15		27.3		5.78		71.2	1.42	0.82	4.7	1.31	15.1	1.28	5.0	<0.2	<5	<5	<10	8.79
Gymi River	6	3	39.75	7.15		23.6		6.57	376	69.5	4.93	2.34	4.1	1.45	31.5	1.51	3.5	<0.2	<5	<5	<10	5.28
	7	7	37.80	12.15	8.88	26.7		5.94	468	100.9	13.39	0.55	2.2	1.00	48.6	0.45	2.0	0.2	<5	<5	<10	4.71
	8	7	37.67	10.67	9.21	27.1	25	4.11	511	311	4.4	3.23	31.8	5.16	<1.0	0.13	31.7	17.6	<5	<5	<10	5.78
	9	3	35.67	13.41		25.6		5.99		50.3	1.05	1.03	3.5	0.01	8.1	2.21	3.9	<0.2	<5	<5	<10	4.34
Meduma	10	7	35.64	16.11	14.96	26.3	53	5.87	419	110	5.92	3.34	10.8	3.33	62.5	0.21	2.8	<0.2	<5	<5	<10	28.69
	11	7	35.94	22.00	11.72	26.3	43	5.95	419	128	8.27	2.29	15.7	2.98	68.9	<0.10	3.9	<0.2	<5	<5	<10	33.15
	12	7	41.02	12.23		26.5		5.75		72	3.27	2.25	6.9	0.22	31.5	0.11	3.2	<0.2	<5	<5	<10	12.63
	13	7	38.71	17.05		25.2	36	6.49	<0.1	311	39.21	7.4	16.8	3.17	198	0.60	6.5	<0.2	<5	<5	<10	39.40
Patakro	14	7	39.72	16.99	2	25.8	18	5.88	459	93.2	4.96	1.48	9.7	2.83	40.4	0.44	4.5	<0.2	<5	<5	<10	23.44
	15	8	41.31	16.72	2.1	25.4	2.13	5.08		52	0.44	0.25	6.6	0.28	4.1	0.21	6.2	0.7	<5	<5	20	7.15
	16	2	41.99	16.65		23.6		5.43		47.9	0.85	0.61	6.9	0.51	12.4	0.32	4.2	0.8	5	100	8.09	
	17	8	39.63	18.26	3.54	25	5.85	5.58		67.4	6.6	0.45	3.1	0.67	25.2	0.19	4.0	0.3	<5	<5	<10	5.59
Ankasa stream	18	3	38.20	19.81		22.7		6.65		55.9	2.51	1.71	6.8	0.44	25.5	0.70	4.2	<0.2	<5	<5	<10	7.34
	19	3	38.15	22.17		24.7		6.56	<0.1	108	6.98	1.64	9.5	6.42	nd	1.01	5.2	<0.2	<5	<5	580	23.44
	20	7	38.41	23.19	8.54	26.6	42	5.79	461	68	2.68	0.65	6.1	4.68	23.1	0.13	3.0	1.1	<5	<5	<10	17.67

Appendix 1A cont'd...

Locality	Field Samp	Long	Lat	Water Temp	Well	pH	Eh	DO	SEC	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃ N	NO ₂ N	NH ₄ N	Si	DOC	
no	s' rce	(1°W)	(6°N)	level	°C	depth	mV	mg l ⁻¹	μS cm ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	μg l ⁻¹	μg l ⁻¹	μg l ⁻¹	mg l ⁻¹	mg l ⁻¹	
Patase	21	7	39.31	22.96	9.65	27.5	33	5.52	377	3.0	138	3.88	1.02	16.7	5.77	26.3	0.50	12.6	5.1	<5	<10	19.71
Sodua	22	3	35.06	18.32		22.9		5.47			56.7	1.2	1.3	4.8	1.71	11.9	0.21	4.7	1.2	<5	30	6.27
Ankasi	23	7	33.12	23.41	4.26	27.2	48	6.06	401	3.2	148	9.89	4.74	13.8	2.52	88.3	0.12	4.0	0.2	<5	<10	33.57
Bogyawe	24	7	32.88	23.22	18.23	25.7	58	6.07	299	3.0	173	8.62	5.17	15.1	3.88	96.3	3.33	3.9	<0.2	<5	<10	33.35
Aminase	25	8	36.47	25.50	3.2	26.1	3.22	5.37			82	2.74	0.79	8.6	6.24	21.1	5.25	6.2	1	<5	<10	16.83
Amoamo	26	8	37.04	25.30	0.7	24	0.95	5.45			281	17.11	3.97	22.2	9.46	25.4	4.65	27.5	16.5	<5	<10	21.84
Dwondoso	27	8	36.48	23.77	4.39	25.2	4.67	5.31			48	2.77	0.84	3.0	1.03	16.5	0.13	3.9	<0.2	<5	20	6.39
Atobiase	28	3	37.14	22.48		22.4		5.78			105	4.71	1.1	13.7	3.98	51.5	0.54	5.0	<0.2	<5	90	30.83
Esereso	29	2	39.32	29.70		22.4		5.85			64.1	0.99	0.48	7.3	4.38	24.0	0.54	4.2	<0.2	5	<10	17.12
Ahwiaa	30	3	37.74	24.33		22.1		5.88			88	2.34	0.67	11.1	2.24	34.7	0.62	4.2	<0.2	<5	10	24.81
Boni	31	7	39.43	27.57	12.21	26.3	65	5.68	429		315	24.01	6.49	22.8	1.2	93.3	11.34	22.2	7.2	<5	<10	25.66
Huntado	32	7	40.31	26.92	16.78	26.8	52	4.79	459		116	2.8	2.27	13.4	1.11	17.1	0.30	8.2	6.1	<5	<10	9.30
Poano	33	7	40.73	26.52	8.3	26	61	5.81	274		191	13.48	7.51	12.6	0.59	117	0.87	5.0	<0.2	<5	<10	28.17
Afransie	34	7	41.39	25.56	14.7	25.8		6.08	349		243	25.74	4.51	16.6	1.26	122	3.63	7.0	2.2	<5	<10	27.56
Ninanko	35	7	41.43	25.73	11.54	26	51	5.71			196	6.84	8.93	18.6	0.88	63.4	0.38	19.0	5.1	<5	<10	17.31
Adjensu stream	36	3	42.79	5.89		22.8		6.81			114.3	7.35	4.84	9.8	1.86	76.8	0.26	8.2	<0.2	<5	40	9.68
Wumase	37	8	41.91	5.28	2.91	25	3.76	5.57			82	7.29	0.81	6.5	0.81	28.6	3.03	8.2	<0.2	8	<10	7.41
Kofikurom	38	7	40.92	11.89	6.52	26.4	38	5.44	399	1.6	113	6.81	3.83	9.5	0.92	38.2	0.30	8.5	3.0	<5	<10	12.09
Kokoteasua	39	7	40.09	12.85		25.9	34	5.38	393	3.3	79	3.27	2.36	8.5	0.23	38.3	0.42	4.7	0.3	<5	<10	12.98
Dunkwa Nkwenta	40	7	41.32	12.91	8.3	27.1		4.61	470		39	0.53	1.18	3.7	0.1	7.07	0.20	3.2	0.9	<5	<10	6.34
Dekyewa	41	7	42.97	12.43		26.4		5.81	255	0.3	121.3	1.8	2.76	10.1	0.57	nd	0.43	6.2	0.6	56	70	13.57
Mile Nine	42	7	46.28	13.49	1.53	26.8	46	5.8	341	<0.1	175.9	14.33	3.18	15.5	0.71	88.6	1.44	7.7	<0.2	<5	<10	31.28
Sabe 2	43	7	47.96	14.49		26.2		6.15	221	<0.1	285	31.71	4.69	19.6	0.7	177	0.13	3.5	<0.2	<5	<10	35.57
Sabe 1	44	7	48.39	14.82		26.6		6.17	253	<0.1	232	16.51	8.97	13.4	1.18	147	<0.10	4.5	<0.2	<5	<10	32.49
Manfo	45	7	49.58	15.22		25.6		6.57	237	<0.1	299	29.1	8.41	17.9	1.07	188	0.26	6.0	<0.2	<5	<10	28.51
Odumto	46	7	50.48	15.43		25.7		5.19	401	1.3	69.3	0.49	0.85	6.0	0.47	20.1	0.11	6.0	<0.2	<5	70	7.39
Mile Eighteen	47	7	51.38	15.08		26.3		5.74	280	<0.1	130.5	4.26	3.62	10.2	0.32	51.5	0.34	5.2	1	27	20	18.08
Mile Fourteen	48	7	49.61	13.47	2.9	25.5	64	6.2	332	<0.1	213	22.14	6.03	16.9	0.71	130	0.30	6.7	<0.2	<5	<10	31.28
Apitiso 1	49	7	43.88	10.65	0.29	27.2	43	5.92	407	<0.1	296	17.69	10.05	26.4	0.83	98.8	2.12	43.0	1.8	<5	<10	26.92
Fenaso	50	3	48.21	10.00		23.6		6.62	127.4			8.5	4.77	12.0	3.57	57.3	3.53	9.5	<0.2	<5	90	4.34
Kofitanokurum	51	8	49.91	9.20	7.2	26.3	7.2	5.28	137		137	12.95	1.63	9.4	1.07	52.4	1.14	6.7	0.5	8	<10	10.59

Appendix 1A cont'd...

Locality	Field Samp	Long	Lat	Water	Temp	Well	pH	Eh	DO	SEC	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃ N	NO ₂ N	NH ₄ N	Si	DOC
no	s' rce	(1°W)	(6°N)	level	°C	depth		mV	mg l ⁻¹	µS cm ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	µg l ⁻¹	µg l ⁻¹	µg l ⁻¹	mg l ⁻¹
Dangase	52	8	50.15	7.10	2.75	25.5	3.25	3.94	37.3	0.26	0.1	4.9	0.38	6.6	0.17	4.0	<0.2	<5	<5	<10	7.97	
Tweapease	53	7	44.33	8.92	2.23	26.1	43	5.7	152	10.12	4.01	16.8	0.51	82.4	0.77	8.0	<0.2	<5	<5	<10	28.48	1.38
Suhyenso	54	3	43.54	8.33		24.3		6.89	143.5	6.15	5.06	16.4	1.33	76.8	1.38	9.0	<0.2	<5	<5	<10	19.38	
Obuasi mine bh 1	55	7	39.57	12.21	41.35	26.6	70	5.94	956	87.3	77.07	26.3	0.76	110	507	11.2	<0.2	14	30	7.94	3.41	
Obuasi mine bh 2	56	7	39.56	12.24	36.75		70	6.17	631	58.72	42.53	23.9	0.74	135	252.7	10.2	<0.2	6	20	12.32	5.90	
Obuasi mine dr'nge	57	13	39.56	12.24			19	6.04	1390	144.73	140	52.3	4.29	35.4	925.76	18.8	0.8	26	70	10.80		
Aboagyekurum	58	3	47.91	17.05		26		6.46	63	3.75	1.89	8.7	0.98	32.1	1.07	15.0	<0.2	8	<10	8.75		
Nankawura	59	8	45.55	15.61		24.9		6.06	100	3.85	3.48	10.0	1.84	45.4	0.89	7.5	<0.2	31	670	12.53		
Fiankoma	60	7	43.62	19.10	5.36	26.6	64	5.93	243	<0.1	119		0.39	78.2	1.49	4.5	<0.2	<5	<10	24.40	1.26	
Abuakwa	61	7	50.31	18.13	10.7	26	48	6.31	282	<0.1	198		0.24	116	3.74	8.5	<0.2	<5	<10	21.26		
Kobro	62	7	52.98	17.47	9.82	26.3		5.52	383	<0.1	128		0.33	38.8	0.56	13.2	3.9	<5	<10	21.70		
Denyasefokurum	63	3	43.44	26.61		23.9		6.64	115	3.9	3.6	8.5	2.46	38.8	3.27	8.2	<0.2	5	510	8.78		
Antoakurum	64	7	47.43	27.14	14.86	26.7	70	6.72	329	<0.1	290		0.49	177	0.34	15.0	<0.2	<5	<10	30.92	3.53	
Antoakurum 3	65	7	47.49	27.28	14.04	27.1	32	5.08	445	<0.1	124		0.91	16.2	0.25	13.0	4.7	<5	<10	9.32		
Nsiana	66	7	48.78	28.00	12.9	25.6	49	5.5	424	0.2	151.6		1.04	45.8	0.54	10.0	3.9	8	<10	12.53	5.17	
Manso Akropon	67	7	48.39	26.38	6.75	26.4	43	5.84	392	<0.1	195		0.41	57.2	3.46	14.2	1.9	11	<10	22.26	3.78	
Abodom	68	7	48.76	25.73	1.53	25.7	46	6.03	405	<0.1	133.2		0.34	69.5	0.54	4.7	<0.2	<5	<10	17.99	3.29	
Brofeyeduru	69	3	49.24	23.42		25.9		6.98	233	17.28	7.07	11.4	10.72	119	1.29	12.0	<0.2	<5	1260	14.98		
Mim 3	70	7	51.28	25.18	2.4	26.4	49	5.89	395	0.8	199		0.72	73.2	0.28	10.2	4.5	<5	<10	19.09	1.07	
Mim 1	71	7	51.20	25.42	0.6	25.3	57	6.37	309	<0.1	212		0.5	117	<0.10	8.2	<0.2	<5	<10	29.60		
Nkampro	72	7	40.80	12.86	12.05	26.7		5.11	495	1.8	52.8		0.39	8.5	0.24	5.0	1.9	11	<10	6.91	2.03	
Kwabrafo strm-up	73	3	39.14	13.45		27.6		6.39	148.1	6.3	4.38	8.9	0.74	59.7	4.39	8.7	<0.2	<5	320	10.58		
Tailings effluent	74	39.71	13.39		32.3			8.45	2960	435.15	9.76	348.7	33.8	154	1746	184	7.3	408	17700	4.47		
Kwabrafo strm-d'n	75	3	39.30	12.53		32.8		7.29	1856	232.5	135	73.4	19.46	95.7	1134	14.7	0.4	123	6250	7.69	4.53	
Abompekrom	76	7	40.22	12.99		26.2		5.41	469	1.1	60		1.1	25.4	0.51	3.5	0.3	<5	<10	8.10		
Abompekrom	77	7	40.24	13.04		26		5.73	424	3.8	72		0.88	38.1	0.29	3.9	<0.2	<5	<10	12.17		
Obuasi mine bh 3	78	7	39.56	12.24	47.9	27.2	100	6.31	0.1	649	35.49	28.5	1	208	198	14.2	3.2	178	30	22.42	0.85	
Asaman	79	7	51.61	26.91		26.3		5.55	<0.1	61	2.06	7.3	0.25	28.6	0.43	4.5	<0.2	<5	<10	12.01		
Yawkurom 1	80	7	52.31	26.28	14.3	26.4	48	6.27	330	<0.1	191		0.54	129	1.54	4.7	<0.2	<5	<10	29.46	4.84	
Manso Atwere	81	7	51.40	27.58		26.4		5.73	385	0.3	109		0.44	61.9	2.85	3.5	<0.2	<5	<10	24.93	2.62	
Manso Atwere h'se	82	7	51.22	27.27		25.5		6.18	296	<0.1	275		0.45	187	0.28	7.0	<0.2	<5	<10	30.23		

Appendix 1A cont'd...

Locality	Field Samp	Long	Lat	Water Temp	Well	pH	Eh	DO	SEC	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃ N	NO ₂ N	NH ₄ N	Si	DOC
no	s' rce	(1°W)	(6°N)	level	°C	dpth	mV	mg l ⁻¹ μS cm ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	mg l ⁻¹	μg l ⁻¹	μg l ⁻¹	μg l ⁻¹	mg l ⁻¹
Suntreso	83	3	55.96	26.97	24.5	5.8	235	219	8	13.6	8	20.7	0.94	98.1	7.17	11.2	3.2	<5	<10	21.15	
Agroyesum hosp'l	84	7	52.79	24.98	14.73	25.3	346	387	10.6	53.9	10.6	21.7	1.03	258	5.20	7.7	<0.2	<5	<10	30.03	2.08
Odahu	85	7	49.43	21.42	12.02	26.1	359	155	7.53	3.51	7.53	17.6	0.45	89	0.64	3.9	<0.2	<5	<10	35.43	
Mile Nineteen	86	7	52.20	15.28	25.4	5.76	332	123.3	2.61	10.52	2.61	8.8	0.29	61.6	0.25	6.0	<0.2	<5	<10	12.87	
Nkyuaso	87	7	53.35	14.97	26.7	5.43	232	144.6	3.28	3.79	3.28	14.5	0.38	46.9	1.13	13.0	1.4	58	30	14.67	2.24
Odaso	88	7	54.35	15.69	27.6	6.11	232	266	11.74	11.74	9.44	17.2	0.45	126	1.84	12.0	<0.2	16	10	27.25	
Kampese	89	3	56.45	23.11	27.4	5.95	262	109	3.39	5.79	3.39	11.9	0.34	57.9	1.92	4.7	<0.2	<5	<10	17.86	1.97
Apanapron	90	7	53.75	23.58	6.85	26.1	595	279	4.63	28.93	4.63	23.1	0.55	159	4.34	5.2	<0.2	<5	<10	33.77	0.90
Ankam 1	91	7	51.97	24.17	0.8	25.9	582	167	11.13	11.13	4.73	17.5	0.49	81.7	4.48	7.0	<0.2	<5	<10	27.15	0.58
Odumase	92	3	55.39	21.49	25.4	5.82	441	99.3	3.91	3.91	3.96	9.5	1.22	43.9	2.72	6.2	<0.2	<5	<10	14.04	
Adubea	93	8	56.24	24.18	23.1	5.95	446	195.1	7.29	11.37	7.29	13.8	1.39	79.9	20.9	9.0	<0.2	<5	1100	18.43	
Kwameduakurom	94	2	38.69	11.06	25.3	5.04	692	103.6	2.76	6.62	2.76	7.3	0.1	33.0	0.81	9.5	0.6	<5	<10	8.67	2.93
Kaw River	95	3	39.33	10.11	24.3	6.64	446	117.1	5.27	9.9	5.27	6.2	2.01	43.9	5.35	7.8	<0.2	<5	<10	4.87	
Gyeboum stream	96	3	39.67	9.50	24.9	6.92	441	248	5.73	8.73	5.73	10.4	0.9	65.8	2.84	9.7	<0.2	<5	<10	10.86	
Nyamso	97	7	41.63	12.56	25.6	5.43	441	86	3.04	1.36	3.04	5.5	0.23	27.1	0.30	2.5	0.2	10	<10	8.59	2.94
Mensakurom	98	8	42.65	9.90	24.4	4.46	628	103.5	0.72	0.86	0.72	6.1	0.67	10.0	0.76	4.0	0.5	10	50	5.01	
Adansi	99	3	42.02	14.97	25.5	6.28	644	64	1.96	2.66	1.96	6.8	0.29	23.3	2.27	4.8	<0.2	<5	<10	7.96	
Dadwen	100	3	39.76	15.15	25.9	6.44	94	94	3.33	4.05	3.33	8.4	1.58	39.0	2.25	8.8	<0.2	<5	10	8.27	

SEC: specific electrical conductance (at 25°C); DO: dissolved oxygen, DOC: dissolved organic carbon, analysed by BGS, Keyworth.

Sample source: 2: spring, 3: stream (includes dugouts), 7: borehole, 8: shallow well, 13: mine drainage.

nd: not determined.

up: upstream of tailings effluent input to stream; d'n: downstream of tailings effluent input.

APPENDIX 1B. Trace-element data for water samples from the Obuasi area. All cations are analysed by ICP-AES, anions by colorimetry.

Locality	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn µg l ⁻¹	Li µg l ⁻¹	B µg l ⁻¹	Be µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Ba µg l ⁻¹	Br µg l ⁻¹	I µg l ⁻¹	F mg l ⁻¹	As _{total} µg l ⁻¹	As(III) µg l ⁻¹
Nyamso north	<0.02	<0.1	0.34	90.3	17	<6	<0.2	<4	12	45	22	21	3.1	0.05	2.6	nd
Nyamso south	<0.02	<0.1	0.18	51.8	15	<6	<0.2	<4	25	14	21	28	3.3	0.04	<0.4	nd
Konka New Town	<0.02	<0.1	0.009	44.2	7	<6	<0.2	<4	9	11	29	41	16.5	0.03	<0.4	nd
Nyiaso	<0.02	<0.1	<0.003	19.3	6	<6	<0.2	<4	9	31	9	25	8.3	0.04	<0.4	nd
Apitikokoo	0.37	<0.1	0.012	53.1	10	<6	0.3	31	26	21	68	28	5.0	0.06	<0.4	nd
Apitiso	<0.02	0.4	0.119	532	59	9	<0.2	<4	10	282	9	107	23.9	0.18	34.7	nd
Kokotenten	0.02	0.3	2.38	198	22	10	<0.2	<4	5	294	32	36	8.6	0.13	10.7	nd
Nyamekeyere	<0.02	<0.1	0.408	44.6	5	<6	<0.2	8	21	19	17	23	21.1	0.04	0.7	nd
Nyamekhere stream	1.20	0.1	9.07	73.7	2	16	<0.2	<4	9	34	23	74	17.5	0.04	37	nd
Kwaku Yaw	<0.02	<0.1	0.014	4.4	1	<6	<0.2	<4	<4	29	7	31	6.0	0.06	1.1	nd
Sanso	<0.02	<0.1	2.48	134	7	<6	<0.2	<4	9	58	6	25	8.6	0.08	17.0	nd
Odumase	<0.02	<0.1	1.93	125	1	<6	<0.2	<4	168	182	10	nd	1.0	0.07	<0.4	nd
Odumase stream	0.04	<0.1	1.08	48.4	2	7	<0.2	<4	<4	45	8	nd	12.3	0.08	7.0	4
Sibiri stream	<0.02	<0.1	0.646	25.2	<1	<6	<0.2	<4	<4	49	12	nd	6.1	0.06	8.0	<3
Akrofuom	2.39	<0.1	0.012	178	<1	<6	0.3	21	53	108	488	nd	12.2	0.19	<0.4	<3
Okyerekrom	<0.02	<0.1	0.099	18.7	2	<6	<0.2	<4	16	14	11	nd	4.7	0.03	2.0	<3
Gymfi Rver	0.03	<0.1	0.26	102	<1	7	<0.2	<4	<4	44	20	nd	8.2	0.04	17.0	3
Brahabeome	<0.02	<0.1	0.006	9.7	<1	<6	<0.2	62	494	96	15	nd	5.0	0.02	0.0	<3
Diewieso	0.49	<0.1	0.011	285	2	<6	0.7	55	66	67	257	nd	3.5	0.11	<0.4	<3
Dwete stream	0.04	<0.1	0.137	3.8	<1	<6	<0.2	<4	4	8	6	nd	0.6	0.03	10.0	<3
Meduma	<0.02	0.1	<0.003	1.3	15	<6	<0.2	7	5	109	129	nd	4.0	0.09	3.0	<3
Old Edubiase	<0.02	<0.1	<0.003	2.7	21	<6	<0.2	13	11	148	101	nd	9.8	0.10	<0.4	<3
Ponkobi	<0.02	<0.1	0.04	54.7	12	<6	<0.2	7	8	38	11	nd	4.6	0.06	4.0	<3
Patakro	<0.02	0.2	2.53	166	28	<6	<0.2	<4	7	541	63	nd	6.3	0.38	<0.4	<3
Wtoso	<0.02	0.2	0.008	14.4	9	<6	0.2	39	24	225	122	nd	0.4	0.18	3.0	<3
Aketekyiso	0.04	<0.1	0.482	15.1	6	7	0.3	7	25	7	17	nd	10.1	0.05	<0.4	<3
Amamon	0.03	<0.1	0.082	33.2	5	7	<0.2	<4	11	12	23	nd	6.5	0.03	<0.4	<3
Abedwum	<0.02	<0.1	0.067	32.1	3	<6	<0.2	<4	35	50	29	nd	20.0	0.04	<0.4	<3
Ankasa stream	0.09	<0.1	0.684	27.2	7	<6	<0.2	<4	<4	27	15	nd	6.5	0.03	43	5
Asikasu	0.09	0.2	6.49	106	15	9	<0.2	<4	6	184	153	nd	25.2	0.10	nd	nd
Afoako	<0.02	<0.1	0.027	9.3	10	<6	0.6	20	16	94	136	nd	3.3	0.09	2.0	<3
Patase	<0.02	0.2	<0.003	32.8	20	<6	0.6	<4	13	138	182	nd	54.7	0.14	<0.4	<3
Sodua	<0.02	<0.1	0.096	13.3	3	<6	0.3	<4	6	21	48	nd	4.6	0.04	<0.4	<3
Ankasi	<0.02	0.1	<0.003	6.6	12	<6	<0.2	15	10	159	102	nd	7.4	0.08	<0.4	<3

Appendix 1B cont'd...

Locality	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn µg l ⁻¹	Li µg l ⁻¹	B µg l ⁻¹	Be µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Ba µg l ⁻¹	Br µg l ⁻¹	I µg l ⁻¹	F mg l ⁻¹	As _{total} µg l ⁻¹	As(III) µg l ⁻¹
Bogyawe	<0.02	0.1	1.25	101	24	<6	<0.2	<4	6	145	86	nd	6.2	0.11	3.0	<3
Aminase	<0.02	<0.1	0.027	48.3	18	7	0.7	<4	30	47	105	nd	19.4	0.08	<0.4	<3
Amoamo	0.02	0.2	0.158	175	40	<6	1.3	<4	32	273	502	nd	90.2	0.11	4.0	<3
Dwondoso	<0.02	<0.1	0.037	9.6	4	<6	<0.2	<4	88	16	45	nd	3.7	0.05	<0.4	<3
Atobiase	0.34	0.4	1.01	19.3	18	<6	<0.2	<4	8	147	99	nd	12.3	0.12	175	93
Esereso	0.22	<0.1	0.217	9.1	5	<6	<0.2	<4	6	27	42	nd	3.4	0.10	6.0	<3
Ahwiaa	0.44	<0.1	0.645	21.7	15	9	0.4	4	9	60	57	nd	6.7	0.12	47.0	5
Boni	0.05	<0.1	0.021	87.7	28	12	0.5	31	27	448	45	nd	8.1	0.09	<0.4	<3
Huntado	0.07	<0.1	0.016	43.7	12	11	0.5	8	11	39	57	nd	6.2	0.03	<0.4	<3
Poano	0.07	0.2	2.60	232	29	13	0.5	4	8	79	11	nd	5.1	0.07	3.0	<3
Afransie	0.06	<0.1	0.131	120	20	12	0.5	12	10	369	10	nd	6.8	0.10	<0.4	<3
Ninanko	0.07	0.1	0.007	13.5	43	13	0.5	16	35	61	30	nd	12.0	0.07	2.0	<3
Adjensu stream, Wumase	0.08	<0.1	0.865	334	8	18	0.3	5	4	60	22	nd	28.6	0.06	5.0	3
Wumase	0.17	<0.1	0.206	53.2	18	18	0.9	9	31	36	42	nd	6.0	0.03	<0.4	<3
Kofikurom	0.05	<0.1	0.053	28.8	13	11	<0.2	11	17	66	39	nd	8.0	0.03	<0.4	<3
Kokoteasua	<0.02	<0.1	<0.003	5.2	10	<6	<0.2	<4	10	41	17	nd	7.6	0.04	<0.4	<3
Dunkwa Nkwanta	0.03	<0.1	0.318	19.7	8	<6	<0.2	<4	9	7	13	nd	22.8	0.02	<0.4	<3
Dekyewa	<0.02	<0.1	9.28	99.4	16	8	<0.2	<4	1100	32	13	nd	12.6	0.04	<0.4	<3
Mile Nine	<0.02	<0.1	0.189	83.4	19	<6	<0.2	10	20	408	12	nd	13.3	0.14	<0.4	<3
Sabe 2	<0.02	0.3	4.45	245	25	<6	<0.2	<4	238	319	14	nd	7.0	0.30	64	*30
Sabe 1	<0.02	0.2	8.65	142	22	<6	<0.2	<4	92	159	7	nd	11.1	0.14	<0.4	<3
Manfo	<0.02	0.1	2.48	165	22	<6	<0.2	<4	44	417	15	nd	8.1	0.24	20.0	<3
Odumto	<0.02	<0.1	4.74	48.6	3	<6	<0.2	6	22	11	22	nd	2.0	<0.01	<0.4	<3
Mile Eighteen	<0.02	<0.1	2.38	26.1	20	<6	<0.2	<4	18	54	7	nd	2.5	0.05	<0.4	<3
Mile Fourteen	<0.02	0.2	0.032	201	29	<6	<0.2	<4	6	334	9	nd	9.6	0.31	54	12
Apitiso 1	<0.02	0.5	0.005	321	82	<6	<0.2	15	38	226	11	nd	150	0.19	7.0	<3
Fenaso	0.21	0.1	3.43	276	6	19	<0.2	6	7	93	33	nd	35.5	0.06	22	3
Kofitanokurom	<0.02	<0.1	0.016	15.3	16	<6	<0.2	<4	48	81	27	nd	6.8	0.04	<0.4	<3
Dangase	<0.02	<0.1	<0.003	11.1	<1	<6	<0.2	<4	9	4	9	nd	8.0	<0.01	<0.4	<3
Tweapease	<0.02	0.2	0.702	66.1	35	<6	<0.2	<4	11	172	7	nd	12.6	0.20	10.0	4
Suhyenso	0.03	<0.1	0.385	26.5	8	<6	<0.2	<4	<4	89	14	nd	8.6	0.10	7.0	<3
Obuasi mine borehole 1	0.07	<0.1	20.4	8790	12	21	<0.2	6	920	395	55	nd	16.0	0.35	8.0	*3
Obuasi mine borehole 2	<0.02	<0.1	4.16	5010	12	14	<0.2	35	2220	305	29	nd	21.2	0.17	5.0	<3
Obuasi mine drainage	0.02	0.2	7.59	4560	13	63	<0.2	334	395	638	80	nd	90	0.38	<0.4	<3

Appendix 1B cont'd...

Locality	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn µg l ⁻¹	Li µg l ⁻¹	B µg l ⁻¹	Be µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Ba µg l ⁻¹	Br µg l ⁻¹	I µg l ⁻¹	F mg l ⁻¹	As _{total} µg l ⁻¹	As(III) µg l ⁻¹
Aboagyekurom	0.06	<0.1	1.51	169	5	<6	<0.2	12	11	42	16	nd	9.2	0.07	11.0	8
Nankawura	<0.02	<0.1	0.366	137	13	<6	<0.2	<4	11	38	22	nd	19.5	0.05	<0.4	<3
Fiankoma	<0.02	0.2	4.76	181	42	<6	<0.2	<4	33	84	26	nd	14.2	0.07	<0.4	<3
Abaakwaa	<0.02	<0.1	0.65	315	24	<6	<0.2	<4	6	251	14	nd	15.9	0.05	4.0	<3
Kobro	<0.02	<0.1	0.248	356	36	<6	<0.2	5	18	65	7	nd	6.6	0.05	2.0	<3
Denyasefokurom	<0.02	<0.1	0.219	39	9	<6	<0.2	<4	6	32	21	nd	7.7	0.04	4.0	<3
Antoakurom	<0.02	0.2	0.048	315	50	<6	<0.2	<4	6	378	3	nd	6.6	0.07	40	<3
Antoakurom 3	<0.02	<0.1	<0.003	85.7	13	<6	<0.2	21	17	38	56	nd	5.3	0.03	<0.4	<3
Nsiana	<0.02	<0.1	<0.003	20.7	14	<6	<0.2	10	14	74	23	nd	6.2	0.06	<0.4	<3
Manso Akropon	<0.02	<0.1	0.39	339	29	<6	<0.2	19	37	82	3	nd	6.6	0.14	<0.4	<3
Abodom	<0.02	0.1	<0.003	14.2	18	<6	<0.2	13	12	118	1	nd	5.6	0.08	3.0	<3
Brofeyeduru	<0.02	0.3	4.10	1020	3	22	<0.2	<4	<4	167	49	nd	38	0.07	7.0	*5
Mim 3	<0.02	<0.1	0.006	9.3	20	<6	<0.2	9	14	143	24	nd	8.7	0.18	<0.4	<3
Mim 1	<0.02	0.2	0.98	78.8	24	<6	<0.2	<4	6	237	12	nd	6.6	0.27	14.0	9
Nkampram	0.02	<0.1	<0.003	19.6	5	<6	<0.2	13	24	16	11	nd	20.4	0.03	<0.4	<3
Kwabrafo stream-upstrm	0.03	<0.1	2.56	642	4	10	<0.2	<4	4	47	18	nd	64	0.09	350	*280
Tailings effluent	0.03	1.4	0.702	78.9	2	286	<0.2	1780	494	1500	23	nd	775	0.49	1810	50
Kwabrafo stream-dnstrm	0.20	1.4	0.063	3580	10	736	<0.2	63	<4	1560	27	nd	533	0.30	7900	675
Abompekrom	0.03	<0.1	0.029	49.7	9	<6	0.3	20	22	28	18	nd	10.3	0.05	42	9
Abompekrom	0.02	<0.1	0.024	104	11	<6	0.3	<4	10	43	16	nd	9.8	0.09	14.0	3
Obuasi mine borehole 3	0.04	0.2	6.07	419	10	20	0.3	<4	229	546	54	nd	84	0.11	17.0	*<3
Asaman	0.03	<0.1	0.004	29.7	11	<6	<0.2	20	45	32	16	nd	4.8	0.05	3.0	<3
Yawkurom 1	0.03	0.2	1.23	243	37	7	<0.2	<4	20	125	10	nd	54	0.13	52	7
Manso Atwere	0.03	<0.1	0.247	87	27	6	0.3	7	14	93	18	nd	3.0	0.08	<0.4	<3
Manso Atwere (house)	<0.02	0.3	0.754	556	30	<6	<0.2	<4	21	364	4	nd	5.2	0.13	57	11
Suntreso	0.02	<0.1	0.082	22.7	29	<6	<0.2	<4	8	176	7	nd	9.0	0.22	<0.4	<3
Agroyesum hospital	<0.02	0.1	1.53	313	48	12	<0.2	<4	7	380	7	nd	10.2	0.17	38	6
Odahu	<0.02	0.2	0.314	98.2	39	<6	<0.2	<4	28	172	21	nd	16.1	0.15	3.0	<3
Mile Nineteen	<0.02	<0.1	3.56	181	13	<6	<0.2	<4	41	108	12	nd	8.0	0.03	7.0	3
Nkyuaso	<0.02	<0.1	5.32	61	16	<6	<0.2	<4	27	31	23	nd	39.4	0.05	<0.4	<3
Odaso	<0.02	<0.1	16.8	449	21	11	<0.2	<4	981	52	20	nd	25.2	0.21	<0.4	<3
Kampese	<0.02	<0.1	0.089	11.4	16	<6	<0.2	<4	13	73	7	nd	10.6	0.08	<0.4	<3
Apanapron	<0.02	0.2	1.48	217	35	<6	<0.2	<4	15	230	11	nd	13.0	0.11	6.0	3
Ankam 1	<0.02	<0.1	0.564	62.7	23	<6	<0.2	5	16	129	7	nd	8.9	0.28	<0.4	<3

Appendix 1B cont'd...

Locality	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn μg l ⁻¹	Li μg l ⁻¹	B μg l ⁻¹	Be μg l ⁻¹	Cu μg l ⁻¹	Zn μg l ⁻¹	Sr μg l ⁻¹	Ba μg l ⁻¹	Br μg l ⁻¹	I μg l ⁻¹	F mg l ⁻¹	As _{total} μg l ⁻¹	As(III) μg l ⁻¹
Odumase	<0.02	<0.1	0.153	9.2	21	6	<0.2	<4	12	42	19	nd	7.8	0.07	<0.4	<3
Adubea	2.27	<0.1	5.38	498	12	13	<0.2	<4	12	115	68	nd	16.2	0.10	nd	nd
Kwameduakurom	<0.02	<0.1	0.019	5.7	3	<6	<0.2	<4	7	27	20	nd	11.5	0.03	<0.4	<3
Kaw River	0.02	0.4	0.363	44.3	4	12	<0.2	<4	<4	59	10	nd	2670	0.05	3.0	<3
Gyeboum stream	0.03	<0.1	0.373	15	7	9	<0.2	<4	<4	55	11	nd	12.5	0.11	5.0	<3
Nyamso	<0.02	<0.1	0.275	52.3	19	<6	<0.2	<4	21	15	23	nd	3.6	0.05	<0.4	<3
Mensakurom	<0.02	<0.1	0.032	19.8	3	<6	<0.2	<4	10	9	15	nd	6.5	0.03	2.0	<3
Adansi	0.15	<0.1	1.28	18.6	5	7	<0.2	<4	<4	24	11	nd	9.3	0.04	64	6
Dadwen	<0.02	<0.1	0.639	37.4	3	6	<0.2	<4	<4	37	11	nd	11.4	0.07	40	9

Detection limits are 3 σ about the blank concentration, except for As_{total} and As(III) which are given at 6 σ.

As_{total} data (sample number in parentheses) for selected unfiltered samples: Amamon (16): 2 μg l⁻¹, Sodua (22): < 2 μg l⁻¹, Adjensu stream, Wumase (36): 8 μg l⁻¹, Mile Eighteen (47): < 2 μg l⁻¹.

* As(III) values quoted represent minimum values due to possible Fe interference on the As spectral line using hydride-generation ICP-AES.

nd: not determined.

APPENDIX 1C. Trace-element data for water samples from the Obuasi area, analysed by ICP-MS.

Locality	Li µg l ⁻¹	Be µg l ⁻¹	B µg l ⁻¹	Al µg l ⁻¹	Cr µg l ⁻¹	Co µg l ⁻¹	Ni µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Y µg l ⁻¹	Zr µg l ⁻¹	Mo µg l ⁻¹	As µg l ⁻¹	Ag µg l ⁻¹	Cd µg l ⁻¹	Ba µg l ⁻¹	Pb µg l ⁻¹	Ga µg l ⁻¹
Nyamso north	21	<0.09	<8	<30	<0.6	3.5	6.9	<0.8	12	45	0.05	<1	0.15	<8	<0.1	<0.1	24	<1.5	0.06
Nyamso south	18	<0.09	<8	<30	<0.6	2.4	6.5	1.4	25	14	0.05	<1	<0.1	<8	<0.1	<0.1	23	<1.5	0.04
Konka New Town	10	0.10	<8	<30	<0.6	2.0	4.4	4.6	10	11	0.10	<1	<0.1	<8	<0.1	<0.1	30	<1.5	<0.04
Nhyiaso	7.6	<0.09	<8	<30	<0.6	1.2	2.6	<0.8	8	32	<0.03	<1	<0.1	<8	<0.1	<0.1	10	<1.5	<0.04
Apitikokoo	11	0.29	<8	376	<0.6	3.6	7.1	31.3	25	21	2.39	<1	<0.1	<8	<0.1	<0.1	72	2.2	0.16
Apitiso	64	<0.09	<8	<30	0.6	4.7	12	2.4	9	287	<0.03	<1	1.1	27	<0.1	<0.1	9	<1.5	0.07
Kokotanten	21	<0.09	<8	<30	<0.6	0.3	<1	<0.8	<3	299	<0.03	<1	0.1	8	<0.1	<0.1	32	<1.5	0.09
Nyamekyere	5.3	<0.09	<8	<30	0.9	1.3	3.3	7.1	19	20	0.04	<1	<0.1	<8	<0.1	<0.1	18	<1.5	0.04
Nyamekere stream	1.3	<0.09	11	214	2.0	1.3	2.0	1.6	5	33	0.44	<1	<0.1	28	<0.1	<0.1	22	<1.5	0.11
Kwaku Yaw	2.1	<0.09	<8	57	1.0	<0.1	<1	<0.8	<3	29	<0.03	<1	<0.1	<8	<0.1	<0.1	8	<1.5	<0.04
Sanso	8.2	<0.09	<8	<30	<0.6	1.6	4.5	<0.8	9	57	<0.03	<1	0.12	13	<0.1	<0.1	6	<1.5	<0.04
Odumase	2.9	<0.06	<8	<30	<0.3	0.1	1.2	3.2	151	177	<0.03	5.9	<0.7	22.0	0.03	<0.05	11	0.09	<0.03
Odumase stream	1.7	<0.06	<8	<30	0.4	0.1	0.5	3.6	3	44	<0.03	5.1	<0.7	10.2	<0.02	<0.05	8	0.12	<0.03
Sibiri stream	1.3	<0.06	<8	<50	<0.3	0.1	<0.3	0.8	<3	48	<0.03	1.6	<0.7	7.6	<0.02	<0.05	12	<0.07	<0.03
Akrofuom	2.2	0.37	10	1182	0.4	4.5	5.6	21	48	106	18	0.9	<0.7	0.5	0.03	0.27	545	8.05	0.79
Okyerokrom	3.5	<0.06	<8	<50	0.7	0.5	1.5	1.4	15	13	0.11	<0.6	<0.7	2.6	<0.02	<0.05	12	0.40	<0.03
Gym River	0.3	<0.06	<8	<50	0.5	0.5	0.9	1.4	<3	43	0.13	3.4	<0.7	7.6	<0.02	<0.05	20	0.26	0.04
Brahabeome	0.7	<0.06	<8	<50	<0.3	0.5	1.4	62	463	95	0.17	<0.6	<0.7	4.2	<0.02	0.07	15	4.98	<0.03
Diewieso	3.7	0.53	<8	226	<0.3	8.3	8.7	54	62	65	5.39	<0.6	<0.7	0.3	<0.02	0.15	265	2.61	0.27
Dwete stream	1.1	<0.06	<8	<50	0.4	0.1	0.4	1.2	4	8	0.11	<0.6	<0.7	11.4	<0.02	<0.05	6	0.19	<0.03
Meduma	18	<0.06	<8	<50	1.9	0.05	3.8	7.9	5	106	0.03	<0.6	<0.7	3.3	<0.02	<0.05	132	0.37	<0.03
Old Edubiase	22	0.10	<8	<50	0.7	0.1	1.6	12	10	142	0.05	<0.6	<0.7	0.3	<0.02	<0.05	101	0.48	<0.03
Ponkobi	12	<0.06	<8	<50	<0.3	1.7	3.0	6.2	8	37	<0.03	<0.6	<0.7	5.0	<0.02	<0.05	10	0.13	<0.03
Patakro	29	<0.06	<8	<50	<0.3	0.1	0.8	<0.3	5	564	<0.03	<0.6	<0.7	1.1	<0.02	<0.05	65	<0.07	<0.03
Wioso	9.0	0.11	<8	<50	1.2	0.2	1.0	36	22	225	<0.03	<0.6	<0.7	3.1	<0.02	0.10	121	0.51	<0.03
Aketekyiso	4.1	0.16	<8	<50	<0.3	1.4	1.7	4.8	24	7	0.10	2.0	<0.7	0.6	0.03	<0.05	17	0.18	<0.03
Amamon	3.1	<0.06	<8	<50	<0.3	2.2	1.5	2.4	10	12	0.06	<0.6	<0.7	1.1	<0.02	<0.05	21	0.10	<0.03
Abedwum	2.5	0.07	<8	<50	<0.3	1.6	2.2	2.7	33	50	0.47	<0.6	<0.7	0.6	<0.02	<0.05	29	0.27	0.05
Ankasa stream	6.4	<0.06	<8	<50	0.3	0.5	1.2	2.3	3	27	0.38	0.9	<0.7	25	<0.02	<0.05	15	0.15	0.05
Asikasu	14	<0.06	<8	<50	1.1	0.8	0.7	1.7	4	179	0.43	0.8	<0.7	137	<0.02	<0.05	158	0.27	0.07
Afoako	11	0.51	<8	<50	0.4	0.1	0.5	18	15	92	<0.03	<0.6	<0.7	2.6	<0.02	<0.05	147	0.99	<0.03
Patase	22	0.53	<8	<50	0.4	0.5	0.8	3.7	12	139	<0.03	<0.6	<0.7	2.0	0.03	<0.05	189	0.34	<0.03
Sodua	2.8	0.11	<8	<50	0.4	1.2	3.5	1.3	6	21	0.04	<0.6	<0.7	1.3	<0.02	<0.05	50	0.10	<0.03
Ankasi	13	<0.06	<8	<50	3.3	0.1	4.5	15	9	158	<0.03	4.0	<0.7	0.9	<0.02	<0.05	107	0.34	<0.03

Appendix 1C cont'd...

Locality	Li μg l ⁻¹	Be μg l ⁻¹	B μg l ⁻¹	Al μg l ⁻¹	Cr μg l ⁻¹	Co μg l ⁻¹	Ni μg l ⁻¹	Cu μg l ⁻¹	Zn μg l ⁻¹	Sr μg l ⁻¹	Y μg l ⁻¹	Zr μg l ⁻¹	Mo μg l ⁻¹	As μg l ⁻¹	Ag μg l ⁻¹	Cd μg l ⁻¹	Ba μg l ⁻¹	Pb μg l ⁻¹	Ga μg l ⁻¹
Bogyawe	26	<0.06	<8	<50	<0.3	0.7	1.6	2.0	5	142	<0.03	1.2	<0.7	3.6	<0.02	<0.05	90	<0.07	0.04
Aminase	19	0.66	<8	<50	0.3	0.9	0.7	1.4	28	45	0.44	<0.6	<0.7	0.4	<0.02	<0.05	107	<0.07	0.03
Amoamo	41	1.35	<8	<50	<0.3	2.0	1.6	1.3	29	266	0.59	<0.6	<0.7	3.9	<0.02	0.09	543	0.17	0.03
Dwondoso	4.2	0.28	<8	<50	1.2	1.6	3.2	0.6	80	15	<0.03	<0.6	<0.7	1.0	<0.02	<0.05	48	0.07	<0.03
Atobiase	18	0.22	<8	231	0.5	0.5	0.6	1.2	8	144	0.27	<0.6	<0.7	170	<0.02	<0.05	107	0.42	0.09
Esereso	5.0	0.06	<8	105	<0.3	0.1	<0.3	1.2	5	26	0.11	<0.6	<0.7	6.6	<0.02	0.06	44	0.47	0.07
Ahwiaa	12	0.07	<8	209	0.3	0.3	0.3	1.1	7	55	0.15	<0.6	<0.7	38	<0.02	<0.05	58	0.31	0.06
Boni	24	<0.06	<8	<50	<0.3	0.6	5.2	24	24	430	<0.03	<0.6	<0.7	0.5	<0.02	<0.05	45	0.43	<0.03
Huntado	7.9	0.11	<8	<50	<0.3	2.3	3.8	3.3	9	37	0.69	<0.6	<0.7	<0.3	<0.02	<0.05	57	0.14	<0.03
Poano	25	<0.06	<8	<50	<0.3	0.3	1.0	<0.3	6	72	0.03	<0.6	<0.7	2.5	<0.02	<0.05	9	<0.07	0.04
Afransie	16	<0.06	<8	<50	<0.3	0.4	2.5	6.8	7	355	<0.03	<0.6	<0.7	0.5	<0.02	<0.05	8	0.11	<0.03
Ntinanko	40	<0.06	<8	<50	0.3	0.8	15	10	31	57	<0.03	4.0	<0.7	2.2	0.03	<0.05	29	0.43	<0.03
Adjensu stream	3.0	<0.06	10	<50	<0.3	0.5	1.4	0.6	<3	55	<0.03	1.4	<0.7	4.1	<0.02	<0.05	19	0.08	0.03
Wumase	13	0.33	<8	115	0.5	2.2	4.7	3.0	27	35	0.30	<0.6	<0.7	0.8	<0.02	<0.05	42	0.11	<0.03
Kofikurom	9.2	<0.06	<8	<50	<0.3	1.9	4.2	6.8	15	63	0.11	<0.6	<0.7	1.5	<0.02	<0.05	39	0.10	<0.03
Kokoteasua	12	<0.06	<8	<50	0.4	0.3	4.3	1.0	11	41	<0.03	<0.6	<0.7	0.7	<0.02	<0.05	19	0.09	<0.03
Dunkwa Nkwanta	8.2	0.10	<8	69	<0.3	1.3	3.3	3.0	8	7	0.17	<0.6	<0.7	0.4	<0.02	<0.05	13	0.65	<0.03
Dekyewa	16	<0.06	<8	<50	<0.3	1.8	4.7	0.7	1012	30	<0.03	<0.6	<0.7	0.9	<0.02	<0.05	12	0.15	0.07
MileNine	19	<0.06	<8	<50	<0.3	0.8	1.9	9.3	19	409	<0.03	<0.6	<0.7	1.1	<0.02	<0.05	13	0.14	<0.03
Sabe 2	28	<0.06	<8	<50	<0.3	5.6	1.2	<0.3	226	321	<0.03	<0.6	<0.7	63	<0.02	0.07	15	<0.07	<0.03
Sabe 1	25	<0.06	<8	<50	<0.3	0.6	3.5	0.8	89	155	<0.03	<0.6	<0.7	0.8	0.03	<0.05	8	0.09	<0.03
Manfo	24	<0.06	<8	<50	<0.3	0.5	1.5	<0.3	41	420	<0.03	<0.6	0.9	20	<0.02	<0.05	16	<0.07	<0.03
Odumto	3.9	0.08	<8	<50	<0.3	2.1	4.1	6.4	21	11	0.54	<0.6	<0.7	0.5	0.04	<0.05	22	<0.07	<0.03
Mile Eighteen	23	<0.06	<8	<50	0.4	0.4	4.0	3.7	18	53	<0.03	1.0	<0.7	0.5	<0.02	<0.05	7	<0.07	<0.03
Mile Fourteen	33	<0.06	<8	<50	<0.3	4.6	0.6	1.8	6	333	<0.03	1.1	<0.7	52	<0.02	<0.05	9	<0.07	0.03
Apitiso 1	93	<0.06	<8	<50	<0.3	4.2	4.1	14	37	225	<0.03	<0.6	<0.7	6.8	<0.02	0.10	11	0.25	0.03
Fenaso	2.9	<0.06	13	310	0.7	1.5	1.8	2.1	4	86	0.16	<0.6	<0.7	22	<0.02	<0.05	31	0.80	0.06
Kofitanokurom	15	<0.09	<8	<50	<0.6	0.7	3.9	1.5	50	81	<0.03	<1	<0.1	1.4	<0.02	<0.1	27	<0.07	<0.04
Dangase	1.5	<0.09	<8	<50	<0.6	0.5	<1.3	0.7	9	4	<0.03	<1	<0.1	<0.7	<0.02	<0.1	10	<0.07	<0.04
Tweapease	36	<0.09	<8	<50	<0.6	2.5	4.3	1.2	11	163	<0.03	<1	<0.1	9.1	<0.02	<0.1	6	<0.07	<0.04
Sulyenso	8.8	<0.09	<8	70	<0.6	0.2	<1.3	1.7	3	84	0.06	<1	0.1	5.9	<0.02	<0.1	15	0.10	<0.04
Obuasi mine bh 1	14	0.14	<8	157	<0.6	66	161	8.3	909	401	33	<1	<0.1	7.0	<0.02	1.23	60	0.23	1.01
Obuasi mine bh 2	12	<0.3	7	<50	<0.3	22	62	31	2502	315	1.36	3.7	0.7	4.4	<0.05	0.56	31	<0.06	0.19
Obuasi mine dr'nage	13	<0.3	59	<50	<0.3	55	110	305	442	697	38	2.2	0.06	2.0	<0.05	0.75	87	<0.06	0.99

Appendix 1C cont'd...

Locality	Li µg l ⁻¹	Be µg l ⁻¹	B µg l ⁻¹	Al µg l ⁻¹	Cr µg l ⁻¹	Co µg l ⁻¹	Ni µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Y µg l ⁻¹	Zr µg l ⁻¹	Mo µg l ⁻¹	As µg l ⁻¹	Ag µg l ⁻¹	Cd µg l ⁻¹	Ba µg l ⁻¹	Pb µg l ⁻¹	Ga µg l ⁻¹
Aboagyekurom	6.3	<0.3	7	117	0.6	3.5	3.0	13	11	41	1.10	0.4	0.20	23	<0.05	<0.2	17	<0.06	0.06
Nankawura	14	<0.3	5	<50	<0.3	2.2	5.8	3.1	11	37	0.13	<0.4	<0.05	1.7	<0.05	<0.2	23	<0.06	<0.04
Fiankoma	45	<0.3	5	<50	<0.3	5.7	10	2.7	36	74	0.07	<0.4	<0.05	<0.7	<0.05	<0.2	26	<0.06	<0.04
Abuakwaa	27	<0.3	5	<50	<0.3	1.3	3.4	2.0	5	241	0.11	<0.4	0.07	4.3	<0.05	<0.2	14	<0.06	<0.04
Kobro	38	<0.3	4	<50	0.5	2.4	6.3	5.4	19	59	0.03	<0.4	<0.05	2.4	<0.05	<0.2	7	<0.06	0.05
Denyasefokurom	10	<0.3	7	<50	<0.3	0.3	2.0	1.7	4	30	0.16	<0.4	<0.05	3.9	<0.05	<0.2	21	<0.06	0.05
Antoakurom	55	<0.3	3	<50	<0.3	1.8	0.8	1.3	5	377	0.09	<0.4	0.07	37	<0.05	<0.2	3	<0.06	<0.04
Antoakurom 3	14	<0.3	2	<50	<0.3	3.1	5.7	19	18	37	0.36	2.9	<0.05	<0.7	<0.05	<0.2	57	0.44	<0.04
Nsiana	17	<0.3	<2	<50	<0.3	1.7	6.5	11	15	75	0.08	0.8	0.05	<0.7	<0.05	<0.2	25	0.20	<0.04
Manso Akropon	31	<0.3	3	<50	<0.3	1.7	4.2	18	43	80	0.06	0.9	<0.05	<0.7	<0.05	<0.2	3	<0.06	0.07
Abodom	18	<0.3	<2	<50	<0.3	0.1	1.2	10	10	112	0.04	<0.4	<0.05	3.0	<0.05	<0.2	1	<0.06	<0.04
Brofeyeduru	3.5	<0.3	25	<50	0.5	2.5	1.7	3.5	3	168	0.31	0.9	0.15	16	<0.05	<0.2	50	<0.06	0.05
Mim 3	22	<0.3	4	<50	<0.3	0.1	4.7	7.9	18	141	0.05	<0.4	0.17	0.9	<0.05	<0.2	24	0.11	<0.04
Mim 1	27	<0.3	3	<50	<0.3	1.4	1.6	1.0	5	240	0.04	<0.4	<0.05	13	<0.05	<0.2	12	<0.06	<0.04
Nkampram	3.9	<0.3	4	<50	<0.3	1.6	1.2	11	30	17	0.21	<0.4	0.10	<0.7	<0.05	<0.2	11	0.40	<0.04
Kwabrafo strn-up	2.9	<0.3	7	<50	<0.3	2.9	1.2	1.6	<3	48	0.10	5.7	0.13	527	<0.05	<0.2	17	<0.06	0.05
Tailings effluent	6.4	<0.3	343	73	0.6	261	1471	9219	631	2115	0.06	4.2	173	2385	19.59	<0.2	27	<0.06	0.51
Kwabrafo strn-dn	11	<0.3	667	243	<0.3	68	62	91	6	1920	0.19	<0.4	7.17	8071	0.24	<0.2	31	<0.06	0.08
Abompekrom	7.4	<0.3	22	<50	<0.3	1.7	3.4	21	22	29	0.18	<0.4	0.09	32	0.07	<0.2	19	0.13	<0.04
Abompekrom	10	<0.3	11	<50	<0.3	1.5	3.8	2.7	9	43	0.09	<0.4	<0.05	8.2	<0.05	<0.2	17	<0.06	<0.04
Obuasi mine bh 3	8.7	<0.3	17	<50	<0.3	2.7	14	15	264	577	0.12	<0.4	0.32	12.9	<0.05	<0.2	56	0.07	<0.04
Asaman	8.6	<0.3	5	<50	<0.3	0.4	2.9	17	48	31	0.28	<0.4	<0.05	2.5	<0.05	<0.2	16	4.3	<0.04
Yawkurom 1	32	<0.3	7	<50	<0.3	1.7	2.4	2.4	19	118	0.07	<0.4	0.12	51	<0.05	<0.2	9	<0.06	<0.04
Manso Atwere	25	<0.3	5	<50	<0.3	1.1	2.9	5.4	14	87	0.04	<0.4	<0.05	1.4	<0.05	<0.2	17	<0.06	<0.04
Manso Atwere (hse)	32	<0.3	4	<50	<0.3	3.5	1.2	0.5	21	375	0.06	<0.4	0.37	61	<0.05	<0.2	3	<0.06	<0.04
Suntreso	29	<0.3	8	<50	<0.3	0.3	2.0	0.7	5	168	0.07	<0.4	<0.05	2.3	<0.05	<0.2	7	<0.06	<0.04
Agroyesum hospital	49	<0.3	13	<50	<0.3	0.7	1.0	0.7	3	382	0.09	<0.4	0.44	41	<0.05	<0.2	7	<0.06	<0.04
Odahu	40	<0.3	4	<50	<0.3	1.4	6.1	2.4	30	159	<0.01	4.4	<0.05	2.3	0.06	<0.2	21	<0.06	<0.04
Mile Nineteen	13	<0.3	<2	<50	<0.3	1.1	1.9	1.7	43	99	0.02	<0.4	0.13	5.9	<0.05	<0.2	12	<0.06	<0.04
Nkyuasoo	18	<0.3	4	<50	<0.3	0.8	4.8	2.8	32	31	0.02	<0.4	0.11	<0.7	<0.05	<0.2	26	<0.06	<0.04
Odaso	21	<0.3	3	<50	<0.3	3.9	7.1	1.5	1147	49	0.04	<0.4	0.12	2.0	<0.05	<0.2	20	<0.06	0.08
Kampese	15	<0.3	2	<50	<0.3	0.1	1.4	0.4	13	69	0.03	<0.4	<0.05	1.4	<0.05	<0.2	7	<0.06	<0.04
Apanapron	39	<0.3	5	<50	<0.3	0.4	0.5	1.0	27	217	0.03	<0.4	<0.05	5.6	<0.05	<0.2	11	<0.06	<0.04
Ankam 1	25	<0.3	5	<50	<0.3	1.2	4.7	4.9	16	122	0.01	<0.4	0.06	1.0	<0.05	<0.2	7	<0.06	<0.04

Appendix 1C cont'd...

Locality	Li $\mu\text{g l}^{-1}$	Be $\mu\text{g l}^{-1}$	B $\mu\text{g l}^{-1}$	Al $\mu\text{g l}^{-1}$	Cr $\mu\text{g l}^{-1}$	Co $\mu\text{g l}^{-1}$	Ni $\mu\text{g l}^{-1}$	Cu $\mu\text{g l}^{-1}$	Zn $\mu\text{g l}^{-1}$	Sr $\mu\text{g l}^{-1}$	Y $\mu\text{g l}^{-1}$	Zr $\mu\text{g l}^{-1}$	Mo $\mu\text{g l}^{-1}$	As $\mu\text{g l}^{-1}$	Ag $\mu\text{g l}^{-1}$	Cd $\mu\text{g l}^{-1}$	Ba $\mu\text{g l}^{-1}$	Pb $\mu\text{g l}^{-1}$	Ga $\mu\text{g l}^{-1}$
Odumase	21	<0.3	6	<50	<0.3	0.1	2.0	1.3	12	39	0.04	<0.4	<0.05	1.3	<0.05	<0.2	19	<0.06	<0.04
Adubea	12	<0.3	10	4089	3.5	4.5	3.4	2.0	11	99	0.27	1.2	0.36	40	<0.05	<0.2	63	0.37	0.41
Kwameduakuum	2.0	<0.3	2	<50	0.6	0.3	1.1	<0.3	6	25	0.26	<0.4	<0.05	1.2	<0.05	<0.2	20	<0.06	<0.04
Kaw River	1.4	<0.3	7	<50	<0.3	0.1	0.4	0.4	<3	51	0.04	<0.4	0.07	2.8	<0.05	<0.2	8	<0.06	<0.04
Gyeboum stream	5.1	<0.3	6	<50	<0.3	0.1	0.5	0.8	<3	53	0.04	5.6	0.33	6.9	<0.05	<0.2	10	<0.06	<0.04
Nyamso	18	<0.3	<2	<50	<0.3	2.3	5.9	0.8	21	14	0.04	<0.4	<0.05	1.2	<0.05	<0.2	21	<0.06	<0.04
Mensakurom	2.3	<0.3	3	<50	<0.3	0.7	1.0	1.3	10	8	0.10	<0.4	<0.05	2.4	<0.05	<0.2	14	<0.06	<0.04
Adansi	4.5	0.3	6	246	<0.3	0.4	1.0	0.8	<3	22	0.15	<0.4	0.06	101	<0.05	<0.2	10	<0.06	<0.04
Dadwen	3.2	<0.3	7	<50	<0.3	0.3	0.8	1.0	<3	35	0.07	<0.4	0.13	94	<0.05	<0.2	11	<0.06	<0.04

Detection limits are 3σ about the variation of the blank concentration.

APPENDIX 1D. Trace-element data for water samples from the Obuasi area, analysed by ICP-MS.

Locality	Ge µg l ⁻¹	Rb µg l ⁻¹	Sb µg l ⁻¹	Cs µg l ⁻¹	La µg l ⁻¹	Ce µg l ⁻¹	Pr µg l ⁻¹	Nd µg l ⁻¹	Eu µg l ⁻¹	Sm µg l ⁻¹	Gd µg l ⁻¹	Tb µg l ⁻¹	Dy µg l ⁻¹	Ho µg l ⁻¹	Er µg l ⁻¹	Tm µg l ⁻¹	Yb µg l ⁻¹	Lu µg l ⁻¹	Tl µg l ⁻¹	U µg l ⁻¹
Nyanso north	<0.06	0.90	<0.03	0.10	0.13	0.22	<0.06	0.10	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Nyanso south	<0.06	0.51	<0.03	0.06	0.21	0.34	<0.06	0.12	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Konka New Town	<0.06	0.45	<0.03	0.07	0.51	0.98	0.13	0.52	<0.06	0.11	0.09	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Nhyiaso	<0.06	0.63	<0.03	0.07	<0.06	<0.06	<0.06	<0.05	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Apitikokoo	<0.06	3.09	<0.03	0.22	6.34	17	2.0	8	0.37	1.59	1.31	0.14	0.56	0.09	0.26	<0.04	0.23	<0.04	<0.2	0.06
Apitiso	0.07	1.13	0.08	1.32	<0.06	<0.06	<0.06	<0.05	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	0.14
Kokotanten	0.10	2.68	0.04	0.51	<0.06	<0.06	<0.06	<0.05	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Nyamekyere	<0.06	0.36	<0.03	0.07	<0.06	<0.06	<0.06	0.05	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Nyamekere stream	<0.06	4.01	<0.03	<0.04	0.62	1.28	0.17	0.66	<0.06	0.14	0.14	<0.05	0.08	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Kwaku Yaw	<0.06	0.69	<0.03	<0.04	<0.06	<0.06	<0.06	<0.05	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Sanso	<0.06	0.68	<0.03	0.24	<0.06	<0.06	<0.06	<0.05	<0.06	<0.06	<0.06	<0.05	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	<0.2	<0.05
Odumase	<0.2	0.87	0.04	0.30	<0.02	0.02	<0.02	<0.03	<0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	<0.005
Odumase stream	<0.2	0.76	0.27	0.02	0.07	0.19	<0.02	0.08	<0.02	<0.02	0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.014
Sibiri stream	<0.2	0.77	0.05	0.01	0.03	0.07	<0.02	0.04	<0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.006
Akrofuom	1.5	20	<0.02	0.31	37	78	8.7	32	1.34	6.0	6.0	0.73	3.52	0.62	1.7	0.21	1.34	0.18	0.27	0.65
Okyerekrom	<0.2	1.80	0.15	0.01	0.18	0.45	0.06	0.19	<0.02	0.05	0.04	<0.02	0.02	<0.02	<0.01	<0.02	<0.02	<0.01	0.02	0.02
Gymi River	<0.2	2.31	0.05	<0.01	0.23	0.56	0.06	0.28	<0.02	0.07	0.05	<0.02	0.03	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.02
Brahabeome	<0.2	2.28	0.08	0.02	0.22	0.45	0.06	0.25	<0.02	0.06	0.05	<0.02	0.03	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.03
Diewieso	0.8	6.08	0.03	0.30	12.8	18	3.5	14	0.66	2.8	2.4	0.25	1.11	0.18	0.49	0.07	0.43	0.06	0.04	0.07
Dwete stream	<0.2	0.12	0.06	<0.01	0.21	0.37	0.06	0.31	<0.02	0.07	0.04	<0.02	0.02	<0.02	0.02	<0.02	<0.02	<0.01	<0.01	<0.005
Meduma	<0.2	1.98	<0.02	0.04	0.03	0.04	<0.02	<0.03	<0.02	0.03	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.06
Old Eubiasse	<0.2	1.66	<0.02	0.01	0.03	0.03	<0.02	<0.03	<0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.09
Ponkobi	<0.2	0.67	<0.02	0.11	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	<0.005
Patakro	0.4	2.07	<0.02	2.03	0.02	0.04	<0.02	<0.03	<0.02	0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	<0.005
Wioso	<0.2	0.54	<0.02	0.02	<0.02	<0.01	<0.02	<0.03	<0.02	0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.03
Aketekyiso	<0.2	0.60	<0.02	0.08	0.18	0.47	0.07	0.30	<0.02	0.04	0.04	<0.02	0.02	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.011
Amamon	<0.2	0.72	<0.02	0.05	0.11	0.15	0.03	0.13	<0.02	0.03	0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.005
Abedwum	<0.2	1.58	0.07	0.09	1.40	3.1	0.39	1.53	0.06	0.28	0.22	0.03	0.09	0.02	0.05	<0.02	0.04	<0.01	0.01	0.03
Ankasa stream	0.2	0.68	0.04	0.02	1.22	2.9	0.38	1.51	0.06	0.31	0.23	<0.02	0.08	<0.02	0.03	<0.02	<0.02	<0.01	<0.01	0.011
Asikasu	0.9	10.1	0.03	0.35	0.81	2.5	0.27	1.06	0.06	0.22	0.15	<0.02	0.10	<0.02	0.04	<0.02	0.03	<0.01	0.01	0.06
Afoako	<0.2	7.88	<0.02	0.05	0.03	0.04	<0.02	<0.03	<0.02	0.04	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.04	0.06
Patase	<0.2	4.56	<0.02	0.19	<0.02	0.01	<0.02	<0.03	0.02	0.03	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.06	0.05
Sodua	<0.2	6.71	<0.02	0.54	0.07	0.13	<0.02	0.05	<0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.04	0.005
Ankasi	<0.2	1.30	<0.02	0.02	<0.02	<0.01	<0.02	<0.03	<0.02	0.03	<0.01	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.02

Appendix 1D cont'd...

Locality	Ge μg l ⁻¹	Rb μg l ⁻¹	Sb μg l ⁻¹	Cs μg l ⁻¹	La μg l ⁻¹	Ce μg l ⁻¹	Pr μg l ⁻¹	Nd μg l ⁻¹	Eu μg l ⁻¹	Sm μg l ⁻¹	Tb μg l ⁻¹	Dy μg l ⁻¹	Ho μg l ⁻¹	Er μg l ⁻¹	Tm μg l ⁻¹	Yb μg l ⁻¹	Lu μg l ⁻¹	Tl μg l ⁻¹	U μg l ⁻¹
Bogyawe	0.2	1.32	<0.02	0.11	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.012
Aminase	<0.2	14	<0.02	0.98	0.09	0.34	0.06	0.37	0.04	0.14	<0.02	0.07	<0.02	0.05	<0.02	0.05	<0.01	0.15	0.82
Amoamo	<0.2	16	<0.02	1.80	0.39	0.89	0.10	0.47	0.06	0.20	<0.02	0.07	<0.02	0.04	<0.02	0.03	<0.01	0.25	0.65
Dwondoso	<0.2	4.07	<0.02	0.07	0.02	0.05	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.03	0.02
Atobiase	<0.2	3.85	<0.02	0.08	0.43	1.19	0.15	0.64	0.03	0.12	<0.02	0.06	<0.02	0.02	<0.02	<0.02	<0.01	0.04	0.07
Esereso	<0.2	12	0.04	0.45	0.50	1.22	0.13	0.47	0.02	0.08	<0.02	0.03	<0.02	0.01	<0.02	<0.02	<0.01	0.07	0.08
Ahwiaa	<0.2	3.65	<0.02	0.11	0.31	0.77	0.09	0.30	0.02	0.07	<0.02	0.03	<0.02	<0.01	<0.02	<0.02	<0.01	0.03	0.07
Boni	<0.2	1.36	<0.02	0.08	<0.02	0.02	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.06
Huntado	<0.2	1.89	<0.02	0.22	0.12	0.28	0.10	0.70	0.06	0.22	<0.02	0.15	0.02	0.08	<0.02	0.05	<0.01	<0.01	<0.005
Poano	0.4	1.50	<0.02	0.34	<0.02	0.02	<0.02	0.04	<0.02	<0.02	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.02
Afransie	<0.2	0.82	0.03	0.07	<0.02	0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.011
Nrinanko	<0.2	1.80	<0.02	0.18	0.03	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.02	0.008
Adjensu stream	<0.2	2.01	<0.02	0.02	0.02	0.08	<0.02	0.05	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.008
Wumase	<0.2	1.25	0.14	0.02	0.11	0.32	0.04	0.24	0.02	0.07	<0.02	0.05	<0.02	0.03	<0.02	0.04	<0.01	0.02	0.08
Kofikuroom	<0.2	1.33	<0.02	0.32	0.10	0.03	0.02	0.08	<0.02	0.03	<0.02	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.008
Kokoteasua	<0.2	0.60	<0.02	0.11	0.02	0.02	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.007
Dunkwa Nkwanta	<0.2	0.32	<0.02	0.08	0.35	0.82	0.11	0.50	0.02	0.11	<0.02	0.04	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.03
Dekyewa	0.9	1.26	<0.02	0.22	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.007
Mile Nine	<0.2	1.26	<0.02	0.09	<0.02	0.02	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.008
Sabe 2	0.6	2.02	0.04	0.54	<0.02	0.02	<0.02	0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.04
Sabe 1	0.8	0.45	<0.02	0.01	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.009
Manfo	0.4	1.57	0.05	0.20	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	0.09
Odumto	0.3	1.17	<0.02	0.09	0.58	0.12	0.13	0.48	0.03	0.10	<0.02	0.09	0.02	0.05	<0.02	0.03	<0.01	<0.01	<0.005
Mile Eighteen	0.4	1.03	<0.02	0.06	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	<0.01	<0.005
Mile Fourteen	<0.2	2.04	0.11	0.63	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.02	0.10
Apitiso 1	<0.2	1.19	<0.02	0.33	<0.02	<0.01	<0.02	<0.03	<0.02	<0.02	<0.01	<0.01	<0.02	<0.01	<0.02	<0.02	<0.01	0.01	0.012
Fenaso	0.29	3.66	0.05	0.03	0.32	0.97	0.09	0.35	0.02	0.09	<0.02	0.04	<0.02	0.02	<0.02	<0.02	<0.01	0.01	0.05
Kofitanokurum	<0.06	2.49	<0.03	0.05	<0.06	0.13	<0.06	0.08	<0.06	<0.06	<0.06	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	0.02	0.04
Dangase	<0.06	0.74	<0.03	0.08	<0.06	<0.06	<0.06	<0.05	<0.06	<0.06	<0.06	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	0.01	<0.005
Tweapease	0.29	1.24	<0.03	0.17	<0.06	<0.06	<0.06	<0.05	<0.06	<0.06	<0.06	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	0.02	<0.005
Suhyenso	<0.06	1.25	0.25	<0.04	0.11	0.24	<0.06	0.17	<0.06	<0.06	<0.06	<0.05	<0.04	<0.04	<0.04	<0.04	<0.04	0.01	0.01
Obuasi mine bh 1	2.4	2.23	1.63	2.9	121	220	24	94	8.79	15.3	14.1	4.9	0.79	1.9	0.22	30.69	0.81	2.3	0.17
Obuasi mine bh 2	<0.3	1.68	1.65	1.7	3.58	4.04	0.43	1.59	0.05	0.24	0.23	0.11	0.02	0.05	<0.01	0.03	<0.01	0.03	0.11
Obuasi mine drainage	1.9	8.58	0.05	2.7	245	353	25	84	1.97	8.82	11.0	2.9	0.51	1.2	0.11	0.53	0.08	0.10	0.03

Appendix 1D cont'd...

Locality	Ge μg l ⁻¹	Rb μg l ⁻¹	Sb μg l ⁻¹	Cs μg l ⁻¹	La μg l ⁻¹	Ce μg l ⁻¹	Pr μg l ⁻¹	Nd μg l ⁻¹	Eu μg l ⁻¹	Sm μg l ⁻¹	Gd μg l ⁻¹	Tb μg l ⁻¹	Dy μg l ⁻¹	Ho μg l ⁻¹	Er μg l ⁻¹	Tm μg l ⁻¹	Yb μg l ⁻¹	Lu μg l ⁻¹	Tl μg l ⁻¹	U μg l ⁻¹
Aboagyekurom	<0.3	1.14	<0.04	<0.2	3.79	7.95	0.82	3.1	0.10	0.46	0.41	0.04	0.15	0.03	0.07	<0.01	0.05	<0.01	<0.02	0.02
Nankawura	<0.3	2.88	<0.04	<0.2	0.34	0.91	0.10	0.48	0.02	0.07	0.05	<0.01	0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004
Fiankoma	<0.3	1.00	<0.04	<0.2	0.13	0.25	0.01	0.08	<0.01	0.02	0.02	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004
Abuakwa	<0.3	0.88	<0.04	1.2	0.27	0.51	0.06	0.19	<0.01	0.02	0.04	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.010
Kobro	<0.3	1.11	<0.04	<0.2	0.11	0.21	0.02	0.11	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.013
Denyasefokurom	<0.3	2.20	<0.04	<0.2	0.63	1.19	0.12	0.53	0.02	0.11	0.07	0.01	0.04	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.007
Antoakurom	<0.3	0.71	<0.04	0.2	0.18	0.38	0.03	0.17	<0.01	0.02	0.04	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.04
Antoakurom 3	<0.3	2.01	<0.04	<0.2	0.74	0.38	0.17	0.62	0.03	0.14	0.10	0.01	0.08	<0.01	0.03	<0.01	<0.02	<0.01	<0.02	0.007
Nsiana	<0.3	2.08	<0.04	<0.2	0.19	0.21	0.05	0.18	<0.01	0.03	0.04	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.02
Manso Akropon	<0.3	1.06	<0.04	<0.2	0.14	0.17	0.03	0.11	<0.01	0.03	<0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.009
Abodom	<0.3	0.83	<0.04	<0.2	0.11	0.17	0.02	0.13	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.010
Brofeyeduru	<0.3	8.93	<0.04	<0.2	1.07	2.31	0.22	0.92	0.03	0.16	0.13	0.01	0.06	<0.01	0.02	<0.01	0.02	<0.01	<0.02	0.02
Mim 3	<0.3	1.38	<0.04	<0.2	0.07	0.11	<0.01	0.07	<0.01	0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004
Mim 1	<0.3	1.46	<0.04	<0.2	0.06	0.15	0.02	0.05	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004
Nkampro	<0.3	1.19	<0.04	<0.2	0.28	0.62	0.07	0.20	<0.01	0.05	0.05	<0.01	0.05	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.011
Kwabrafo stream-up	<0.3	1.31	0.46	<0.2	0.30	0.75	0.08	0.37	<0.01	0.06	0.04	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.010
Tailings effluent	0.3	34	93	0.6	0.14	0.22	0.02	0.10	<0.01	0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.13
Kwabrafo stream-down	<0.3	32	10.0	1.0	0.44	0.57	0.06	0.24	<0.01	0.02	0.03	<0.01	0.03	<0.01	<0.01	<0.01	<0.02	<0.01	0.02	0.15
Abomekrom	<0.3	1.83	<0.04	0.3	0.34	0.13	0.08	0.33	<0.01	0.04	0.05	<0.01	0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.004
Abomekrom	<0.3	1.47	<0.04	0.3	0.10	0.07	0.01	0.09	<0.01	0.02	0.02	<0.01	0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.005
Obuasi mine bh 3	0.6	1.63	2.31	1.9	0.25	0.32	0.03	0.14	<0.01	0.05	0.04	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	0.02	0.09
Asaman	<0.3	0.67	<0.04	<0.2	0.19	0.08	0.03	0.12	<0.01	<0.01	0.03	<0.01	0.03	<0.01	0.02	<0.01	<0.02	<0.01	<0.02	0.006
Yawkurom 1	<0.3	0.99	<0.04	0.4	0.10	0.19	0.03	0.10	<0.01	0.02	0.02	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.005
Manso Atwere	<0.3	1.24	<0.04	<0.2	0.04	0.05	<0.01	0.04	<0.01	0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.03
Manso Atwere (house)	<0.3	0.63	<0.04	0.4	0.09	0.16	0.02	0.08	<0.01	0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.13
Suntreso	<0.3	0.57	<0.04	<0.2	0.09	0.19	0.02	0.13	0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.008
Agroyesum hospital	0.3	2.20	<0.04	0.4	0.11	0.20	0.03	0.07	<0.01	0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.005
Odahu	<0.3	1.24	<0.04	<0.2	0.02	0.04	<0.01	<0.03	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004
Mile Nineteen	<0.3	0.75	0.06	<0.2	0.02	0.04	<0.01	<0.03	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.02
Nkyuasoo	0.3	1.04	<0.04	<0.2	0.02	0.02	<0.01	<0.03	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.005
Odaso	0.6	0.90	<0.04	0.5	0.06	0.10	0.01	0.05	<0.01	0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.005
Kampese	<0.3	0.49	<0.04	<0.2	0.03	0.07	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004
Apanapron	0.3	1.55	<0.04	0.5	0.02	0.04	<0.01	<0.03	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004
Ankam 1	<0.3	1.35	<0.04	<0.2	0.02	0.02	<0.01	<0.03	<0.01	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	<0.004

Appendix 1D cont'd...

Locality	Ge μg l ⁻¹	Rb μg l ⁻¹	Sb μg l ⁻¹	Cs μg l ⁻¹	La μg l ⁻¹	Ce μg l ⁻¹	Pr μg l ⁻¹	Nd μg l ⁻¹	Eu μg l ⁻¹	Sm μg l ⁻¹	Gd μg l ⁻¹	Tb μg l ⁻¹	Dy μg l ⁻¹	Ho μg l ⁻¹	Er μg l ⁻¹	Tm μg l ⁻¹	Yb μg l ⁻¹	Lu μg l ⁻¹	Tl μg l ⁻¹	U μg l ⁻¹
Odumase	<0.3	1.00	<0.04	<0.2	0.08	0.15	0.02	0.06	<0.01	0.02	0.01	<0.01	0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.007
Adubea	<0.3	1.77	<0.04	<0.2	0.85	2.2	0.27	0.99	0.06	0.21	0.11	0.02	0.08	0.01	0.02	<0.01	0.02	<0.01	<0.02	0.07
Kwameduakurom	<0.3	0.11	<0.04	<0.2	0.36	0.11	0.08	0.35	<0.01	0.05	0.06	<0.01	0.04	0.01	0.02	<0.01	<0.02	<0.01	<0.02	<0.004
Kaw River	<0.3	2.61	0.10	<0.2	0.07	0.13	0.02	0.12	<0.01	0.02	0.02	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.011
Gyeboum stream	<0.3	1.01	0.36	<0.2	0.06	0.13	0.02	0.07	<0.01	<0.01	0.02	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.02
Nyamso	<0.3	0.48	<0.04	<0.2	0.02	0.04	<0.01	<0.03	<0.01	0.02	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.013
Mensakurom	<0.3	0.84	<0.04	<0.2	0.14	0.34	0.05	0.28	0.01	0.05	0.04	<0.01	0.03	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.02
Adansi	<0.3	0.42	0.07	<0.2	0.27	0.55	0.08	0.27	0.02	0.04	0.04	<0.01	0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.02
Dadwen	<0.3	1.96	0.17	<0.2	0.10	0.25	0.02	0.13	<0.01	0.02	0.02	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.02	0.006

Detection limits are 3 σ about the variation of the blank concentration.

Concentrations of Bi all below detection limit, except Mine exploration borehole 1 (Sample 55): 0.06 μg l⁻¹.

Concentrations of W and Au were also determined in Tailings effluent (Sample 74), Kwabrafo stream (Sample 73, upstream of effluent input) and Kwabrafo stream (Sample 75, downstream of effluent input). Concentrations for these sites respectively were: W: 911 μg l⁻¹, Au: 120 μg l⁻¹; W: < 2 μg l⁻¹, Au: < 4 μg l⁻¹; W: 24.8 μg l⁻¹, Au: 97 μg l⁻¹.

APPENDIX 1E. Microbiological data for water samples from the Obuasi area.

Locality	Field number	Sample source	Aerobic heterotrophic bacteria (CFU ml ⁻¹)	Total microbes (bacteria x 10 ³ ml ⁻¹)
Odumase	1	7	415	nd
Odumase str'm	2	3	545	30.4
Sibiri stream	3	3	60	nd
Akrofuom	4	8	430	79.2
Okyerekrom	5	8	tntc	nd
Gymi River	6	3	tntc	nd
Brahabehome	7	7	tntc	56.2
Diewieso	8	7	25	nd
Dwete stream	9	3	610	nd
Meduma	10	7	5	68.7
Old Edubiase	11	7	0	nd
Ponkobi	12	7	5	13.3
Patakro	13	7	5	2130
Wioso	14	7	2080	nd
Aketekyiso	15	8	785	78.5
Amamon	16	2	1515	nd
Abedwum	17	8	680	63.2
Ankasa stream	18	3	tntc	nd
Asikasu	19	3	nd	nd
Afoako	20	7	90	42.6
Patase	21	7	70	nd
Sodua	22	3	780	nd
Ankasi	23	7	130	94.5
Bogyawe	24	7	245	nd
Aminase	25	8	tntc	22.3
Amoamo	26	8	3520	nd
Dwondoso	27	8	2500	34.6
Atobiase	28	3	3750	nd
Esereso	29	2	1915	nd
Ahwiaa	30	3	4290	nd
Boni	31	7	20	81.8
Huntado	32	7	50	42.7
Poano	33	7	5	nd
Afransie	34	7	15	nd
Ntinanko	35	7	0	nd
Adjensu stream	36	3	2380	nd
Wumase	37	8	360	47.5
Kofikurom	38	7	35	62.1
Kokoteasua	39	7	5	nd
Dunkwa Nkwenta	40	7	5	nd
Dekyewa	41	7	805	107
Mile Nine	42	7	45	nd
Sabe 2	43	7	25	29.3
Sabe 1	44	7	70	nd
Manfo	45	7	15	nd
Odumto	46	7	0	nd
Mile Eighteen	47	7	75	nd

Appendix 1E cont'd...

Locality	Field number	Sample source	Aerobic heterotrophic bacteria (CFU ml ⁻¹)	Total microbes (bacteria x 10 ³ ml ⁻¹)
Mile Fourteen	48	7	5	nd
Apitiso 1	49	7	5	118
Fenaso	50	3	4720	nd
Kofitanokurom	51	8	3300	nd
Dangase	52	8	tntc	nd
Tweapease	53	7	45	24.7
Suhyenso	54	3	tntc	nd
Obuasi mine bh 1	55	7	155	26.2
Obuasi mine bh 2	56	7	35	nd
Obuasi mine dr'nge	57	13	20	nd
Aboagyekurom	58	3	tntc	nd
Nankawura	59	8	1260	nd
Fiankoma	60	7	tntc	98
Abuakwaa	61	7	30	nd
Kobro	62	7	15	33.5
Denyasefokurom	63	3	tntc	nd
Antoakurom	64	7	80	18.1
Antoakurom 3	65	7	65	nd
Nsiana	66	7	25	54.8
Manso Akropon	67	7	15	nd
Abodom	68	7	65	28.3
Brofoyeduru	69	3	tntc	nd
Mim 3	70	7	45	nd
Mim 1	71	7	15	nd
Nkamprom	72	7	435	8.03
Kwabrafo strm-up	73	3	tntc	nd
Tailings effluent	74		560	nd
Kwabrafo strm-d'n	75	3	1840	30.7
Abompekrom	76	7	40	nd
Abompekrom	77	7	140	nd
Obuasi mine bh 3	78	7	270	130
Asaman	79	7	50	nd
Yawkurom 1	80	7	6	38.0
Manso Atwere	81	7	1	18.2
Manso Atwere h'se	82	7	1	nd
Suntreso	83	3	tntc	nd
Agroyesum hosp'l	84	7	1	31.4
Odahu	85	7	13	nd
Mile Nineteen	86	7	2	nd
Nkyuaso	87	7	0	24.5
Odaso	88	7	8	nd
Kampese	89	3	100	nd
Apanapron	90	7	3	62
Ankam 1	91	7	7	27.9
Odumase	92	3	tntc	nd
Adubea	93	8	tntc	nd
Kwameduakurom	94	2	41	24.8

Appendix 1E cont'd...

Locality	Field number	Sample source	Aerobic heterotrophic bacteria (CFU ml ⁻¹)	Total microbes (bacteria x 10 ³ ml ⁻¹)
Kaw River	95	3	tntc	nd
Gyeboum stream	96	3	tntc	nd
Nyamso	97	7	0	48.1
Mensakurom	98	8	tntc	nd
Adansi	99	3	tntc	nd
Dadwen	100	3	tntc	nd

Sample source: 2: spring, 3: stream (includes dugouts), 7: borehole, 8: shallow well, 13: mine drainage.

tntc: too numerous to count.

nd: not determined.

APPENDIX 2A. Sample details and major-element data for water samples from the Bolgatanga area.

Locality	N°	Smp s'rice	Lat (10°N)	Long (0°W)	screen top	screen bottom	Temp °C	pH	Eh mV	DO mg l ⁻¹	SEC μS cm ⁻¹	Ca mg l ⁻¹	Mg mg l ⁻¹	Na mg l ⁻¹	K mg l ⁻¹	HCO ₃ mg l ⁻¹	SO ₄ mg l ⁻¹	Cl mg l ⁻¹	NO ₃ -N mg l ⁻¹	NO ₂ -N mg l ⁻¹	NH ₄ -N mg l ⁻¹	Si mg l ⁻¹	DOC mg l ⁻¹
Gowrie	1	7	51.64	50.52	13.7	38.1	31.1	6.70	241	3.6	366	29.51	13.23	23.7	1.67	190	2.96	3.73	3.41	<0.03	<0.02	31.86	2.31
Yorogu Abagabisi	2	7	50.83	49.49	23.1	29.3	29.2	6.78	252	0.1	257	18.75	8.47	16.0	2.29	116	1.02	3.15	4.00	<0.03	<0.02	33.79	
Yorogu Abagabisi	3	7	52.04	48.95	20.1	26.2	31.2	6.63	267	1.2	336	27.60	13.66	18.8	1.56	146	1.65	5.89	4.92	<0.03	<0.02	34.44	6.19
Yorogo Atiabisi	4	8	50.39	49.76		7.34	29.4	6.01			124	4.92	1.54	7.8	7.74	14.9	3.12	10.8	4.86	<0.03	<0.02	11.37	
Sekoti	5	7	48.37	37.87	21.9	29.3	31.1	6.88	241	0.6	356	35.33	6.96	22.4	1.64	160	5.18	4.19	6.10	<0.03	<0.02	36.46	3.78
Bolga Daporitindongo	6	8	47.33	50.95		6.78	29.5	6.79			409	29.45	8.46	34.8	14.12	70.7	22.9	38.2	18.1	0.04	0.08	14.86	5.45
Bukere	7	8	47.60	50.86		8.12	29.7	6.61			431	34.89	7.79	24.0	8.01	67.7	15.5	35.3	16.8	0.03	0.04	13.24	
Bolga Soe	8	7	48.79	50.63	15.3	23.1	29.3	6.57	271	0.5	269	19.28	8.78	18.2	1.91	96.3	6.19	12.2	5.60	0.05	<0.02	33.41	1.65
Yorogu	9	7	50.13	49.84	0.0	22.2	30.6	7.18	253	1.9	391	14.91	19.91	33.5	2.12	226	1.50	4.0	2.48	<0.03	<0.02	16.42	
Bongo Sabo	10	8	52.52	48.99		6.47	29.1	6.47			141	20.62	2.15	7.8	1.54	81.7	1.67	<2.0	0.06	<0.03	<0.02	25.86	
Bongo Nabisi	11	7	53.55	48.80	11.2	17.4	30.9	6.70	263	1.3	343	18.26	11.11	19.3	1.12	114	2.91	4.92	7.09	0.03	<0.02	32.71	<1.0
Bongo Anabisi	12	7	54.38	48.30	15.8	31.1	30.3	6.58	285	3.2	432	28.51	18.73	22.7	1.36	135	8.14	16.1	14.1	<0.03	<0.02	33.52	1.63
Bongo Centre	13	7	54.65	48.48	0.0	34.1	30.8	6.59	282	0.9	666	37.29	19.74	20.3	1.74	117	10.0	30.3	19.1	<0.03	<0.02	37.50	
Bongo Anafobisi	14	7	54.78	47.98	17.3	23.1	29.0	6.95	261	2.0	390	23.33	10.62	15.9	1.72	136	5.93	3.15	2.73	0.12	<0.02	28.68	
Borogo	15	7	54.11	47.28	17.4	23.1	30.6	6.66	281	3.8	385	18.61	9.83	17.0	1.72	102	3.15	8.52	6.14	<0.03	<0.02	29.56	4.93
Yichene	16	7	52.83	47.57	11.0	17.1	30.3	6.45	280	2.0	315	15.19	8.25	17.3	1.21	109	2.36	3.38	2.78	<0.03	<0.02	29.15	
Yorogo Abagabisi	17	7	51.94	48.44	21.3	29.0	31.2	6.83	274	1.2	424	32.90	20.48	22.6	1.28	220	1.13	5.23	4.92	0.04	<0.02	32.59	9.88
Yorogo Abagabisi	18	7	51.35	48.94	29.3	35.4	31.2	6.78	163	<0.1	633	33.11	17.18	27.1	3.07	258	4.28	<2.0	0.48	0.04	<0.02	27.83	
Amenteyoko	19	7	55.05	46.99	14.6	20.4	31.4	7.01	155	1.5	1160	31.74	19.48	108	1.71	452	6.50	6.58	4.29	<0.03	<0.02	25.34	3.36
Apatanga	20	7	55.02	45.60	23.1	29.3	31.3	6.65	162	<0.1	660	34.81	20.24	36.1	3.04	299	1.01	<2.0	0.31	<0.03	<0.02	24.64	
Adaboya	21	7	53.87	44.00	17.1	23.1	30.1	6.55	237	0.1	661	38.90	13.84	30.7	2.54	259	2.23	2.29	2.91	<0.03	<0.02	28.36	5.91
Sapero	22	7	52.52	43.85	20.1	29.3	30.5	6.71	262	2.7	726	40.41	12.90	37.1	2.72	264	1.96	6.48	3.59	<0.03	<0.02	32.48	
Beo	23	7	51.73	44.75	13.8	19.9	31.1	6.35	257	2.3	531	28.57	7.02	26.1	1.56	145	1.62	12.3	6.23	<0.03	<0.02	35.70	1.53
Kumbosigo	24	7	51.59	43.79	1.6	22.9	31.0	6.55	254	3.4	448	26.97	6.78	19.8	1.92	164	0.70	2.01	1.20	<0.03	<0.02	27.63	
Kumbosigo Angl'n Sch	25	7	47.63	48.47	21.0	23.5	31.3	6.88	225	1.3	502	58.15	11.03	38.8	4.23	288	5.07	9.77	6.08	<0.03	<0.02	28.93	1.19
Kumbosigo	26	7	48.10	48.73	22.9	29.0	31.1	6.67	223	0.1	454	50.80	10.87	25.4	2.28	257	2.11	4.62	3.70	<0.03	<0.02	31.43	
Kumbosigo	27	7	47.59	49.20	28.6	34.7	30.8	6.87			543	51.01	10.78	26.5	2.42	247	3.86	6.38	4.70	<0.03	<0.02	32.33	2.24
Zuarungu Katanga	28	7	49.10	47.68	22.9	29.0	30.7	6.59		2.5	625	42.64	11.46	21.8	2.59	200	2.67	6.05	5.60	<0.03	<0.02	26.44	
Zuarungu	29	7	47.94	47.17	16.2	19.2	31.0	6.72	172	<0.1	715	41.89	11.99	27.0	3.93	216	7.83	12.2	3.86	0.12	<0.02	23.73	4.32
Zuarungu Benkote	30	7	48.27	46.65	21.0	27.4	30.8	6.72	190	0.1	623	43.21	9.73	19.6	2.82	208	2.75	4.82	4.00	<0.03	<0.02	28.26	
Asonge	31	7	48.89	45.13	17.1	23.1	31.4	6.81	209	0.1	530	32.43	14.38	11.4	0.68	191	1.19	<2.0	1.56	<0.03	<0.02	29.07	1.06
Asonge	32	8	48.65	45.72		8.70	30.4	7.22			306	15.03	3.41	12.4	3.30	70.7	2.42	6.51	3.12	<0.03	<0.02	23.62	
Zuarungu Moshie	33	7	50.54	44.55	24.0	29.9	30.2	6.70	263	0.8	630	38.12	9.49	20.5	3.26	201	1.61	2.43	3.50	<0.03	<0.02	27.66	1.74
Kongo	34	7	51.12	43.2	16.6	22.7	31.2	6.67	224	0.4	928	47.41	23.32	32.0	2.02	338	0.29	<2.0	0.20	<0.03	<0.02	24.30	
Kongo	35	7	50.47	41.95	8.7	14.9	30.9	7.03	254	0.7	517	29.09	12.60	9.6	0.26	164	2.43	3.0	1.34	<0.03	<0.02	25.61	2.78

Appendix 2A cont'd...

Locality	N°	Smp s'rice	Lat (10°N)	Long (0°W)	screen top	screen bottom	Temp °C	pH	Eh mV	DO mg l ⁻¹	SEC µS cm ⁻¹	Ca mg l ⁻¹	Mg mg l ⁻¹	Na mg l ⁻¹	K mg l ⁻¹	HCO ₃ mg l ⁻¹	SO ₄ mg l ⁻¹	Cl mg l ⁻¹	NO ₃ -N mg l ⁻¹	NO ₂ -N mg l ⁻¹	NH ₄ -N mg l ⁻¹	Si mg l ⁻¹	DOC mg l ⁻¹
Zoa	36	7	51.16	41.27	9.4	14.0	30.9	6.89	275	<0.1	654	38.17	16.81	11.3	0.33	218	1.05	<2.0	1.66	<0.03	<0.02	28.35	
Nangodi Yakoti	37	7	50.40	40.72	17.1	23.3	30.7	6.90	290	0.4	948	44.49	19.56	37.6	0.44	332	0.83	2.56	0.22	<0.03	<0.02	21.34	<1.0
Damulugu	38	7	48.69	41.68	14.6	20.8	30.8	6.50	299	0.3	464	19.03	11.11	21.2	0.23	155	3.23	3.13	1.71	<0.03	<0.02	29.11	
Pelungu	39	7	47.87	41.60		35.9	30.7	6.82	356	1.9	708	32.66	14.14	26.5	0.34	210	7.86	8.47	3.52	<0.03	<0.02	27.05	1.01
Zanlerigu	40	7	48.15	43.54	9.8	17.4	31.0	6.88	275	0.9	692	37.60	17.62	14.6	0.19	252	3.68	3.38	<0.10	<0.03	<0.02	16.78	
Daliga Zanlerigu	41	7	48.32	44.19	12.2	18.3	31.7	6.76	323	1.3	792	34.63	15.71	25.7	0.32	240	1.93	9.36	3.11	<0.03	<0.02	26.48	1.03
Nangodi Nakpaligo	42	7	50.69	39.76	17.1	23.1	30.4	6.98	176	<0.1	861	45.53	16.08	30.1	0.14	313	2.21	4.26	0.22	<0.03	<0.02	17.98	<1.0
Nangodi	43	7	51.10	40.24	27.4	32.3	30.9	7.07	200	1.0	878	42.44	18.05	27.7	0.23	301	1.26	7.54	0.08	<0.03	<0.02	19.86	
Nangodi Clinic	44	7	51.72	39.72	29.3	35.4	30.9	7.16	267	1.0	921	40.96	28.30	29.4	0.29	336	5.26	4.30	0.98	<0.03	<0.02	16.14	2.79
Nangodi Nyobota	45	7	49.55	38.16	21.9	28.1	30.5	7.02	256	0.8	886	34.75	26.63	21.3	6.58	316	0.82	2.08	0.32	<0.03	<0.02	31.30	
Sekoti Kotentabiga	46	7	49.25	39.20	23.1	29.3	31.4	6.57	261	0.9	644	32.32	9.72	23.8	0.34	227	1.08	<2.0	0.06	<0.03	<0.02	29.44	1.42
Sekoti Kotendabiga	47	7	48.81	39.16	23.1	29.3	31.2	6.99	257	0.7	771	43.12	16.69	18.6	0.22	288	0.42	<2.0	0.39	<0.03	<0.02	27.61	
Sekoti	48	7	48.00	37.23	12.5	18.6	30.0	7.11	265	4.1	546	35.21	6.54	17.1	1.02	160	8.94	3.72	1.58	<0.03	<0.02	24.87	1.88
Sekoti Clinic	49	7	47.51	38.03	23.8	32.9	30.8	6.65	258	0.9	663	42.42	7.36	23.0	1.63	215	6.08	<2.0	1.32	<0.03	<0.02	37.24	
Sekoti	50	7	46.48	37.79	21.7	27.7	30.1	6.82	258	0.4	624	34.83	8.28	22.8	1.36	178	2.45	<2.0	2.11	<0.03	0.08	32.49	<1.0
Nyua	51	7	45.71	37.22	17.6	23.5	30.9	6.74	306	0.9	661	36.33	10.44	24.2	0.82	222	0.72	<2.0	0.21	<0.03	0.05	34.28	
Nyua	52	8	45.44	38.25		2.60	29.3	7.32			590	34.35	7.21	21.5	1.48	191	3.59	<2.0	0.60	<0.03	0.02	32.18	
Datoko Kulpeliga	53	7	45.06	38.31	28.6	34.7	30.8	6.69	330	2.8	555	32.11	5.50	19.1	0.92	156	1.79	<4.0	3.80	<0.03	0.04	36.31	4.51
Datoko Kulpeliga	54	7	44.27	38.33	15.8	18.9	31.0	6.69	331	3.1	520	32.23	4.05	17.1	0.98	138	4.15	<4.0	3.77	<0.03	0.04	30.45	
Datoko	55	7	42.86	38.91	17.6	20.8	30.6	7.25	314	<0.1	942	53.21	22.43	31.2	1.14	332	3.69	5.61	2.60	<0.06	<0.02	20.25	3.09
Shiega	56	7	43.56	43.29	0.0	18.6	30.7	6.85	287	0.5	575	32.41	13.02	9.0	<0.04	118	8.47	13.7	7.32	<0.03	0.02	25.41	
Shiega Tindongo	57	7	44.34	42.86	8.5	14.6	31.1	7.04	280	0.7	453	27.05	9.73	8.9	<0.03	142	2.26	3.62	0.70	<0.03	<0.02	28.55	1.02
Nangodi Takoti	58	7	49.88	41.03	12.2	14.4	31.5	6.82	173	0.3	929	41.43	17.01	40.2	0.20	332	1.48	<2.0	<0.02	<0.03	<0.02	25.58	2.44
Pelungu	59	7	46.65	41.47	29.3	35.4	31.1	6.77	290	2.6	598	22.46	11.56	22.4	0.28	143	4.67	6.33	5.22	<0.03	0.07	36.50	
Dusi	60	7	46.75	41.60	17.2	23.3	31.0	6.64	299	2.4	517	22.73	12.18	14.5	0.35	154	2.57	4.29	2.91	<0.03	0.03	30.54	<1.0
Dusi Gari	61	7	45.28	42.14	8.2	14.4	30.2	7.07	280	0.6	675	44.15	14.80	10.4	0.02	140	6.60	2.86	1.03	<0.03	<0.02	25.81	
Gari	62	7	45.45	42.50	7.3	9.8	30.0	7.08	299	0.7	614	38.87	9.32	10.0	0.11	181	1.98	5.98	0.93	<0.03	<0.02	20.50	<1.0
Shiega Tindongo	63	7	44.53	43.44	7.3	10.3	30.2	6.95	313	0.8	814	51.99	16.66	11.2	0.14	200	11.6	13.7	7.97	<0.03	<0.02	24.28	
Yameriga	64	7	42.77	46.05	14.6	20.8	30.5	6.93	287	0.1	677	45.78	14.31	9.8	0.13	226	1.70	3.20	1.76	<0.03	<0.02	19.26	1.52
Gbanbiega	65	7	42.64	47.26	8.0	11.0	31.0	6.78	201	0.2	728	44.23	15.57	11.8	0.69	226	7.03	6.39	1.60	<0.03	<0.02	30.37	
Tongo	66	7	42.52	47.93	10.3	16.5	31.4	6.51	253	2.8	568	21.13	10.72	15.3	1.98	116	6.24	14.8	6.82	<0.03	<0.02	31.51	<1.0
Zuarungu	67	7	47.21	47.17			30.5	6.58	202	0.4	335	32.45	10.97	18.4	3.02	179	3.47	3.40	3.50	<0.03	<0.02	30.74	1.89
Zuarungu Zono	68	7	47.16	46.50	16.7	22.9	31.0	6.69	257	1.0	295	29.30	8.36	17.5	2.57	165	2.11	3.20	2.80	<0.03	<0.02	25.49	
Yazore Sakwati	69	7	45.97	45.67	12.8	15.8	31.7	6.74	240	1.5	379	37.99	18.80	12.0	0.58	241	1.71	<2.0	1.43	<0.03	<0.02	26.29	<1.0
Yazore Kpatia	70	7	45.79	44.70	24.0	30.2	30.7	6.95	196	0.3	662	71.05	27.91	43.4	0.57	451	5.70	<2.0	0.05	<0.03	<0.02	23.25	

Appendix 2A cont'd...

Locality	N°	Smp s'rice	Lat (10°N)	Long (0°W)	screen top	screen bottom	Temp °C	pH	Eh mV	DO mg l ⁻¹	SEC μS cm ⁻¹	Ca mg l ⁻¹	Mg mg l ⁻¹	Na mg l ⁻¹	K mg l ⁻¹	HCO ₃ mg l ⁻¹	SO ₄ mg l ⁻¹	Cl mg l ⁻¹	NO ₃ -N mg l ⁻¹	NO ₂ -N mg l ⁻¹	NH ₄ -N mg l ⁻¹	Si mg l ⁻¹	DOC mg l ⁻¹
Zuarungu Kangoo	71	7	47.84	46.46	19.8	25.6	30.2	6.17	269	3.3	209	13.97	3.04	14.7	1.59	87.1	<4.00	<4.0	3.73	<0.03	<0.02	31.22	<1.0
Dulugu	72	7	46.60	49.14	16.5	22.6	31.1	6.58	292	0.3	408	30.99	10.49	23.7	1.87	199	2.51	3.96	1.42	<0.03	<0.02	26.91	
Dulugu	73	7	45.36	49.41	19.2	25.3	31.2	6.52	294	1.7	348	30.86	8.26	25.2	2.70	200	1.27	<2.0	1.43	<0.03	0.03	31.63	1.03
Gambibigo	74	7	46.07	50.11	17.6	26.8	30.7	6.79	306	0.8	441	47.95	9.70	23.3	1.79	218	2.24	<8.0	4.20	<0.03	0.02	25.18	
Gambibigo	75	7	45.24	50.65	28.1	34.1	30.0	6.53	285	4.3	286	24.61	5.35	24.5	1.57	158	2.59	<8.0	3.98	<0.03	<0.02	32.39	1.86
Gambibigo	76	7	45.02	50.90	16.7	22.9	30.7	6.52	267	3.0	321	28.97	8.66	25.2	0.69	155	3.76	<8.0	5.11	<0.03	<0.02	34.84	
Dulugu	77	7	47.23	48.85	31.7	34.7	31.2	6.70	212	0.2	476	49.19	16.42	24.0	3.38	277	4.91	6.14	3.48	<0.03	<0.02	26.40	1.72
Tongobeo	78	7	46.67	48.10	19.8	22.9	30.2	6.70	266	1.8	357	27.30	8.33	29.4	3.56	156	12.9	9.83	4.50	<0.03	<0.02	25.59	
Zuarungu	79	7	46.19	47.39	14.6	20.8	30.3	6.72	288	3.4	323	29.64	8.81	22.4	2.60	164	2.28	<8.0	3.68	<0.03	<0.02	28.37	2.04
Beo	80	7	45.84	48.04	17.4	23.5	30.7	6.85	225	0.6	355	30.47	13.93	21.0	2.09	194	9.97	<4.0	2.44	<0.03	<0.02	28.66	
Beo	81	7	45.37	47.68	12.5	18.6	30.7	6.80	215	1.4	386	26.11	11.33	19.2	1.82	181	1.03	3.27	0.94	<0.03	<0.02	24.63	1.31
Baare	82	7	44.41	47.75	21.6	28.1	30.0	6.73	289	0.8	371	24.94	8.47	23.1	3.16	177	1.78	<2.0	1.91	<0.03	<0.02	24.95	
Baare Tongo	83	7	44.09	48.27			30.4	6.92	250	1.1	403	30.65	7.86	20.7	3.68	163	2.32	8.84	3.59	0.04	<0.02	23.46	3.02
Baare	84	7	44.24	49.89	31.1	34.1	31.2	6.83	236	<0.1	341	34.00	15.08	17.3	3.04	227	1.46	<2.0	0.74	<0.03	<0.02	24.23	
Tongo Local Council	85	7	43.21	47.61	11.9	18.0	30.5	6.86	288	1.2	464	41.74	20.97	13.0	2.12	226	5.20	14.8	6.66	<0.03	0.06	25.78	<1.0
Tongo	86	7	42.94	48.41	14.4	17.4	30.5	6.47	270	1.1	264	18.24	8.41	15.6	2.70	105	3.66	6.64	6.60	<0.03	<0.02	34.18	
Gorogu	87	7	42.36	49.86	13.7	19.8	30.1	6.96	249	1.3	341	25.00	12.97	25.3	2.67	179	3.80	10.9	3.61	0.04	<0.02	28.03	<1.0
Winkogo Alabisi	88	7	43.10	50.93	18.9	25.0	30.3	6.55	298	1.9	394	21.33	6.34	27.8	2.67	163	0.75	<2.0	1.47	<0.03	<0.02	35.27	
Winkogo	89	7	43.14	51.94	26.2	55.8	31.2	6.56	325	2.7	475	29.90	8.92	26.4	2.50	163	3.64	5.67	5.62	<0.03	<0.02	36.32	3.24
Awaradoni	90	7	42.63	52.18	17.1	22.9	31.5	6.54	234	1.2	437	26.78	7.24	24.3	1.48	178	0.98	2.21	2.76	0.09	<0.02	38.76	
Abokrebisi	91	7	44.03	50.84	19.5	26.2	30.9	6.75	302	2.4	422	26.52	6.23	25.5	2.72	168	1.84	<2.0	3.61	<0.03	<0.02	30.40	1.35
Abokrebisi	92	7	43.68	52.02	35.4	41.4	31.2	6.53	311	1.1	537	35.49	7.95	30.5	2.66	215	2.92	3.41	3.89	<0.03	<0.02	33.30	
Gambibigo	93	7	44.92	51.69	22.9	29.0	31.1	6.42	297	0.1	282	13.69	3.21	23.9	1.38	118	0.59	<2.0	0.58	<0.03	<0.02	38.71	<1.0
Tindonmolugu	94	7	45.69	51.58	25.6	28.6	30.7	6.54	274	0.2	416	23.33	8.72	21.7	1.01	169	1.48	5.81	2.16	<0.03	<0.02	34.54	
Bolgatanga	95	7	46.37	51.41	21.7	34.1	30.9	6.55	362	3.4	482	39.75	9.62	30.4	13.17	188	22.9	30.5	1.40	0.09	<0.02	11.95	1.44
Tindonmolugu	96	7	46.80	52.32	16.5	22.6	31.2	6.69	241	1.6	263	17.53	10.10	17.2	1.21	134	2.55	7.90	1.99	<0.03	<0.02	25.50	
Sokabisi	97	7	47.39	52.91	21.7	27.7	31.2	6.08	369	5.2	153	8.39	4.74	12.7	2.64	57.9	0.30	3.55	5.53	<0.03	<0.02	34.85	1.59
Tanzui Sokabisi	98	7	47.66	52.29	14.9	21.0	30.7	6.37	308	3.2	224	13.82	7.15	16.7	1.57	61	1.40	13.4	8.34	<0.03	<0.02	38.93	
Yikene	99	7	48.26	52.65	23.1	29.3	30.9	6.65	353	3.2	224	14.71	7.72	14.5	1.99	101	0.91	2.44	3.43	0.03	<0.02	36.88	2.91
Sokabisi	100	7	48.11	52.26	15.5	21.7	31.1	6.43	331	3.5	519	23.52	11.89	19.8	2.22	102	10.9	19.9	7.79	<0.03	<0.02	36.85	
Zaare	101	7	49.40	52.24	18.0	24.0	30.9	6.82	359	2.8	469	21.34	10.60	18.1	1.72	132	12.2	3.64	3.09	0.05	<0.02	35.69	<1.0
Gowrie	102	8	51.07	50.38		6.77	29.5	7.35			233	18.93	1.67	6.3	1.40	68.3	1.51	<2.0	3.55	<0.03	<0.02	19.47	
Gowrie	103	7	50.72	50.81	22.2	28.3	31.4	6.30	292	4.9	307	12.67	3.90	18.8	2.39	108	1.32	<2.0	1.55	<0.03	<0.02	40.71	2.50
Vea-Gunga	104	7	52.72	52.44	15.5	21.9	30.3	6.60	242	4.7	360	11.23	6.65	24.5	0.93	113	0.90	2.27	2.82	0.03	<0.02	36.01	
Vea-Akugrebisi	105	7	52.74	51.57	17.4	23.5	30.2	6.72	213	0.4	500	22.24	12.45	22.0	1.57	178	2.87	2.19	1.61	0.05	<0.02	29.01	<1.0

Appendix 2A cont'd...

Locality	N°	Smp s'rice	Lat (10°N)	Long (0°W)	screen top	screen bottom	Temp °C	pH	Eh mV	DO mg l ⁻¹	SEC µS cm ⁻¹	Ca mg l ⁻¹	Mg mg l ⁻¹	Na mg l ⁻¹	K mg l ⁻¹	HCO ₃ mg l ⁻¹	SO ₄ mg l ⁻¹	Cl mg l ⁻¹	NO ₃ -N mg l ⁻¹	NO ₂ -N mg l ⁻¹	NH ₄ -N mg l ⁻¹	Si mg l ⁻¹	DOC mg l ⁻¹
Bongo Kunkoa	106	7	52.65	49.90	15.5	21.7	30.5	6.51	280	1.2	405	21.23	8.40	16.7	1.45	106	8.33	2.63	3.59	1.16	<0.02	34.93	
Bongo Kupelingo	107	7	54.28	49.02	17.1	29.3	30.2	6.68	285	2.6	484	20.27	8.14	22.6	1.03	92.7	3.35	14.2	8.22	<0.03	<0.02	35.47	1.91
Dua	108	7	53.39	47.03	15.5	20.1	30.1	6.64	195	<0.1	1080	70.98	19.38	43.8	3.03	396	13.9	9.67	0.83	0.36	<0.02	23.60	
Dua	109	7	52.94	46.37	15.8	21.9	31.0	6.58	252	2.2	458	20.56	11.76	16.2	1.47	138	2.57	8.90	5.65	<0.03	<0.02	31.08	2.40
Akanaba	110	7	54.45	45.23	16.7	22.9	31.1	6.86	144	1.6	1020	57.40	23.52	43.7	2.43	385	4.05	5.29	1.94	1.05	0.03	24.21	
Zaare Ayoribisi	111	7	49.20	51.75			29.9	6.70	317	2.0	434	20.08	10.19	17.6	1.34	127	3.18	3.23	2.87	<0.03	<0.02	31.12	2.35
Zaare Avombisi	112	7	49.18	51.20	20.8	20.1	31.0	6.36	313	3.3	375	15.91	5.76	21.5	2.92	117	1.12	2.71	8.56	<0.03	<0.02	41.70	
Yorogo Sorobisi	113	7	49.80	51.08	18.9	28.1	30.9	6.47	317	3.8	313	15.32	6.79	20.3	1.70	122	1.25	<2.0	1.61	0.03	<0.02	37.76	1.15
Bolga Soe	114	7	47.97	50.75	22.9	29.0	31.0	6.48	272	3.8	441	17.26	8.82	20.8	2.21	87.8	1.71	15.0	7.75	0.1	<0.02	36.67	
Bolga Soe	115	7	47.75	50.41	15.8	20.4	31.2	7.11	196	1.3	1010	40.40	29.20	46.8	1.88	313	8.99	25.9	6.33	<0.03	<0.02	18.52	<1.0
Yorogo	116	7	49.30	49.79	7.6	13.7	30.1	6.74	200	0.2	571	26.58	14.85	23.1	1.43	191	2.36	6.82	2.62	11.6	<0.02	29.25	
Yorogo	117	7	50.20	48.93	17.1	14.0	30.5	6.73	220	<0.1	663	35.61	15.87	27.9	2.31	237	2.73	7.72	1.23	0.08	<0.02	28.69	
Yorogo Abangabisi	118	7	50.78	48.87	13.7	20.1	31.0	6.58	239	0.2	590	32.44	14.65	22.3	2.30	227	0.83	<2.0	0.07	<0.03	<0.02	30.17	

Sample sources: 7 = borehole, 8 = dug well. In the case of dug wells, 'screen bottom' is the total well depth (m).
DO: dissolved oxygen; SEC: specific electrical conductance (corrected to 25°C); DOC: dissolved organic carbon, analysed by BGS, Keyworth.

APPENDIX 2B. Trace-element data for water samples from the Bolgatanga area. All cations are analysed by ICP-AES, anions by colorimetry.

Locality	N°	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn µg l ⁻¹	Li µg l ⁻¹	B µg l ⁻¹	Be µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Ba µg l ⁻¹	Br µg l ⁻¹	I µg l ⁻¹	F mg l ⁻¹	As _{total} µg l ⁻¹
Gowrie	1	<0.02	<0.1	0.044	1.1	17	18	<0.2	<4	143	957	225	33	4.2	3.1	<0.4
Yorogu Abagabisi	2	0.03	0.1	0.260	5.4	2	11	0.6	12	110	668	220	26	2.9	3.2	<0.4
Yorogu Agagabisi	3	0.03	0.2	0.374	7.4	16	8	1.0	<4	96	905	215	37	2.8	3.6	<0.4
Yorogu Atiabisi	4	1.68	<0.1	0.456	6.0	1	10	0.3	<4	15	263	504	20	1.3	0.09	<0.4
Sekoti	5	0.02	<0.1	0.266	2.9	30	8	<0.2	<4	25	608	97	27	2.8	1.6	<0.4
Bolga Daporitindongo	6	<0.02	0.1	0.015	11.7	<1	11	<0.2	<4	17	918	388	52	2.5	0.61	<0.4
Bukere	7	<0.02	0.1	<0.003	11.3	<1	<6	<0.2	<4	37	1120	585	40	2.0	0.3	<0.4
Bolga Soe	8	<0.02	0.1	0.026	1.1	14	10	0.3	<4	12	602	131	41	3.3	3.6	<0.4
Yorogu	9	<0.02	<0.1	<0.003	1.5	44	14	<0.2	<4	5	564	118	24	5.6	2	2
Bongo Sabo	10	7.27	<0.1	2.51	6.3	3	7	0.5	<4	12	333	100	11	<1.0	0.37	<0.4
Bongo Nabisi	11	<0.02	<0.1	0.314	5.1	24	8	0.7	8	55	485	68	27	3.1	3.8	<0.4
Bongo Anabisi	12	<0.02	<0.1	0.071	1.4	34	26	0.7	6	94	645	103	41	3.1	3.5	<0.4
Bongo Centre	13	<0.02	<0.1	<0.003	<0.6	30	9	0.9	<4	7	1080	212	50	3.2	2.8	<0.4
Bongo Anafobisi	14	0.03	<0.1	0.430	3.6	15	12	0.4	<4	14	499	112	29	4.8	3.4	<0.4
Borogo	15	<0.02	<0.1	0.100	0.7	16	6	0.2	<4	24	561	149	21	2.5	2.5	<0.4
Yichene	16	<0.02	<0.1	0.091	1.4	10	<6	<0.2	<4	16	365	95	16	3.1	1.7	2
Yorogu Abagabisi	17	<0.02	<0.1	0.165	5.7	11	7	0.4	9	223	776	100	37	3.7	3.8	<0.4
Yorogu Abagabisi	18	<0.02	<0.1	0.438	12.3	29	42	<0.2	<4	115	784	109	17	6.6	1.4	5
Amenteyoko	19	<0.02	<0.1	0.250	4.6	9	<6	0.2	<4	78	221	114	14	4.1	1.1	<0.4
Apatanga	20	<0.02	<0.1	0.621	51	41	11	0.3	<4	26	323	10	8	2.5	0.5	<0.4
Adaboya	21	<0.02	0.1	0.153	1.5	8	<6	<0.2	<4	53	1100	374	21	2.7	0.6	<0.4
Sapero	22	<0.02	0.1	0.089	2.0	7	<6	<0.2	5	227	738	99	20	6.3	0.5	<0.4
Beo	23	<0.02	0.2	0.152	1.8	7	<6	<0.2	<4	63	746	19	35	3.9	0.4	<0.4
Kumbosigo	24	<0.02	0.2	0.130	2.2	1	<6	<0.2	<4	116	341	3.5	6	1.5	0.4	<0.4
Kumbosigo Angl'n Sch	25	<0.02	<0.1	0.504	4.1	8	<6	<0.2	19	127	612	8.9	43	8.8	0.7	<0.4
Kumbosigo	26	<0.02	<0.1	0.397	5.2	9	6	<0.2	<4	148	751	43	22	4.2	0.32	<0.4
Kumbosigo	27	<0.02	0.1	0.391	4.0	11	8	<0.2	4	32	846	43	31	4.7	0.41	<0.4
Zuarungu Katanga	28	<0.02	<0.1	0.261	3.3	5	<6	<0.2	<4	34	862	31	28	2.9	0.35	<0.4
Zuarungu	29	0.03	<0.1	0.951	9.5	7	8	0.4	<4	100	523	66	17	8.0	0.55	<0.4
Zuarungu Benkote	30	0.06	0.1	0.441	6.7	9	10	0.6	<4	29	573	36	21	3.8	0.39	<0.4
Asonge	31	0.03	0.1	0.420	4.6	4	10	0.3	<4	9	90	1.3	5	1.2	0.15	<0.4
Asonge	32	0.27	0.3	0.161	55	4	11	<0.2	<4	6	167	46	24	4.0	0.34	<0.4
Zuarungu Moshie	33	0.02	0.1	0.275	7.7	17	11	<0.2	16	339	492	24	20	2.9	0.36	<0.4
Kongo	34	0.04	0.1	0.808	10.8	16	12	0.5	<4	218	317	5.8	75	2.7	0.31	<0.4
Kongo	35	0.04	<0.1	0.158	118	1	64	0.3	<4	23	34.1	0.9	8	1.7	0.17	4
Zoa	36	<0.02	<0.1	0.134	122	2	130	<0.2	<4	27	48.7	<0.6	5	1.1	0.15	29

Appendix 2B cont'd...

Locality	N°	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn µg l ⁻¹	Li µg l ⁻¹	B µg l ⁻¹	Be µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Ba µg l ⁻¹	Br µg l ⁻¹	I µg l ⁻¹	F mg l ⁻¹	As _{total} µg l ⁻¹
Nangodi Yakoti	37	<0.02	<0.1	0.133	11.4	5	70	<0.2	<4	10	177	0.8	8	9.4	0.41	2
Damulugu	38	<0.02	0.1	0.368	7.4	6	21	<0.2	<4	21	167	9.2	9	3.6	0.44	<0.4
Pelungu	39	0.02	0.1	0.003	1.4	3	55	<0.2	<4	8	318	52	16	3.7	0.47	<0.4
Zanlerigu	40	<0.02	<0.1	0.212	41	9	34	<0.2	<4	31	179	1.0	10	3.3	0.22	<0.4
Daliga Zanlerigu	41	<0.02	<0.1	0.257	17.8	4	<6	<0.2	<4	20	158	<0.6	12	2.8	0.41	<0.4
Nangodi Nakpaligo	42	<0.02	0.1	0.181	11.5	4	<6	<0.2	<4	37	993	<0.6	7	2.6	0.4	2
Nangodi	43	<0.02	<0.1	0.115	30	1	17	<0.2	<4	16	272	3.8	6	3.4	0.15	5
Nangodi Clinic	44	<0.02	<0.1	<0.003	4.5	1	24	<0.2	<4	7	358	8.9	8	1.8	0.2	141
Nangodi Nyobota	45	<0.02	<0.1	0.231	12.6	12	<6	<0.2	<4	87	262	141	10	2.1	0.64	2
Sekoti Kotentabiga	46	<0.02	<0.1	1.01	16.9	11	8	<0.2	<4	30	201	11	7	3.3	0.44	<0.4
Sekoti Kotendabiga	47	<0.02	<0.1	0.098	2.4	4	20	<0.2	<4	10	189	<0.6	5	1.7	0.14	5
Sekoti	48	<0.02	<0.1	0.070	8.2	27	6	<0.2	<4	285	855	64	19	2.1	3.2	<0.4
Sekoti Clinic	49	<0.02	<0.1	<0.003	<0.6	21	<6	<0.2	<4	12	938	124	16	2.3	1.02	<0.4
Sekoti	50	<0.02	<0.1	0.089	0.9	23	<6	<0.2	<4	52	659	63	23	2.8	1.5	<0.4
Nyua	51	<0.02	<0.1	0.180	1.7	10	<6	<0.2	7	34	614	49	10	2.9	0.86	<0.4
Nyua	52	<0.02	<0.1	0.019	10.0	20	<6	<0.2	<4	<4	718	86	13	1.7	1.3	<0.4
Datoko Kulpeliga	53	<0.02	<0.1	0.038	<0.6	3	<6	<0.2	13	95	697	207	26	2.6	1.08	<0.4
Datoko Kulpeliga	54	<0.02	<0.1	0.084	<0.6	10	<6	<0.2	<4	65	817	110	25	3.0	1.9	<0.4
Datoko	55	<0.02	<0.1	0.064	79.7	<1	<6	<0.2	<4	18	365	22	36	8.3	0.43	<0.4
Shiega	56	<0.02	<0.1	<0.003	5.4	<1	7	<0.2	<4	<4	54.7	<0.6	24	0.6	0.14	7
Shiega Tindongo	57	<0.02	<0.1	0.520	191	<1	<6	<0.2	<4	23	35.1	<0.6	9	1.0	0.17	<0.4
Nangodi Takoti	58	<0.02	<0.1	0.403	18.3	3	86	<0.2	<4	15	192	13	10	9.7	0.63	<0.4
Pelungu	59	<0.02	0.2	0.043	2.1	4	14	<0.2	17	43	323	20	28	4.8	0.75	<0.4
Dusi	60	<0.02	0.1	0.181	2.1	2	21	<0.2	<4	39	135	1.0	9	1.7	0.54	<0.4
Dusi Gari	61	<0.02	<0.1	0.107	406	<1	<6	<0.2	<4	4	98.2	<0.6	11	1.4	0.2	<0.4
Gari	62	<0.02	<0.1	0.072	60	<1	67	<0.2	<4	48	49.9	<0.6	9	3.0	0.18	<0.4
Shiega Tindongo	63	<0.02	<0.1	0.099	51	<1	25	<0.2	<4	11	74.2	<0.6	16	<0.6	0.19	2
Yameriga	64	<0.02	<0.1	0.245	87	<1	<6	<0.2	<4	30	130	<0.6	5	0.8	0.18	7
Gbanbiega	65	<0.02	<0.1	0.216	203	<1	<6	<0.2	<4	11	85.5	10	15	<0.6	0.22	<0.4
Tongo	66	<0.02	<0.1	0.058	1.0	<1	<6	<0.2	<4	104	279	47	24	2.5	0.34	<0.4
Zuarungu	67	<0.02	<0.1	0.316	2.3	<1	<6	<0.2	<4	68	528	58	25	3.0	0.34	<0.4
Zuarungu Zono	68	0.09	0.1	0.142	4.7	12	24	0.7	7	123	392	9.1	17	3.2	0.45	<0.4
Yazore Sakwati	69	0.06	<0.1	0.299	6.7	7	24	0.4	5	104	70.6	2.4	4	<0.6	0.19	<0.4
Yazore Kpatia	70	<0.02	<0.1	0.803	30	13	31	<0.2	<4	39	569	<0.6	11	4.6	0.16	3
Zuarungu Kangoo	71	<0.02	<0.1	0.117	0.8	<1	<6	<0.2	<4	207	223	7.1	15	2.0	0.2	<0.4
Dulugu	72	<0.02	<0.1	0.614	7.2	4	<6	<0.2	<4	103	417	25	21	4.9	0.4	<0.4

Appendix 2B cont'd...

Locality	N°	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn µg l ⁻¹	Li µg l ⁻¹	B µg l ⁻¹	Be µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Ba µg l ⁻¹	Br µg l ⁻¹	I µg l ⁻¹	F mg l ⁻¹	As _{total} µg l ⁻¹
Dulugu	73	<0.02	0.2	0.598	5.7	4	<6	<0.2	<4	290	601	37	17	3.8	0.37	<0.4
Gambibigo	74	<0.02	0.1	0.112	2.5	3	<6	<0.2	<4	365	834	92	35	3.4	0.51	<0.4
Gambibigo	75	<0.02	0.2	0.176	0.8	<1	<6	<0.2	<4	76	621	60	27	3.3	0.41	<0.4
Gambibigo	76	<0.02	0.2	0.070	<0.6	4	<6	<0.2	25	28	727	90	33	2.4	0.44	<0.4
Dulugu	77	<0.02	0.1	0.519	6.6	5	<6	<0.2	<4	342	731	97	59	2.8	0.31	<0.4
Tongobeo	78	<0.02	<0.1	0.227	2.2	1	<6	<0.2	<4	222	332	21	21	6.1	0.56	<0.4
Zuarungu	79	0.03	0.2	0.144	2.8	10	14	<0.2	<4	353	465	28	36	4.8	0.59	<0.4
Beo	80	<0.02	0.1	0.308	4.4	12	12	<0.2	8	21	442	7.7	19	4.9	0.56	<0.4
Beo	81	<0.02	<0.1	0.522	4.9	<1	<6	<0.2	<4	24	268	41	35	1.3	0.59	<0.4
Baare	82	0.05	<0.1	0.011	1.8	13	21	0.5	7	12	257	27	16	4.2	0.61	<0.4
Baare Tongo	83	<0.02	<0.1	0.202	1.9	<1	<6	<0.2	<4	20	313	35	10	2.5	0.46	<0.4
Baare	84	0.03	<0.1	0.113	4.9	12	26	<0.2	4	90	355	117	93	1.5	0.4	<0.4
Tongo Local Council	85	<0.02	<0.1	0.030	0.9	3	<6	<0.2	10	319	290	47	16	2.0	0.23	<0.4
Tongo	86	<0.02	<0.1	0.223	29	16	10	<0.2	<4	15	226	19	25	3.5	0.46	<0.4
Gorogu	87	0.02	<0.1	0.144	3.4	13	13	<0.2	<4	100	436	44	22	3.7	0.69	<0.4
Winkogo Alabisi	88	0.06	0.2	0.407	4.8	12	8	0.4	20	77	504	106	12	2.8	0.4	<0.4
Winkogo	89	<0.02	0.1	<0.003	<0.6	11	<6	0.2	<4	8	707	78	33	4.3	0.37	<0.4
Awaradoni	90	<0.02	<0.1	2.440	14.0	2	<6	<0.2	<4	20	678	95	23	4.1	0.4	<0.4
Abokrebisi	91	0.08	0.1	0.051	3.1	21	18	<0.2	12	295	518	65	39	2.3	0.34	<0.4
Abokrebisi	92	0.04	0.2	0.260	6.4	16	18	<0.2	6	19	994	67	26	2.6	0.38	<0.4
Gambibigo	93	0.06	0.2	0.230	3.9	13	14	<0.2	6	18	409	47	30	3.6	0.3	<0.4
Tindonmolugu	94	<0.02	<0.1	0.611	6.3	10	<6	<0.2	<4	120	380	183	32	11.4	0.44	<0.4
Bolgatanga	95	<0.02	<0.1	<0.003	<0.6	<1	<6	<0.2	<4	<4	1070	340	58	10.1	0.3	<0.4
Tindonmolugu	96	<0.02	<0.1	0.120	1.7	11	7	<0.2	9	24	361	80	13	2.7	1.74	<0.4
Sokabisi	97	<0.02	0.4	0.015	<0.6	2	<6	<0.2	<4	4	239	94	22	3.8	0.8	<0.4
Tanzui Sokabisi	98	0.05	<0.1	0.055	2.7	13	20	0.7	17	88	410	107	27	4.8	3.6	<0.4
Yikene	99	0.12	<0.1	0.011	2.2	18	25	1.0	11	10	401	109	27	4.8	2.8	<0.4
Sokabisi	100	0.08	<0.1	0.117	3.8	18	18	1.1	21	484	686	153	55	4.6	3	<0.4
Zaare	101	<0.02	<0.1	<0.003	<0.6	7	19	<0.2	<4	13	690	64	31	3.7	3.6	<0.4
Gowrie	102	0.1	<0.1	0.036	15.4	14	19	<0.2	7	8	298	136	17	1.7	0.16	<0.4
Gowrie	103	<0.02	0.2	0.158	5.8	12	22	<0.2	15	118	571	197	21	3.5	1.45	<0.4
Vea-Gunga	104	<0.02	<0.1	0.060	0.7	8	<6	<0.2	<4	129	336	88	17	4.2	3.8	<0.4
Vea-Akugrebisi	105	<0.02	<0.1	0.924	6.9	28	6	<0.2	<4	22	807	114	19	2.6	2.2	<0.4
Bongo Kunkoa	106	0.12	<0.1	0.048	3.0	31	30	0.8	13	17	742	100	27	2.2	2.75	<0.4
Bongo Kupelingo	107	<0.02	<0.1	0.049	2.1	15	13	<0.2	<4	158	685	81	30	3.3	3.8	<0.4
Dua	108	<0.02	0.1	0.456	98	24	35	<0.2	<4	52	2490	337	50	61	2.75	<0.4

Appendix 2B cont'd...

Locality	N°	Al mg l ⁻¹	P _{total} mg l ⁻¹	Fe _{total} mg l ⁻¹	Mn µg l ⁻¹	Li µg l ⁻¹	B µg l ⁻¹	Be µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Ba µg l ⁻¹	Br µg l ⁻¹	I µg l ⁻¹	F mg l ⁻¹	As _{total} µg l ⁻¹
Dua	109	<0.02	<0.1	0.248	9.1	7	<6	<0.2	<4	14	236	27	13	1.7	0.2	<0.4
Akanaba	110	<0.02	<0.1	2.06	34	32	<6	<0.2	<4	70	605	122	12	2.4	0.31	<0.4
Zaare Ayoribisi	111	<0.02	<0.1	0.017	<0.6	15	7	0.3	<4	<4	561	55	26	3.0	3.4	<0.4
Zaare Avombisi	112	0.03	0.2	0.014	1.0	7	13	<0.2	<4	6	1130	520	19	3.8	0.93	<0.4
Yorogo Sorobisi	113	<0.02	0.1	0.010	1.0	11	15	0.3	<4	5	682	164	23	3.0	2.25	<0.4
Bolga Soe	114	<0.02	0.1	0.114	0.9	2	<6	<0.2	<4	26	668	175	41	4.0	2.9	<0.4
Bolga Soe	115	<0.02	<0.1	0.133	24	53	61	<0.2	<4	62	857	53	63	80	1.18	<0.4
Yorogo	116	0.04	<0.1	0.605	8.1	14	24	0.4	5	98	477	87	19	4.6	1.65	3
Yorogo	117	<0.02	0.1	0.286	4.4	32	<6	0.3	<4	11	508	79	21	7.1	0.64	<0.4
Yorogo Abangabisi	118	<0.02	<0.1	0.420	5.5	35	<6	<0.2	<4	16	559	206	10	4.6	0.35	<0.4

Detection limits are 3 σ about the blank concentration, except for As_{total} and As(III) values, for which detection limits are given at 6 σ . As(III) concentrations are all below 0.4 $\mu\text{g l}^{-1}$ except Nangodi Clinic (sample 44) which has 4.4 $\mu\text{g l}^{-1}$.

APPENDIX 2C. Trace-element data for water samples from the Bolgatanga area, analysed by ICP-MS.

Locality	Li µg l ⁻¹	Be µg l ⁻¹	B µg l ⁻¹	Al µg l ⁻¹	Cr µg l ⁻¹	Co µg l ⁻¹	Ni µg l ⁻¹	Cu µg l ⁻¹	Zn µg l ⁻¹	Sr µg l ⁻¹	Y µg l ⁻¹	Mo µg l ⁻¹	As µg l ⁻¹	Cd µg l ⁻¹	Ba µg l ⁻¹	Pb µg l ⁻¹	Ge µg l ⁻¹
Gowrie	19	0.07	17.24	<4	<0.3	<0.07	4.0	<0.9	137	1031	<0.02	2.3	<1	<0.09	236	<0.3	<0.4
Yorogu Abagabisi	2.1	0.28	6.65	<4	0.6	<0.07	3.6	11	100	645	<0.02	1.2	<1	<0.09	226	<0.3	0.5
Yorogu Agagabisi	17	0.52	7.53	6	<0.3	0.11	2.1	<0.9	90	915	<0.02	2.0	<1	<0.09	221	<0.3	0.6
Yorogu Atiabisi	0.2	0.11	4.19	294	0.8	0.10	1.5	0.9	12	242	1.80	<0.1	<1	<0.09	526	0.3	0.5
Sekoti	32	<0.04	8.21	30	0.4	<0.07	1.8	<0.9	24	567	0.12	0.1	<1	<0.09	106	<0.3	<0.4
Bolga Daporitindongo	0.4	<0.04	15.79	6	<0.3	0.37	1.3	1.6	19	920	0.10	0.4	<1	0.10	412	1.1	<0.4
Bukere	0.4	<0.04	8.60	<4	0.4	0.21	1.4	1.1	40	1245	0.06	0.2	<1	<0.09	617	0.6	<0.4
Bolga Soe	16	0.40	13.38	8	0.6	0.08	0.9	2.4	14	555	0.03	1.6	<1	<0.09	134	<0.3	<0.4
Yorogu	46	<0.04	13.91	<4	0.4	<0.07	<0.7	<0.9	3	503	<0.02	1.4	<1	<0.09	128	<0.3	<0.4
Bongo Sabo	3.1	0.31	5.15	7122	3.5	0.57	3.0	2.1	8	285	1.08	<0.1	<1	<0.09	101	1.1	0.7
Bongo Nabisi	26	0.52	8.57	21	0.4	0.11	1.0	7.9	56	446	<0.02	1.8	<1	<0.09	71	0.3	<0.4
Bongo Anabisi	40	0.54	22.47	8	0.4	0.08	1.1	6.6	97	623	0.03	1.7	<1	<0.09	110	0.3	<0.4
Bongo Centre	34	0.56	10.81	<4	0.6	0.10	1.4	<0.9	7	1116	<0.02	0.9	<1	0.10	222	0.4	0.4
Bongo Anafobisi	16	<0.04	11.83	<4	1.0	0.09	1.2	<0.9	14	451	0.02	3.1	<1	<0.09	116	<0.3	<0.4
Borogo	18	0.07	7.45	<4	1.9	<0.07	0.8	<0.9	25	511	<0.02	1.2	<1	<0.09	148	<0.3	0.4
Yichene	14	<0.04	7.06	<4	0.6	<0.07	1.2	<0.9	18	344	<0.02	1.1	2	<0.09	105	<0.3	<0.4
Yorogu Abagabisi	13	0.35	8.65	<4	0.5	0.11	1.7	9.3	226	755	0.02	2.1	<1	<0.09	103	<0.3	<0.4
Yorogu Abagabisi	30	<0.04	37.57	<4	<0.3	0.13	1.3	1.2	110	763	<0.02	4.3	5	<0.09	113	<0.3	<0.4
Amenteyoko	11	<0.04	9.94	<4	<0.3	0.13	1.1	<0.9	80	215	0.02	1.7	<1	0.10	125	<0.3	<0.4
Apatanga	44	<0.04	13.63	<4	0.4	0.22	1.0	0.9	26	296	<0.02	1.5	<1	<0.09	12	<0.3	<0.4
Adaboya	12	<0.04	7.70	<4	0.4	0.10	2.4	3.2	64	1292	<0.02	2.7	<1	<0.09	411	<0.3	0.6
Sapero	10	<0.04	6.20	<4	0.5	0.11	1.8	7.5	249	840	<0.02	8.2	<1	0.13	108	<0.3	0.5
Beo	9.3	<0.04	7.07	<4	0.8	0.08	1.4	1.0	69	811	<0.02	0.6	<1	0.10	21	<0.3	0.5
Kumbosigo	4.3	<0.04	3.92	<4	0.4	0.08	1.2	<0.9	135	373	<0.02	5.3	<1	0.10	5	<0.3	<0.4
Kumbosigo Angl'n Sch	14	<0.04	8.95	<4	<0.3	0.23	2.3	26	165	776	<0.02	3.1	<1	<0.09	10	0.4	0.4
Kumbosigo	15	<0.04	11.63	<4	0.4	0.26	2.4	7.2	203	1055	0.02	2.3	<1	<0.09	46	<0.3	0.6
Kumbosigo	20	<0.04	14.80	<4	0.4	0.23	2.5	8.1	50	1241	<0.02	2.0	<1	<0.09	46	<0.3	0.6
Zuarungu Katanga	11	<0.04	7.77	<4	0.8	0.18	2.5	1.9	56	1305	0.02	0.8	<1	0.10	33	<0.3	0.5
Zuarungu	12	<0.04	7.49	<4	0.4	0.23	2.5	1.6	153	817	0.02	5.5	<1	<0.09	71	<0.3	0.9
Zuarungu Benkote	14	<0.04	11.75	<4	0.6	0.23	2.8	2.9	52	1102	<0.02	2.3	<1	<0.09	37	<0.3	0.5
Asonge	7.9	<0.04	9.15	<4	0.8	0.16	2.4	<0.9	15	181	0.03	9.8	<1	<0.09	1	<0.3	0.9
Asonge	5.8	<0.04	12.71	316	1.0	0.47	2.1	2.6	9	333	0.30	2.5	<1	<0.09	47	<0.3	<0.4
Zuarungu Moshie	16	<0.04	5.43	<4	<0.3	0.14	1.4	14	324	473	<0.02	2.2	<1	<0.09	26	<0.3	<0.4
Kongo	15	<0.04	7.39	<4	<0.3	0.18	2.3	1.2	216	304	0.02	1.3	<1	<0.09	6	<0.3	<0.4
Kongo	1.4	<0.04	53.88	<4	<0.3	0.21	1.1	<0.9	23	32	<0.02	0.5	3	<0.09	1	<0.3	<0.4
Zoa	1.6	<0.04	110.01	<4	<0.3	0.15	1.1	<0.9	26	44	<0.02	0.4	26	0.10	<1	<0.3	<0.4

Appendix 2C cont'd...

Locality	Li $\mu\text{g l}^{-1}$	Be $\mu\text{g l}^{-1}$	B $\mu\text{g l}^{-1}$	Al $\mu\text{g l}^{-1}$	Cr $\mu\text{g l}^{-1}$	Co $\mu\text{g l}^{-1}$	Ni $\mu\text{g l}^{-1}$	Cu $\mu\text{g l}^{-1}$	Zn $\mu\text{g l}^{-1}$	Sr $\mu\text{g l}^{-1}$	Y $\mu\text{g l}^{-1}$	Mo $\mu\text{g l}^{-1}$	As $\mu\text{g l}^{-1}$	Cd $\mu\text{g l}^{-1}$	Ba $\mu\text{g l}^{-1}$	Pb $\mu\text{g l}^{-1}$	Ge $\mu\text{g l}^{-1}$
Nangodi Yakoti	4.8	<0.04	62.17	<4	<0.3	0.09	0.8	<0.9	11	170	<0.02	2.4	2	<0.09	1	<0.3	<0.4
Damulugu	6.5	<0.04	18.72	<4	<0.3	0.24	0.8	3.9	32	159	<0.02	2.7	2	0.12	10	<0.3	0.5
Pelungu	3.2	<0.04	46.76	<4	<0.3	<0.07	1.3	<0.9	5	304	<0.02	5.3	<1	<0.09	55	<0.3	0.5
Zanlerigu	11	<0.04	31.20	<4	<0.3	0.22	0.8	<0.9	32	173	<0.02	0.8	2	<0.09	1	<0.3	<0.4
Daliga Zanlerigu	8.5	<0.04	9.33	<4	<0.3	0.12	1.1	<0.9	21	151	<0.02	14.3	2	0.11	1	<0.3	<0.4
Nangodi Nakpaligo	5.9	<0.04	6.26	<4	<0.3	0.14	1.0	2.6	37	977	0.02	2.6	<1	<0.09	1	<0.3	<0.4
Nangodi	2.8	<0.04	18.30	<4	<0.3	0.15	0.9	<0.9	17	256	0.02	3.7	4	<0.09	5	<0.3	<0.4
Nangodi Clinic	4.3	<0.04	29.56	<4	<0.3	0.15	0.9	<0.9	5	346	<0.02	3.7	152	<0.09	10	<0.3	<0.4
Nangodi Nyobota	16	<0.04	7.12	<4	<0.3	0.10	1.1	<0.9	87	242	0.04	4.5	2	<0.09	146	<0.3	<0.4
Sekoti Kotentabiga	16	<0.04	11.34	<4	<0.3	0.11	1.3	<0.9	30	188	<0.02	9.4	<1	<0.09	14	<0.3	<0.4
Sekoti Kotendabiga	7.5	<0.04	22.58	<4	<0.3	0.07	0.9	<0.9	12	173	<0.02	1.3	4	<0.09	1	<0.3	<0.4
Sekoti	33	<0.04	15.05	28	<0.3	0.09	1.2	<0.9	264	833	<0.02	0.4	<1	<0.09	68	<0.3	<0.4
Sekoti Clinic	26	<0.04	9.74	<4	<0.3	<0.07	1.3	<0.9	14	867	<0.02	0.2	<1	<0.09	129	<0.3	<0.4
Sekoti	29	<0.04	11.09	4	<0.3	0.07	1.0	3.4	49	586	<0.02	0.3	<1	<0.09	64	<0.3	<0.4
Nyua	18	<0.04	6.34	<4	<0.3	<0.07	<0.7	13	33	552	<0.02	0.3	<1	<0.09	51	<0.3	0.5
Nyua	29	<0.04	13.97	42	0.4	0.20	2.1	<0.9	7	710	0.06	0.3	2	<0.09	90	<0.3	0.4
Datoko Kulpeliga	11	<0.04	5.83	<4	<0.3	0.07	1.4	20	92	689	<0.02	0.4	<1	0.09	220	<0.3	<0.4
Datoko Kulpeliga	17	<0.04	8.97	68	0.4	0.07	1.0	<0.9	64	854	0.03	0.7	<1	0.09	118	<0.3	<0.4
Datoko	4.8	<0.04	10.57	<4	<0.3	0.20	1.0	2.1	21	342	0.10	1.0	<1	<0.09	25	<0.3	<0.4
Shiega	1.0	<0.04	18.28	<4	<0.3	<0.07	0.9	<0.9	4	52	<0.02	0.2	7	<0.09	2	<0.3	<0.4
Shiega Tindongo	1.0	<0.04	10.76	<4	<0.3	0.13	1.2	<0.9	25	32	<0.02	0.5	<1	<0.09	1	<0.3	<0.4
Nangodi Takoti	5.4	<0.04	85.11	<4	<0.3	0.11	1.4	<0.9	15	185	0.02	7.0	<1	<0.09	14	<0.3	<0.4
Pelungu	6.4	<0.04	18.17	<4	<0.3	<0.07	<0.7	21	42	311	<0.02	1.0	<1	<0.09	20	<0.3	<0.4
Dusi	3.4	<0.09	19.97	<8	0.3	0.10	1.5	2.7	39	125	0.03	1.0	<1	<0.1	2	0.15	<0.7
Dusi Gari	1.1	<0.09	9.15	<8	0.3	0.30	1.7	0.6	5	89	0.03	0.4	6	<0.1	<1	0.11	<0.7
Gari	0.6	<0.09	57.50	<8	0.4	0.11	1.7	1.1	47	49	0.04	0.3	<1	<0.1	<1	0.10	<0.7
Shiega Tindongo	1.0	<0.09	24.26	<8	0.2	0.17	1.7	0.5	10	68	0.03	0.6	2	<0.1	<1	0.11	<0.7
Yameriga	3.9	<0.09	13.03	<8	0.2	0.21	1.7	1.7	29	127	0.02	0.5	7	<0.1	<1	0.08	<0.7
Gbanbiega	3.3	<0.09	9.65	<8	0.3	0.77	2.6	3.1	14	83	0.05	1.9	2	<0.1	11	0.12	<0.7
Tongo	9.7	<0.09	8.13	<8	0.5	0.11	1.7	4.2	101	273	0.01	2.0	<1	<0.1	50	0.18	<0.7
Zuarungu	6.4	<0.09	5.63	<8	0.4	0.16	2.2	1.5	61	493	<0.01	0.5	<1	<0.1	58	<0.05	<0.7
Zuarungu Zono	5.3	<0.09	4.62	<8	0.3	0.10	1.5	3.1	110	360	0.01	1.2	<1	<0.1	7	0.11	<0.7
Yazore Sakwati	1.7	<0.09	8.82	<8	0.3	0.19	2.3	2.9	97	65	0.01	0.2	<1	<0.1	1	0.06	<0.7
Yazore Kpatia	18	<0.09	32.17	<8	0.3	0.28	2.8	1.1	38	511	0.04	3.1	2	<0.1	<1	0.05	0.7
Zuarungu Kangoo	4.1	<0.09	3.17	<8	0.4	0.07	0.8	7.6	201	203	<0.01	0.7	<1	<0.1	9	0.21	<0.7
Dulugu	12	<0.09	10.13	<8	0.4	0.18	1.9	4.1	106	389	0.03	1.8	<1	<0.1	26	0.15	<0.7

Appendix 2C cont'd...

Locality	Li $\mu\text{g l}^{-1}$	Be $\mu\text{g l}^{-1}$	B $\mu\text{g l}^{-1}$	Al $\mu\text{g l}^{-1}$	Cr $\mu\text{g l}^{-1}$	Co $\mu\text{g l}^{-1}$	Ni $\mu\text{g l}^{-1}$	Cu $\mu\text{g l}^{-1}$	Zn $\mu\text{g l}^{-1}$	Sr $\mu\text{g l}^{-1}$	Y $\mu\text{g l}^{-1}$	Mo $\mu\text{g l}^{-1}$	As $\mu\text{g l}^{-1}$	Cd $\mu\text{g l}^{-1}$	Ba $\mu\text{g l}^{-1}$	Pb $\mu\text{g l}^{-1}$	Ge $\mu\text{g l}^{-1}$
Dulugu	7.8	<0.09	5.87	<8	0.4	0.18	2.1	3.6	262	555	0.01	0.4	<1	<0.1	36	0.08	<0.7
Gambibigo	6.3	<0.09	5.13	<8	0.3	0.14	2.0	9.5	300	755	<0.01	2.2	<1	<0.1	89	0.21	<0.7
Gambibigo	5.0	<0.09	7.45	<8	0.6	0.12	1.5	2.3	73	577	0.01	0.7	<1	<0.1	62	0.06	<0.7
Gambibigo	9.3	<0.09	6.43	<8	0.7	0.14	2.1	30	30	673	<0.01	0.1	<1	<0.1	86	0.32	<0.7
Dulugu	11	<0.09	8.16	<8	0.4	0.20	2.9	10	333	721	0.03	2.2	<1	<0.1	98	0.22	<0.7
Tongobeo	9.3	<0.09	9.26	<8	0.4	0.13	1.4	12	225	314	0.01	3.5	<1	<0.1	24	0.26	<0.7
Zuarungu	7.1	<0.09	5.31	<8	0.4	0.14	1.7	6.0	347	450	0.02	0.7	<1	<0.1	27	0.17	<0.7
Beo	12	<0.09	8.36	<8	0.4	0.12	2.2	10	24	438	<0.01	3.1	<1	<0.1	8	0.16	<0.7
Beo	5.2	<0.09	5.98	16	0.3	0.12	1.4	1.6	27	257	<0.01	2.5	<1	<0.1	46	<0.05	<0.7
Baare	6.6	<0.09	6.78	<8	0.3	0.07	1.3	0.6	8	246	<0.01	4.0	<1	<0.1	26	0.09	<0.7
Baare Tongo	8.5	<0.09	7.42	<8	0.3	0.15	1.9	3.9	23	313	0.02	2.4	<1	<0.1	37	0.19	<0.7
Baare	8.8	<0.09	15.72	<8	0.2	0.11	1.8	2.1	93	362	0.02	1.7	<1	<0.1	119	0.06	<0.7
Tongo Local Council	3.8	<0.09	5.70	<8	0.3	0.16	2.2	18	341	301	0.05	1.7	<1	<0.1	49	0.24	<0.7
Tongo	19	<0.09	11.35	<8	0.3	0.12	1.0	1.7	13	221	<0.01	7.6	<1	<0.1	19	0.13	<0.7
Gorogu	9.7	<0.09	8.28	<8	0.4	0.07	1.2	1.8	93	409	0.04	1.8	<1	<0.1	42	0.06	<0.7
Winkogo Alabisi	8.3	<0.09	4.71	<8	0.5	0.08	1.5	17	68	449	0.02	0.7	<1	<0.1	103	0.14	<0.7
Winkogo	12	<0.09	6.30	<8	0.5	0.08	1.1	1.4	7	616	0.01	0.5	<1	<0.1	78	0.09	<0.7
Awaradoni	7.0	<0.09	5.27	<8	0.5	0.36	2.6	2.3	22	618	<0.01	0.9	<1	<0.1	97	0.07	<0.7
Abokrebisi	14	<0.09	6.42	<8	0.4	0.07	1.3	12	282	487	0.01	0.3	<1	<0.1	65	0.37	<0.7
Abokrebisi	11	<0.09	5.89	<8	0.5	0.16	2.0	2.8	15	944	0.02	0.2	<1	<0.1	67	0.08	<0.7
Gambibigo	7.4	<0.09	4.39	<8	0.5	0.06	1.1	3.3	15	363	<0.01	0.2	<1	<0.1	45	0.05	<0.7
Tindonmolugu	18	<0.09	6.93	<8	0.3	0.13	1.6	3.5	124	344	<0.01	1.4	<1	<0.1	181	0.10	<0.7
Bolgatanga	<0.4	<0.09	17.21	<8	0.4	0.19	1.6	2.0	5	1012	0.13	0.3	1	<0.1	353	0.17	<0.7
Tindonmolugu	11	<0.09	7.25	<8	0.4	0.07	1.2	9.1	24	338	<0.01	1.3	9	<0.1	82	0.37	<0.7
Sokabisi	6.1	<0.09	2.42	<8	4.7	0.04	1.8	2.1	5	192	<0.01	0.7	<1	<0.1	96	0.14	<0.7
Tanzui Sokabisi	4.1	0.83	3.66	<8	0.5	0.07	1.1	12	83	324	<0.01	0.4	<1	<0.1	104	0.34	<0.7
Yikene	6.6	0.39	6.19	<8	1.6	0.06	1.0	0.7	5	298	<0.01	1.0	<1	<0.1	104	0.12	<0.7
Sokabisi	10	0.93	6.13	<8	0.4	0.08	1.4	18	436	508	<0.01	1.3	<1	<0.1	147	0.45	<0.7
Zaare	9.7	0.42	22.34	<8	0.4	0.06	1.3	1.3	12	485	<0.01	2.2	<1	<0.1	63	0.08	<0.7
Gowrie	4.0	<0.09	4.75	18	1.0	0.17	1.0	1.1	4	218	0.03	0.2	<1	<0.1	127	0.08	<0.7
Gowrie	7.4	0.27	13.27	<8	0.8	0.10	1.3	13	110	416	0.01	0.6	<1	<0.1	202	0.32	<0.7
Vea-Gunga	13	0.29	6.23	<8	1.2	<0.03	0.9	2.3	117	227	0.01	2.1	<1	<0.1	87	0.12	<0.7
Vea-Akugrebisi	31	0.22	16.69	14	0.3	0.15	1.3	0.7	21	546	0.01	2.7	<1	<0.1	114	<0.05	<0.7
Bongo Kunkoa	20	0.39	13.04	19	0.6	0.04	1.1	4.6	11	490	<0.01	1.7	<1	<0.1	98	0.09	<0.7
Bongo Kupelingo	14	0.10	8.96	<8	0.3	0.05	0.7	1.7	130	469	<0.01	2.2	<1	<0.1	78	0.11	0.9
Dua	27	<0.09	37.20	<8	0.3	0.43	3.0	3.0	43	1893	0.06	4.8	<1	<0.1	324	0.06	<0.7

Appendix 2C cont'd...

Locality	Li $\mu\text{g l}^{-1}$	Be $\mu\text{g l}^{-1}$	B $\mu\text{g l}^{-1}$	Al $\mu\text{g l}^{-1}$	Cr $\mu\text{g l}^{-1}$	Co $\mu\text{g l}^{-1}$	Ni $\mu\text{g l}^{-1}$	Cu $\mu\text{g l}^{-1}$	Zn $\mu\text{g l}^{-1}$	Sr $\mu\text{g l}^{-1}$	Y $\mu\text{g l}^{-1}$	Mo $\mu\text{g l}^{-1}$	As $\mu\text{g l}^{-1}$	Cd $\mu\text{g l}^{-1}$	Ba $\mu\text{g l}^{-1}$	Pb $\mu\text{g l}^{-1}$	Ge $\mu\text{g l}^{-1}$
Dua	7.3	<0.09	4.41	<8	0.4	0.13	1.2	0.7	14	166	0.03	1.0	<1	<0.1	27	0.09	<0.7
Akanaba	39	<0.09	10.71	<8	0.4	0.54	4.2	1.2	61	424	0.06	2.2	<1	<0.1	125	0.08	<0.7
Zaare Ayoribisi	22	0.47	17.21	<8	0.4	0.07	1.3	0.5	3	373	0.03	2.6	<1	<0.1	56	<0.05	<0.7
Zaare Avombisi	4.5	0.20	7.41	<8	1.8	0.05	1.4	0.6	5	827	0.01	0.3	<1	<0.1	503	0.11	0.7
Yorogo Sorobisi	11	0.29	9.48	<8	1.1	0.06	1.3	0.4	5	501	<0.01	0.9	<1	<0.1	165	0.06	<0.7
Bolga Soe	11	0.42	8.90	<8	0.7	0.06	1.2	1.0	28	506	<0.01	1.0	<1	<0.1	173	0.06	<0.7
Bolga Soe	61	<0.09	71.04	<8	0.3	0.18	2.4	2.5	58	661	0.15	15.2	<1	<0.1	58	0.33	<0.7
Yorogo	11	<0.09	18.73	<8	0.4	0.18	2.0	3.1	89	403	0.03	2.0	2	<0.1	89	0.44	<0.7
Yorogo	34	<0.09	10.01	<8	0.3	0.09	1.8	1.0	11	409	0.04	4.5	<1	<0.1	78	0.12	<0.7
Yorogo Abangabisi	36	<0.09	7.45	<8	0.3	0.17	2.2	0.9	15	463	0.02	1.0	<1	<0.1	197	0.07	<0.7

Detection limits are 3 σ about the variation on the blank concentration.

APPENDIX 2D. Trace-element data for water samples from the Bolgatanga area, analysed by ICP-MS.

Locality	Rb $\mu\text{g l}^{-1}$	Sb $\mu\text{g l}^{-1}$	Cs $\mu\text{g l}^{-1}$	La $\mu\text{g l}^{-1}$	Ce $\mu\text{g l}^{-1}$	Pr $\mu\text{g l}^{-1}$	Nd $\mu\text{g l}^{-1}$	Sm $\mu\text{g l}^{-1}$	Eu $\mu\text{g l}^{-1}$	Gd $\mu\text{g l}^{-1}$	Tb $\mu\text{g l}^{-1}$	Dy $\mu\text{g l}^{-1}$	Ho $\mu\text{g l}^{-1}$	Er $\mu\text{g l}^{-1}$	Tm $\mu\text{g l}^{-1}$	Yb $\mu\text{g l}^{-1}$	Lu $\mu\text{g l}^{-1}$	U $\mu\text{g l}^{-1}$
Gowrie	0.61	<0.07	0.06	<0.04	<0.07	<0.06	<0.04	<0.06	0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	2.47
Yorogo Abangabisi	1.03	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.20
Yorogu Agagabisi	3.51	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.27
Yorogo Atiabisi	23	<0.07	0.17	5.74	2.58	1.83	6.81	1.17	0.37	0.90	0.11	0.48	0.09	0.19	<0.05	0.17	<0.05	0.08
Sekoti	1.22	<0.07	<0.06	0.43	0.12	0.13	0.53	0.09	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.70
Bolga Daporitindongo	14	<0.07	0.07	0.12	<0.07	<0.06	0.14	<0.06	0.05	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.07
Bukere	16	<0.07	<0.06	0.11	<0.07	<0.06	0.11	<0.06	0.07	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.19
Bolga Soe	0.79	<0.07	<0.06	0.08	<0.07	<0.06	0.07	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.12
Yorogu	3.09	<0.07	0.94	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	6.16
Bongo Sabo	8.83	0.10	0.28	2.42	4.33	0.69	2.63	0.46	0.16	0.38	0.05	0.20	<0.05	0.09	<0.05	0.07	<0.05	0.35
Bongo Nabisi	0.73	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.14
Bongo Anabisi	1.03	<0.07	0.20	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.99
Bongo Centre	1.45	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.33
Bongo Anafobisi	0.24	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.41
Borogo	0.17	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.07
Yichene	0.10	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.13
Yorogo Abagabisi	1.93	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.01
Yorogo Abagabisi	0.13	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.74
Amenteyoko	0.15	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.72
Apatanga	0.15	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.26
Adaboya	0.14	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	0.05	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.92
Sapero	0.63	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	2.04
Beo	0.20	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.06
Kumbosigo	0.43	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.19
Kumbosigo Angl'n Sch	0.69	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	2.26
Kumbosigo	0.53	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.16
Kumbosigo	0.58	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.53
Zuarungu Katanga	0.21	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.84
Zuarungu	0.49	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.74
Zuarungu Benkote	0.56	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.45
Asonge	0.42	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.10
Asonge	4.00	0.09	<0.06	0.21	0.22	<0.06	0.14	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.15
Zuarungu Moshie	0.40	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.52
Kongo	0.70	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.36
Kongo	0.20	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	<0.05
Zoa	0.40	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	<0.05

Appendix 2D cont'd...

Locality	Rb $\mu\text{g l}^{-1}$	Sb $\mu\text{g l}^{-1}$	Cs $\mu\text{g l}^{-1}$	La $\mu\text{g l}^{-1}$	Ce $\mu\text{g l}^{-1}$	Pr $\mu\text{g l}^{-1}$	Nd $\mu\text{g l}^{-1}$	Sm $\mu\text{g l}^{-1}$	Eu $\mu\text{g l}^{-1}$	Gd $\mu\text{g l}^{-1}$	Tb $\mu\text{g l}^{-1}$	Dy $\mu\text{g l}^{-1}$	Ho $\mu\text{g l}^{-1}$	Er $\mu\text{g l}^{-1}$	Tm $\mu\text{g l}^{-1}$	Yb $\mu\text{g l}^{-1}$	Lu $\mu\text{g l}^{-1}$	U $\mu\text{g l}^{-1}$
Nangodi Yakoti	0.47	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.32
Damulugu	0.26	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	<0.05
Pelungu	0.55	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.24
Zanlerigu	0.24	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.15
Daliga Zanlerigu	0.32	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.07
Nangodi Nakpaligo	0.11	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.33
Nangodi	0.28	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.15
Nangodi Clinic	0.46	0.28	0.08	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.21
Nangodi Nyobota	1.81	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.10
Sekoti Kotentabiga	0.54	<0.07	0.07	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.06
Sekoti Kotendabiga	0.41	0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.14
Sekoti	1.65	<0.07	0.12	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	7.88
Sekoti Clinic	0.74	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	2.11
Sekoti	1.89	<0.07	0.10	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.09
Nyua	0.25	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.39
Nyua	1.23	<0.07	<0.06	0.09	0.14	<0.06	0.14	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.93
Datoko Kulpeliga	0.46	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.75
Datoko Kulpeliga	0.83	<0.07	0.08	0.06	0.07	<0.06	0.08	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	1.00
Datoko	0.53	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	2.16
Shiega	0.12	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	<0.05
Shiega Tindongo	0.21	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	<0.05
Nangodi Takoti	0.33	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.36
Pelungu	0.32	<0.07	<0.06	<0.04	<0.07	<0.06	<0.04	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	0.10
Dusi	0.55	0.09	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.05	<0.05	<0.06	<0.05	<0.05	<0.05	<0.06
Dusi Gari	0.26	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	0.02	<0.02	<0.02	<0.03	0.02	<0.03	<0.06
Gari	0.30	0.08	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	<0.06
Shiega Tindongo	0.09	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	<0.06
Yameriga	0.33	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.07
Ghanbiega	0.40	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.09
Tongo	0.34	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.07
Zuarungu	0.23	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.31
Zuarungu Zono	0.18	<0.07	<0.09	<0.03	<0.02	<0.03	0.03	<0.06	<0.04	<0.06	<0.04	0.04	<0.02	<0.02	<0.03	0.03	<0.03	0.26
Yazore Sakwati	0.16	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	<0.06
Yazore Kpatia	0.58	0.10	<0.09	<0.03	<0.02	<0.03	0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.91
Zuarungu Kangoo	0.11	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	<0.06
Dulugu	0.31	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.04	<0.06	<0.04	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.30

Appendix 2D cont'd...

Locality	Rb $\mu\text{g l}^{-1}$	Sb $\mu\text{g l}^{-1}$	Cs $\mu\text{g l}^{-1}$	La $\mu\text{g l}^{-1}$	Ce $\mu\text{g l}^{-1}$	Pr $\mu\text{g l}^{-1}$	Nd $\mu\text{g l}^{-1}$	Sm $\mu\text{g l}^{-1}$	Eu $\mu\text{g l}^{-1}$	Gd $\mu\text{g l}^{-1}$	Tb $\mu\text{g l}^{-1}$	Dy $\mu\text{g l}^{-1}$	Ho $\mu\text{g l}^{-1}$	Er $\mu\text{g l}^{-1}$	Tm $\mu\text{g l}^{-1}$	Yb $\mu\text{g l}^{-1}$	Lu $\mu\text{g l}^{-1}$	U $\mu\text{g l}^{-1}$
Dulugu	0.36	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.21
Gambigbo	0.37	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	1.17
Gambigbo	0.59	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.09
Gambigbo	1.10	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.07
Dulugu	0.25	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	1.49
Tongobeo	0.64	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.29
Zuarungu	0.19	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	0.02	<0.02	0.02	<0.03	0.02	<0.03	0.39
Beo	0.52	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.35
Beo	0.70	<0.07	<0.09	<0.03	<0.02	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.15
Baare	0.25	<0.07	<0.09	<0.03	<0.02	<0.03	0.03	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.20
Baare Tongo	0.16	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.17
Baare	0.10	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.28
Tongo Local Council	0.18	<0.07	<0.09	0.04	0.05	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	0.02	<0.03	<0.02	<0.03	0.22
Tongo	0.22	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	0.02	<0.02	<0.02	<0.03	0.02	<0.03	0.13
Gorogu	0.14	<0.07	<0.09	0.03	<0.02	<0.03	0.03	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	0.02	<0.03	<0.02	<0.03	0.16
Winkogo Alabisi	0.20	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.08
Winkogo	0.36	<0.07	<0.09	<0.03	<0.02	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.16
Awaradoni	0.39	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.11
Abokrebisi	0.29	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.17
Abokrebisi	0.16	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	0.02	<0.03	<0.02	<0.03	0.30
Gambigbo	0.58	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	0.02	<0.02	<0.02	<0.03	<0.02	<0.03	<0.06
Tindonmolugu	1.11	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	0.02	<0.03	0.35
Bolgatanga	1.28	<0.07	<0.09	0.08	<0.02	<0.03	0.08	<0.06	0.04	<0.03	<0.03	0.02	<0.02	0.02	<0.03	0.02	<0.03	0.38
Tindonmolugu	0.15	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.32
Sokabisi	0.21	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	0.02	<0.02	<0.02	<0.03	<0.02	<0.03	<0.06
Tanzui Sokabisi	4.89	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.08
Yikene	0.38	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	<0.06
Sokabisi	4.61	<0.07	<0.09	<0.03	<0.02	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.17
Zaare	1.29	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.40
Gowrie	3.32	<0.07	<0.09	0.08	0.06	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.17
Gowrie	0.40	<0.07	<0.09	<0.03	<0.02	<0.03	0.05	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.07
Vea-Gunga	0.85	<0.07	<0.09	<0.03	<0.02	<0.03	0.03	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.13
Vea-Akugrebisi	2.46	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	0.02	<0.02	<0.02	<0.03	<0.02	<0.03	1.68
Bongo Kunkoa	2.12	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	0.02	<0.03	0.02	<0.03	0.33
Bongo Kupelingo	1.53	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.19
Dua	0.14	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	0.02	<0.03	<0.02	<0.03	5.66

Appendix 2D cont'd...

Locality	Rb $\mu\text{g l}^{-1}$	Sb $\mu\text{g l}^{-1}$	Cs $\mu\text{g l}^{-1}$	La $\mu\text{g l}^{-1}$	Ce $\mu\text{g l}^{-1}$	Pr $\mu\text{g l}^{-1}$	Nd $\mu\text{g l}^{-1}$	Sm $\mu\text{g l}^{-1}$	Eu $\mu\text{g l}^{-1}$	Gd $\mu\text{g l}^{-1}$	Tb $\mu\text{g l}^{-1}$	Dy $\mu\text{g l}^{-1}$	Ho $\mu\text{g l}^{-1}$	Er $\mu\text{g l}^{-1}$	Tm $\mu\text{g l}^{-1}$	Yb $\mu\text{g l}^{-1}$	Lu $\mu\text{g l}^{-1}$	U $\mu\text{g l}^{-1}$
Dua	0.25	<0.07	<0.09	<0.03	<0.02	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	0.02	<0.03	0.10
Akanaba	0.19	0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	3.57
Zaare Ayoribisi	0.67	<0.07	<0.09	<0.03	0.04	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.30
Zaare Avombisi	8.13	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	0.03	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.08
Yorogo Sorobisi	1.31	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.21
Bolga Soe	1.85	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.09
Bolga Soe	2.59	<0.07	0.37	<0.03	<0.02	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	0.02	<0.03	<0.02	<0.03	13.2
Yorogo	0.09	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.70
Yorogo	0.18	<0.07	<0.09	<0.03	<0.02	<0.03	0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.73
Yorogo Abangabisi	0.16	<0.07	<0.09	<0.03	<0.02	<0.03	<0.02	<0.06	<0.02	<0.03	<0.03	<0.02	<0.02	<0.02	<0.03	<0.02	<0.03	0.53

Detection limits are 3 σ about the variation of the blank concentration.

Concentrations of Ga < 0.1 $\mu\text{g l}^{-1}$ (except for Sample 10: 2.1 $\mu\text{g l}^{-1}$, Sample 32: 0.2 $\mu\text{g l}^{-1}$, Sample 71: 0.2 $\mu\text{g l}^{-1}$); Ti < 0.08 $\mu\text{g l}^{-1}$ (except Sample 4: 0.11 $\mu\text{g l}^{-1}$); Bi < 0.1 $\mu\text{g l}^{-1}$; Ag < 0.1 $\mu\text{g l}^{-1}$; Gd < 0.06 $\mu\text{g l}^{-1}$ (except Sample 4: 0.90 $\mu\text{g l}^{-1}$, Sample 10: 0.38 $\mu\text{g l}^{-1}$); Tb 0.04 $\mu\text{g l}^{-1}$ (except Sample 4: 0.11 $\mu\text{g l}^{-1}$, Sample 10: 0.05 $\mu\text{g l}^{-1}$); Dy < 0.05 $\mu\text{g l}^{-1}$ (except Sample 4: 0.48 $\mu\text{g l}^{-1}$, Sample 10: 0.20 $\mu\text{g l}^{-1}$); Ho: < 0.05 $\mu\text{g l}^{-1}$ (except Sample 4: 0.09 $\mu\text{g l}^{-1}$); Er: < 0.06 $\mu\text{g l}^{-1}$ (except Sample 4: 0.09 $\mu\text{g l}^{-1}$); Er: < 0.06 $\mu\text{g l}^{-1}$ (except Sample 4: 0.19 $\mu\text{g l}^{-1}$, Sample 10: 0.09 $\mu\text{g l}^{-1}$); Tm < 0.05 $\mu\text{g l}^{-1}$; Yb: < 0.05 $\mu\text{g l}^{-1}$, Sample 10: 0.07 $\mu\text{g l}^{-1}$; Lu: < 0.05 $\mu\text{g l}^{-1}$.

APPENDIX 2E. Microbiological data for water samples from the Bolgatanga area.

Locality	Field no	Sample source	Faecal coliforms (CFU 100 ml ⁻¹)	Total coliforms (CFU 100 ml ⁻¹)	Aerobic heterotrophic bacteria (CFU ml ⁻¹)	Total microbes (bacteria x 10 ⁻³ ml ⁻¹)
Gowrie	1	7	0	0	175	24.6
Yorogu Abagabisi	2	7	0	0	95	31.8
Yorogu Agagabisi	3	7	5	12	57	68.9
Yorogo Atiabisi	4	8	tntc	tntc	287	7.14
Sekoti	5	7	0	12	0	6.93
Bolga Daporitindongo	6	8	tntc	tntc	2190	13.9
Bukere	7	8	tntc	tntc	1105	10.0
Bolga Soe	8	7	0	0	10	17.5
Yorogu	9	7	62	6	200	26.4
Bongo Sabo	10	8	260	470	195	12.9
Bongo Nabisi	11	7	6	8	50	13.6
Bongo Anabisi	12	7	2	8	40	59.62
Bongo Centre	13	7	40	64	25	119
Bongo Anafobisi	14	7	4	2	230	12.91
Borogo	15	7	0	0	0	518
Yichene	16	7	2	2	30	21.8
Yorogo Abagabisi	17	7	0	2	6500	26.8
Yorogo Abagabisi	18	7	4	32	190	17.9
Amenteyoko	19	7	0	0	120	14.3
Apatanga	20	7	0	16	45	11.8
Adaboya	21	7	6	16	20	10.7
Sapero	22	7	0	0	35	9.82
Beo	23	7	4	12	35	10.7
Kumbosigo	24	7	0	0	10	9.82
Kumbosigo Angl'n Sch	25	7	0	0	50	10.7
Kumbosigo	26	7	0	0	55	23.2
Kumbosigo	27	7	0	0	105	17.9
Zuarungu Katanga	28	7	0	0	15	19.6
Zuarungu	29	7	58	172	5	36.6
Zuarungu Benkote	30	7	42	12	3150	18.7
Asonge	31	7	2	10	5	41.9
Asonge	32	8	tntc	tntc	tntc	9.82
Zuarungu Moshie	33	7	0	360	105	8.03
Kongo	34	7	4	0	735	21.4
Kongo	35	7	0	0	205	33.9
Zoa	36	7	0	0	35	25.0
Nangodi Yakoti	37	7	0	0	40	58.0
Damulugu	38	7	0	4	4700	25.6
Pelungu	39	7	4	8	2720	21.4
Zanlerigu	40	7	0	0	1200	15.2
Daliga Zanlerigu	41	7	0	0	90	4.46
Nangodi Nakpaligo	42	7	2	8	20	10.7
Nangodi	43	7	2	0	5	33.0
Nangodi Clinic	44	7	0	0	30	14.3
Nangodi Nyobota	45	7	0	0	60	60.7
Sekoti Kotentabiga	46	7	0	0		16.1
Sekoti Kotendabiga	47	7	0	0	185	9.82

Appendix 2E cont'd...

Locality	Field no	Sample source	Faecal coliforms (CFU 100 ml ⁻¹)	Total coliforms (CFU 100 ml ⁻¹)	Aerobic heterotrophic bacteria (CFU ml ⁻¹)	Total microbes (bacteria x 10 ⁻³ ml ⁻¹)
Sekoti	48	7	0	0	135	0.89
Sekoti Clinic	49	7	6	14	1660	9.82
Sekoti	50	7	0	0	1315	25.9
Nyua	51	7	10	58	50	73.2
Nyua	52	8	tntc	tntc	3595	10.7
Datoko Kulpeliga	53	7	2	4	55	18.7
Datoko Kulpeliga	54	7	2	0	75	11.6
Datoko	55	7	0	0	60	26.8
Shiega	56	7	58	158	35	3.57
Shiega Tindongo	57	7	6	4	10	26.8
Nangodi Takoti	58	7	0	0	695	17.0
Pelungu	59	7	4	80	820	25.9
Dusi	60	7	22	86	2025	9.82
Dusi Gari	61	7	0	2	195	8.93
Gari	62	7	36	56	65	28.6
Shiega Tindongo	63	7	0	0	50	12.5
Yameriga	64	7	0	0	0	119
Gbanbiega	65	7	0	0	175	34.8
Tongo	66	7	2	30	240	nd
Zuarungu	67	7	2	6	40	6.25
Zuarungu Zono	68	7	2	2	210	4.46
Yazore Sakwati	69	7	0	0	85	8.93
Yazore Kpatia	70	7	0	0	50	3.57
Zuarungu Kangoo	71	7	2	72	55	6.25
Dulugu	72	7	2	12	35	6.25
Dulugu	73	7	0	4	5	2.68
Gambibigo	74	7	28	136	225	15.2
Gambibigo	75	7	0	2	240	8.03
Gambibigo	76	7	0	0	10	5.36
Dulugu	77	7	0	0	70	4.46
Tongobeo	78	7	0	0	200	41.9
Zuarungu	79	7	6	18	260	5.36
Beo	80	7	0	0	10	5.36
Beo	81	7	8	80	130	42.8
Baare	82	7	0	6	80	12.5
Baare Tongo	83	7	0	0	nd	29.5
Baare	84	7	0	0	nd	20.5
Tongo Local Council	85	7	0	2	330	9.82
Tongo	86	7	0	2	305	45.5
Gorogu	87	7	78	tntc	855	27.7
Winkogo Alabisi	88	7	0	0	25	23.2
Winkogo	89	7	2	6	145	17.9
Awaradoni	90	7	0	0	30	11.6
Abokrebisi	91	7	6	18	40	29.5
Abokrebisi	92	7	0	0	50	8.03
Gambibigo	93	7	0	4	80	3.57
Tindonmolugu	94	7	0	12	1020	29.5

Appendix 2E cont'd...

Locality	Field no	Sample source	Faecal coliforms (CFU 100 ml ⁻¹)	Total coliforms (CFU 100 ml ⁻¹)	Aerobic heterotrophic bacteria (CFU ml ⁻¹)	Total microbes (bacteria x 10 ⁻³ ml ⁻¹)
Bolgatanga	95	7	42	92	tntc	10.7
Tindonmolugu	96	7	2	4	45	12.5
Sokabisi	97	7	0	0	55	18.7
Tanzui Sokabisi	98	7	24	24	70	nd
Yikene	99	7	0	0	80	nd
Sokabisi	100	7	102	78	25	nd
Zaare	101	7	0	4	185	nd
Gowrie	102	8	tntc	tntc	tntc	nd
Gowrie	103	7	nd	nd	3520	nd
Vea-Gunga	104	7	76	nd	195	nd
Vea-Akugrebisi	105	7	0	nd	60	nd
Bongo Kunkoa	106	7	4	nd	40	nd
Bongo Kupeligo	107	7	2	nd	22	nd
Dua	108	7	0	nd	15	nd
Dua	109	7	200	nd	50	nd
Akanaba	110	7	0	nd	640	nd
Zaare Ayoribisi	111	7	nd	0	60	nd
Zaare Avombisi	112	7	nd	0	40	nd
Yorogo Sorobisi	113	7	nd	0	270	nd
Bolga Soe	114	7	nd	0	65	nd
Bolga Soe	115	7	nd	0	5	nd
Yorogo	116	7	nd	0	225	nd
Yorogo	117	7	nd	0	115	nd
Yorogo Abangabisi	118	7	nd	0	20	nd

Sample source: 2: spring, 3: stream (includes dugouts), 7: borehole, 8: shallow well, 13: mine drainage.

nd: not determined.

Sample numbers 104-110: total coliforms not determined due to battery failure.

CFU: Colony-forming units.

tntc: too numerous to count.